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Subseabed Disposal Program Annual Report January to December 1980

Volume II Appendices (Principal Investigator Progress Reports) Part 1 of 2

Kenneth R. Hinga, Editor

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SUBSEABED DISPOSAL PROGRAM ANNUAL REPORT,
JANUARY TO DECEMBER 1980, #3
VOLUME II, #2
APPENDICES (PRINCIPAL INVESTIGATOR PROGRESS REPORTS), #3
Part 1 of 2

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Abstract

Volume II of the sixth annual report describing the progress and evaluating the status of the Subseabed Disposal Program contains the appendices referred to in Volume I, Summary and Status. Because of the length of Volume II, it has been split into two parts for publication purposes. Part 1 contains Appendices A-Q; Part 2 contains Appendices R-MM.

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Appendix A
Subseabed Disposal Safety Analysis
C. M. Koplik, D. A. Ensminger

SUBSEABED DISPOSAL SAFETY ANALYSIS

Progress Report

January 1, 1980 - December 31, 1980

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February 1981

Prepared for:

SANDIA NATIONAL LABORATORIES
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INTRODUCTION

Present information is now sufficient to initiate safety assessment studies that can provide a basis for judgments concerning the acceptability of subseabed disposal of nuclear wastes. Safety assessment studies can help guide the content of the SDP research program. Assessments can be made of alternative disposal options and procedures. Key parameters affecting safety can be identified and research focused on those areas where information is most required.

Safety analysis work was begun by TASC (The Analytic Sciences Corporation) in late 1979 and had three parts:

- Assessment of information available for application to subseabed safety analysis
- Definition of the methods and information requirements for assessments of subseabed disposal operations
- Development of a program plan for carrying out detailed studies.

The results of this work are documented in Ref. 1, "Subseabed Disposal Risk Assessment: Review and Program Plan."

Safety analysis for subseabed disposal was divided into two phases: pre-emplacment which includes all transportation, handling, and emplacment activities, and long-term (post-emplacment) which is concerned with the potential hazard after waste is safely emplaced. During the pre-emplacment phase (from tens to hundreds of years) there are both occupational and public risks. During the long-term phase there are potential risks to future generations and to faunal species within the ocean.

Pre-emplacment activities were broken down into the following elements: land transportation to a port facility, storage, transfer from dock to ship, sea transportation to the disposal site, and emplacement of waste packages. For the activities that take place on land, risk analyses are being performed within the continental disposal programs. These can be adapted for use in the SDP when the waste package and sea transportation requirements are better defined.

Comparatively little work has been done on sea transportation risks. Some research has been performed on sea transportation of spent nuclear fuel for which there is a considerable

operating experience. However, this is not directly applicable to subseabed disposal risk analysis due to the larger quantities of waste involved in disposal operations, differences in packaging and ship design, and the additional equipment required for emplacement. The various studies that have been performed suggest that sea transportation poses very low risks.

Long-term (post-emplacement) safety assessment is based on models for prediction of sediment and oceanic ion transport of waste materials. Little information from continental disposal programs was found to be directly applicable to these problems. The major elements of the disposal system and some of the outputs required for a safety assessment are listed in Table 1-1.

TABLE 1-1
SYSTEM ELEMENTS AND MODEL OUTPUTS

SYSTEM ELEMENT	OUTPUTS
Site Selection	Probability and/or Description: <ul style="list-style-type: none"> - Geologic Anomalies - Sudden Disruptive Events - Slow Processes - Intrusion Scenarios
Emplacement	Hole Closure Success Engineering Measures
Canister	Expected Lifetime Probability of Initial Failure
Waste Form	Release Rate by Nuclide
Chemical, Thermal, and Radiolytic Interactions	Effects on Canister Corrosion and Waste Form Dissolution Disruptive Effects Influence on Sediment Transport
Sediment Transport	Travel Time Release Rate to Benthic Boundary Layer Integrated Release Concentrations
Biological Transport	Concentration in Faunal Species at Risk Concentration in Aquatic Food Product
Physical Oceanographic Transport	Concentration in Water (Bathing) Concentration in Sediment (Shoreline)
Environmental Consequences	Environmental Concentrations Individual Dose Population Dose Health Effects Integrated Impacts

The models currently being developed at Sandia are deterministic. Two issues of a probabilistic nature must be addressed in a safety analysis:

- What credible scenarios can lead to the release of waste and what is the likelihood that they will occur?
- Given the uncertainty in models and data what level of confidence is there in safety predictions?

Complex probabilistic models to deal with the first issue are not appropriate at the present time. There appears to be little potential for disruptive events and processes to occur, due to the simplicity of the disposal system and the stability and uniformity of the sediment environment.

The second issue has received considerable attention in continental disposal programs. Some specialized techniques have been developed which appear applicable to subseabed disposal. Monte Carlo approaches (as described in Section 3.1) will be especially useful.

The next two chapters describe the safety analysis program plan which was developed based on the work in Ref. 1. An overview of the subseabed systems analysis effort of which this is a part is also provided.

2.

GENERAL SYSTEMS OVERVIEW

Figure 2-1 illustrates the subseabed systems analysis effort and shows TASC's functional roles. The objective of TASC's work is to carry out safety analyses of both pre- and post-emplacement waste management systems and to use this as an input to systems design. The safety analysis work begins with descriptions of scenarios which result in exposures to radioactive materials. These scenarios will depend upon the waste management facility and operational design and upon the various physical processes that may act to cause exposures. Various models are then applied to determine the radiological consequences of each scenario. Where possible, the probability that a given scenario will occur is estimated. The results of the safety analysis are then used to assess facility and operational design, and to determine requirements for data acquisition and modeling. A key element of this work will be the sensitivity and uncertainty analyses. The sensitivity analysis will determine those key model parameters upon which safety analysis predictions most depend. The uncertainty analysis

Figure 2-1 Systems Analysis Overview

will determine the relationship between input parameter distributions and output uncertainty.

A cost/benefit analysis will be performed in conjunction with Sandia based on economic models and data generated by Sandia and the results of the design safety studies. The economic analyses will combine information on the cost versus performance of waste management facilities and operations, the cost versus the effectiveness of data acquisition, and modeling costs.

As the waste management system becomes better defined and as the models and the data they depend on are improved, the design safety analysis will eventually evolve into a risk analysis of the subseabed disposal concept.

3. SAFETY ANALYSIS PROGRAM PLAN (FY'81 AND FY'82)

The TASC statement of work for FY'81 includes the following four tasks:

Task 1 Continuation of integration of Sandia thermal, physical, and chemical models with TASC risk models. Initiate development of a general computer code for

integrating model outputs for risk analysis of the disposal system. The code should be flexible, allowing changes in or replacement of individual submodels.

Develop a list and description of waste release scenarios. Scenario descriptions may be either deterministic or probabilistic.

Perform sensitivity and uncertainty analysis for specific submodels with emphasis on the compartmental models.

Task 2 Apply a cost/benefit analysis to data and modeling accuracy in conjunction with R.D. Klett, Sandia Labs. Determine the effect of parameter uncertainty and model complexity on the accuracy of model output. Identify critical parameters and the areas requiring further research and data acquisition.

Perform integrated model analysis. Determine sensitivity of risk estimates to changes in model parameters and assumptions. Identify areas of uncertainty significant to risk assessment.

Task 3 Continue investigation of sea transport risks in conjunction with J. McClure, Sandia Labs.

Task 4 Investigate experiment optimization as it applies to Task 2.

A general breakdown of the work for both FY'81 and FY'82 is given in Figure 3-1. In the figure, the work is organized into four main areas roughly corresponding to the tasks in the above statement of work. The four areas are post-emplacement studies (analysis of repository performance following emplacement of wastes in ocean sediments), a cost/benefit study, pre-emplacement studies (analysis of waste management activities occurring prior to emplacement of wastes), and optimal experimental design.

3.1 POST-EMPLACEMENT STUDIES

As indicated on the line items in Figure 3-1, TASC will:

Develop systems-level models for consequences of release to oceans - The models will include the following: a flexible compartmental model for biological and oceanographic transport; a pathways-to-man model; a dosimetry model for external exposure, ingestion, and inhalation of radionuclides;

FY '81

FY '82

Figure 3-1 Work Breakdown for FY'81 and FY'82

and a health-effects model. For ingestion and inhalation, the new INREM-II computer code (Ref. 2) will be used. External exposure will be based on NRC's Regulatory Guide 1.109 (Ref. 3). A simple health-effects model based on ICRP 26 (Ref. 4) and the BEIR-III report (Ref. 5) will be employed.

Integrate codes and perform baseline safety analysis - The computer modules for radionuclide inventory, canister failure, waste leach, transport through sediments, and consequences of release will be integrated. Radionuclide inventories of spent fuel and HLW are currently on data files for times up to 5 million years. ORIGEN2 (Ref. 6) will be the basis for any additional inventory calculations that might be necessary at some future time. Baseline safety analyses will be carried out and an interim report issued.

Perform sensitivity study of integrated models - Sensitivity of the baseline safety analysis to variations in input parameters will be evaluated. A key requirement for this will be input parameter ranges and design limits. Additional analyses will be carried out in FY'82 based on alternative waste release scenarios.

Address model complexity and uncertainty - The initial focus of this task will be the Sandia model for biological ocean transport. Model complexity will be assessed using Monte Carlo simulation techniques. The objective is to quantify the tradeoffs between models of varying degrees of complexity. The more complex a model is, the better it may represent the physical processes under study. However, a simpler model has the advantage of requiring estimation of fewer parameters. Model sensitivity and uncertainty analyses will also be carried out using Monte Carlo simulation techniques. These techniques are especially applicable to large computer codes with significant uncertainties in input parameters (such as ecosystem, multicompartamental models).

Figure 3.1-1 illustrates the Monte Carlo approach. Each input model parameter is assigned a probability density distribution (normal, uniform, log-normal, etc.). From these distributions sets of input parameter values are chosen, each set representing a possible physical situation. The model is run for each set of input parameter values and a statistical analysis is performed on the output. Model complexity is assessed by changing the model structure (for example, reducing the number of compartments in multicompartamental models) and performing a second Monte Carlo simulation. The benefit of more accurately determining model parameters may be quantitatively assessed by changing parameter distributions and performing additional simulations.

Figure 3.1-1 Monte Carlo Approach

Computer codes available at TASC for this analysis include MONC (Ref. 7), SAS (Ref. 7) and Latin Hypercube (Ref. 8). Since the latter code appears to represent the best current approach to Monte Carlo simulation, a description of the approach is appropriate here. The Latin Hypercube code generates the random parameter values (see Fig. 3.1-1) by Latin hypercube sampling (LHS) rather than by random sampling. An LHS is obtained by dividing each parameter distribution into exactly n intervals, each interval containing probability $1/n$. A set of input parameter values is chosen by selecting a point from an interval chosen at random for each input parameter. Points are selected within each interval taking into account the density of the variable within that interval. The process is repeated n times to produce n sets of input parameter values. The only requirement imposed is that for the entire set of parameter values each interval must be selected exactly once. The benefit derived from LHS is that, under quite general conditions, far fewer monte carlo simulations are required as compared to simple random sampling.

Develop list and description of waste release scenarios -
Alternative waste release scenarios will be described; accident scenarios will be included.

2.2 COST/BENEFIT STUDY

Scope relationship between performance requirements and design requirements - Acceptability criteria and possible performance objectives for subseabed disposal will be assessed. The "retention quotient" method (Ref. 9) will be used to relate performance requirements to design and model requirements. The "retention quotient" (RQ) method uses a type of hazard index. The RQ for a single radionuclide is defined as the product of its inventory in the waste and an appropriate dose conversion factor, divided by a selected allowable dose. The RQ may be viewed as the attenuation of hazard needed to reduce the hazard of the original inventory to allowable proportions. The effective RQ of the waste is then defined as the RQ as it is reduced by elements of the repository system -- e.g., the waste form, sediment barrier, etc. This reduction of the effective RQ can be illustrated graphically and provides a simple means for relating possible performance requirements to repository design requirements.

Develop and apply cost/benefit models for disposal systems - This work is closely connected to the sensitivity analyses carried out in Task 1. Simplified cost models for both pre- and post-emplacement will be developed and applied.

2.3 PRE-EMPLACEMENT STUDIES

It is anticipated that most of the FY'81 pre-emplacment work will involve a first-cut sea transportation safety analysis. As the parameters for canister size, thermal loading, etc. become better defined by post-emplacement criteria, this analysis will be broadened to include land transportation, storage, and handling operations as they are considered. Simple models of radionuclide transport in the air and sea water will be employed, the latter to be based on the systems-level, post-emplacement models being developed in Task 1. The topics to be addressed, indicated as line items in Figure 3-1, are:

Analysis of sea transportation accident statistics - Available literature will be reviewed to establish a data base for evaluating the probabilities of sea transportation accidents. Identification of the spatial distribution of ship accident rates with respect to the distance from port, traffic densities, size of other ships, and weather is of particular interest. Promising data sources include previous studies by Haeberlin (Ref. 10) and Nagakura (Ref. 11) as well as U.S. Navy climatic data bases available through the Transportation Technology Center at Sandia. Other potential resources include the U.S. Coast Guard, the MIT Ocean Engineering Department, the Maritime Research Information System, and periodicals such as the Journal of Navigation.

Reference facility design and operation - Preliminary operative designs for port, ship, and emplacement facilities are necessary inputs to the pre-emplacment risk analysis. The Boeing study (Ref. 12) will be used to formulate a working description of shipboard operations for use in the pre-emplacment risk analysis. This will involve storing canisters aboard ship in a water basin (no transport cask) and emplacing them via the penetrometer concept. Refinements will later be made to these facility and operational designs to accommodate port, ship, and emplacement designs for the drilled-hole concept (Atlantic Ocean). Logistical models of waste generation developed by Stoller Corp. (DISFUL) and Oak Ridge National Laboratories will be applied as needed in future risk and cost analyses.

Identification of accident scenarios; estimation of accident probabilities and release fractions - A report by Operations Research Inc. (Ref. 13), currently in preparation, will provide necessary data for developing release models for ship accidents. Event-tree analysis will be used to link accident probabilities and consequences. Key radionuclides and release mechanisms will be identified.

Development of consequence models and performance of initial safety analysis - It is anticipated that the simple sea column transport model developed in Task 1 will be available for use in pre-emplacment studies sometime in February 1981 (Fig. 3-1). This model will be used in conjunction with the INREM-II dose commitment models (Ref. 2) and the BEIR-III health-effects model (Ref. 5) to produce estimates of radiological consequences to the public from pre-emplacment accidents. Results of the preliminary safety analysis of sea transportation accidents will be summarized in a mid-fiscal-year interim report.

2.4 OPTIMAL EXPERIMENTAL DESIGN

Assess data collection for biological studies - Data collection techniques will be reviewed and approaches for optimal experimental design will be chosen.

Relate data collection effectiveness, costs, and data requirements - Data requirements will be based on work in Task 1 and programmatic requirements as specified by Sandia. Curves relating costs and data collection effectiveness will be used to generate an optimal design.

2.5 DELIVERABLES

At the end of each fiscal year a report summarizing the work to date will be prepared. Three interim progress reports are anticipated in FY'81, one for each of Tasks 1, 2, and 3.

One objective of the FY'81 and '82 studies will be to prepare information on subseabed disposal safety for inclusion in a report on the status of the subseabed disposal concept. However, the FY'81 and '82 work will only be preliminary. Future work will be needed to incorporate additional data on pre-emplacement designs and operations, data and models for physical processes in the sediments and oceans, and information on alternative emplacement techniques. A continuing appraisal of non-U.S. approaches to subseabed disposal will also be required. This philosophy of an iterative approach has been and is an integral part of the Subseabed Disposal Program.

REFERENCES

1. Koplik, C.M., "Subseabed Disposal Risk Assessment: Review and Program Plan," The Analytic Sciences Corporation, TR-3008-1, March 1980.
2. Killough, G.C., et al., "INREM-II: A Computer Implementation of Recent Models for Estimating the Dose Equivalent to Organs to Man from an Inhaled or Ingested Radionuclide," U.S. Nuclear Regulatory Commission, NUREG/CR0114, June 1978.
3. "Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR Part 50, Appendix I," U.S. Nuclear Regulatory Commission, Regulatory Guide 1.109, March 1976.
4. "Recommendations of the International Commission on Radiological Protection," Annals of the ICRP, 1, No. 3, ICRP Publication 26, Pergamon Press, Oxford, 1977.
5. "The Effects on Populations of Exposure to Low Levels of Ionizing Radiation (BEIR-III Report), National Academy of Sciences, Committee on the Biological Effects of Ionizing Radiation, July 1980.
6. Croff, A.G., "A User's Manual for the ORIGEN2 Computer Code," Oak Ridge National Laboratory, ORNL/TM-7175, July 1980.
7. Ross, B.I., et al., "NUTRAN: A Computer Model of Long Term Hazards from Waste Repositories," The Analytic Sciences Corporation, TR-1797-7, prepared for Lawrence Livermore Laboratory, UCRL-15150, December 1979.

REFERENCES (Cont.)

8. Iman, R.L., et al., "Latin Hypercube Sampling (A Program User's Guide)," Sandia Laboratories, SAND79-1473, 1980.
9. Giuffre, M.S., et al., "Integrated Technical and R&D Assessment of Nuclear Waste Disposal," The Analytic Sciences Corporation, TR-3336-2, September 1980.
10. Haeberlin, S.W., et al., "Consequences of Postulated Losses of LWR Spent Fuel and Plutonium Shipping Packages at Sea," Pacific Northwest Laboratories, PNL-2093, October 1977.
11. Nagakura, T., et al., "Safety Evaluation on Transport of Fuel at Sea and Test Program on Full Scale Cask in Japan," Proceedings of the Fifth International Symposium on Packaging and Transportation of Radioactive Materials, Las Vegas, Nevada, May 1978, pp. 143-153.
12. McCartnay, J.S., et al., "International Fuel Cycle Transportation System Assessment," prepared by the Boeing Engineering and Construction Company for the Transportation Technology Center, Sandia Laboratories, TTC-0039 (SAND 79-7115), July 1980.
13. "Hazardous Environments Experiences by Radioactive Material Packages Transported by Water," (DRAFT), prepared by Operations Research, Inc., for the Transportation Technology Center, Sandia Laboratories, TTC-0081, November 1980.

Appendix B
Initial Phase of the Subseabed
Thermal Sensitivity Studies

R. D. Klett

Sandia Laboratories

Albuquerque, New Mexico
Livermore, California

date: May 20, 1980

to: D. R. Anderson, 4536

Robert D. Klett

from: R. D. Klett, 4536

subject: Initial Phase of the Subseabed Thermal Sensitivity Studies

- References:
1. R. D. Klett, E. S. Hertel and M. A. Ellis, "Systems Engineering Programs for Geologic Nuclear Waste Disposal, SAND-0440, To Be Published.
 2. Memo D. F. McVey, 5512, to C. M. Percival, "ISHTe Thermal Instrumentation," Dt'd February 20, 1980

The functions of sensitivity and other systems studies in the Subseabed Nuclear Waste Disposal Program are shown in Figure 1. Sensitivity studies minimize R&D and reduce the number of variables in analyses by eliminating parameters that have little or no effect on results. These studies are conducted for each scientific and engineering discipline and the results are combined to formulate constraints, requirements and responses for the system. The major input to risk analyses comes from sensitivity studies in the form of expected values, derivatives and limits of the system parameters. Sensitivity also provides the accuracy requirements for data acquisition and the constraint equations for system optimization. Sensitivity studies generally require a large number of computations for each of the many parameters being analyzed and they begin prior to the conceptual design phase of the program and continue until the design is finalized. These characteristics require computer programs that are inexpensive to develop, easily modified and are based on analytic solutions. The initial study is based on a reference design and the best available data. The analyses are then updated as more and better data become available and as designs become more fixed. This memo describes the initial phase of the thermal sensitivity study.

The reference repository consists of a single, vertically oriented, HLW or PWR spent fuel canister in a penetrator housing buried 30 m deep on a 200 m square grid in the red

clay sediments located in the North Pacific mid-ocean gyre. The water and initial sediment temperatures were assumed to be 2°C. The 10 year old HLW concentration was scaled to produce a peak canister temperature of 200°C at reference conditions. The standard SF packaging produces a peak canister temperature well below the maximum allowable. Table 1 summarizes the properties and dimensions of the reference repository. The parameters in this table were varied individually and collectively to determine the sensitivity over the maximum expected range of values. Volumetric heating rates for both waste forms were computed from data given in Reference 1.

Thermal studies conducted by Department 5510 (Ref. 2) using the MARIAH computer program showed that although convection would affect ion transport, the effects on heat transfer would be negligible. Because of the low Rayleigh number, a three order of magnitude change in permeability would result in less than a 1°C change in peak canister temperature. Therefore, the thermal systems studies could be conducted with less complex computer programs which consider only conduction heat transfer in the sediment. Program TMAXC which computes peak temperature of heat generating cylinders in an infinite medium was used for the sediment thermophysical property studies. The $(\frac{A}{A_{ref}})^N$ decay option was used. Program ARRAYF computes temperatures as a function of time in the disposal medium and inside a multilayered canister which contains an exponentially decaying heat source. The disposal media has one isothermal surface and the canister is a finite length. The canisters can be in a square or hexagonal horizontal array and can be stacked vertically with or without vertical separation. ARRAYF was used for the repository layout and waste form studies. Both programs are described in Reference 1.

Table 2 lists the functional divisions of this sensitivity study. Limiting variables are those that restrict the repository layout. An example would be horizontal canister spacing. Adjacent canisters have no effect on peak temperature providing the separation is greater than some computed value; but peak temperatures rise significantly as the separation distance is decreased below this value. Operational values are those that cannot be controlled after the repository site and configuration have been fixed. These include thermophysical properties of the sediment that could vary with location or from measured values. Any uncertainty in this group of variables can be compensated for by including a safety factor in one or more of the other variables. Optimization variables are the design parameters

that can be varied to produce the least expensive repository that will meet given safety criteria. Increased temperatures caused by concentrating more waste in one location (i.e., increasing the diameter, length or proximity of canisters) can be compensated for by aging or diluting the waste. Optimization then consists of tradeoffs between waste form, canister, emplacement, surveillance and transportation costs.

Figures 2 through 12 give the results of the thermal sensitivity study for HLW and Figures 13 through 16 cover PWR spent fuel. Reference conditions are indicated by a circle, the 200°C peak canister temperature value or the zero % change value. Figure 2 shows the linear relationship between the peak canister temperature and the waste concentration. Borosilicate glass loading is not maximum for the reference conditions so this variable can be used to adjust temperatures either up or down. Decreasing the concentration increases waste, canister and all handling costs. Another way of controlling the temperature is varying the age of the waste at the time of disposal as shown in Figure 3. The costs and risks of storage will be weighed against savings that can be made by increasing the waste concentration. Figure 4 shows the temperature/time plots for the first 7 years after emplacement. When effective half life decay rates must be used to describe the heating rates of mixed isotope wastes, as in ARRAYF, the predicted temperatures are only accurate for a period equal to about one third of the half life (Reference 1). If 4 canisters are stacked in a well, the waste concentration would have to be 21.3% lower than the reference case to prevent peak canister temperature from exceeding 200°C. The temperature peaks later in the 4 canister well and remains at high temperatures for a longer time than the single canister well.

The effects of horizontal spacing are shown in Figure 5. Separation distances greater than 11 m have no effect on peak temperatures of the reference configuration. Separation distances greater than 16 m do not affect the 4 canisters per well configuration. Some criteria other than temperature will probably limit the horizontal spacing. The same holds true for depth of burial. Loading could not be increased over the reference value unless the burial depth is less than 4 m (Figure 6). This is much less than the minimum depth needed to isolate the radionuclides from the ocean.

The changes in peak canister temperatures that could be expected with changes in the thermal conductivity of the sediments are shown in Figure 7. Loading adjustments to

compensate for these changes can be found using Figure 2. A 10% deviation from values measured in a laboratory, which is not unusual, would result in a 9% change in temperature or allowable loading. Heat capacity of the sediment has a much smaller effect on temperatures as shown in Figure 8. A 10% variation in ρC_p would only change the temperature 1%. Reference 2 showed that since convection heat transfer is negligible, permeability has no effect on temperature and effect of porosity is indirect--that of changing thermal conductivity.

One of the design parameters that can be used to adjust temperatures is the canister radius. Peak temperature is proportional to the 1.725 power of radius (Figure 9) compared to the linear relationship of temperature to waste concentration (Figure 2). Therefore a small radius change could make a large change in allowable waste concentration. Because of this high sensitivity, canister radius will be an important factor in economic optimization. This will be particularly true if the multi-canister drilled-hole disposal concept is selected. Another design parameter is canister length. Increasing the canister length would reduce emplacement and handling costs using the penetrator option but cost of the borosilicate waste would increase. Canister costs could either increase or decrease depending on design. Figure 10 shows the sensitivity of waste volume (inverse of waste concentration) and time to peak temperature, to the heated length of a canister. Canister lengths greater than 30 m (or 10 stacked reference canisters) do not affect peak temperatures so TMAXC can be used in this range. The number of canisters per well and the vertical spacing between canisters were varied collectively. The configuration used for this part of the study is shown in Figure 11. Figure 12 shows the increase in the number of canisters (or volume of waste) for the multi-canister well, over the number required for single canister emplacement. Increasing the number of canisters per well reduces the number of wells but decreases the allowable waste concentration because of reduced heat dissipation. This increases the number of canisters that are needed to dispose of a given amount of waste. Increasing vertical spacing decreases the number of canisters but increases the number of wells. If vertical spacing is greater than 8 m, peak temperatures are reached before there is any thermal interaction between canisters. The results shown in Figure 12, along with cost estimates, will be inputs to the selection of an emplacement process and optimization of a multi-canister drill-hole if that concept is selected. The results of the HLW part of this study are

summarized in Table 3. The effects of waste concentration and canister radii can be described analytically. The effects of the other parameters are described by changes in allowable canister loadings or by the ranges of parameter values that affect allowable loading.

Because of the low effective volumetric heating rates of 10 year old PWR spent fuel, peak canister temperatures do not approach the 200°C limit regardless of the configuration. This greatly reduces the number of optimization variables. In addition, radius is not a variable for fuel assembly canisters. Figure 13 shows the time/temperature response for 1 and 4 canisters per well. Peak temperature for an infinite column of PWR canisters is only 62.7°C. Figure 14 shows that thermal criteria do not require 10 year storage of spent fuel prior to seabed disposal. Any reasonable variation in sediment conductivity would not cause a problem for SF (Figure 15) and the effects of heat capacity are negligible (Figure 16). The limiting dimensions of burial depth and horizontal spacing would be even smaller than for HLW. Since the peak temperature of an infinite column of SF is well below the allowable, there would be no thermal benefit from limiting the number of canisters per hole or from vertical spacing of the canister.

All of the parameters in this study with the exception of waste concentration affected the time to reach peak temperature and the length of time the canister stayed at elevated temperature. If time/temperature limits can be set for canister corrosion and waste leaching, they could be incorporated in subsequent updates of the study. Nothing showed up in this thermal study that would question the feasibility of the Subseabed Nuclear Waste Disposal concept and no serious design problems were uncovered. The results from this study will be combined with the other sensitivity studies to set limits and to establish system responses for design and optimization.

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TABLE 1
REFERENCE CONDITIONS FOR THERMAL SENSITIVITY

WASTE FORM

A. High Level Waste

- Average Mixed Oxide Fuel In Year 2000 With U And Pu Recycled
- 10 Years Out Of Reactor
- 10.7% Loaded Borosilicate Glass
- 6.71 MTHM/m³ Waste
- Initial Heating Rate = 7.43 kW/m³
- Effective Half Life For Peak Temperature Calculations = 17 Years

B. Spent Fuel Bundles

- Initial Heating Rate = 1.23 kW/m³
- Effective Half Life For Peak Temperature Calculations = 28 Years

SEDIMENT

- Thermal Conductivity = 0.0010 kW/m°C
- Heat Capacity (ρ Cp) = 3850 kJ/m³°C

CANISTER

- Length = 3 m HLW, 5.4 m SF
- Inner Radius = 0.140 m HLW, 0.1683 m SF
- Outer Radius = 0.150 m HLW, 0.1778 m SF
- Material - Titanium Alloy
- Maximum Allowable Temperature = 200°C

PENETRATOR

- Inner Radius = 0.160 m HLW, 0.1878 m SF
- Outer Radius = 0.170 m HLW, 0.1978 m SF
- Material - Carbon Steel
- Water In Gaps

REPOSITORY

- 1 Canister Per Hole
- Burial Depth = 30 m
- Spacing = 200 m In Square Array

TABLE 2

FUNCTIONAL DIVISIONS OF THERMAL SENSITIVITY

Limiting Variables

- Burial Depth
- Horizontal Spacing

Operational Variables

- Conductivity
- Heat Capacity
- Porosity
- Permeability

Optimization Variables

- Length And Radius Of Canisters
- Age And Concentration Of Waste
- Canisters Per Well And Vertical
Canister Spacing

TABLE 3

THERMAL SENSITIVITY SUMMARY

Waste Properties

$$\text{Concentration, } T = 2 + 29.5 \left(\frac{\text{MTHM}}{\text{m}^3 \text{ Waste}} \right)$$

$$\text{OR } T = 2 + 26.7 \text{ QI}$$

Age At Time Of Burial, 15 Years Old Increases Loading 25%
5 Years Old Decreases Loading 30%

Sediment Properties

Conductivity, 10% Decrease, Decreases Loading 9%
Heat Capacity (ρC_p), 10% Decrease, Decreases Loading 1%
Porosity, 10% Increase, Decreases Conductivity 6%
Permeability, Insensitive

Repository Design

Depth of Burial, Insensitive $> 4 \text{ m}$
Horizontal Spacing, Insensitive $> 11 \text{ m}$
Canister Radius, $T = 5284 R^{1.725}$
Canister Length, Insensitive $> 18 \text{ m}$
Canisters Per Well, Insensitive $> 6 \text{ Per Well}$
Vertical Canister Spacing, Sensitive $< 7 \text{ m}$

Figure 1. Systems Analysis for the Subseabed Nuclear Waste Disposal Program

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

FIGURE 7

SEDIMENT CONDUCTIVITY SENSITIVITY

FIGURE 8

FIGURE 9

CANISTER RADIUS SENSITIVITY

FIGURE 10 Canister Length Sensitivity

FIGURE 11

Reference Configuration For Borehole Emplacement

Vertical Separation Sensitivity

FIGURE 12

FIGURE 13

FIGURE 14

FIGURE 15

Spent Fuel Sediment Conductivity Sensitivity

Spent Fuel Sediment Heat Capacity Sensitivity

FIGURE 16

Appendix C

Significant Times for Ion Transport
Systems Study in the SDP

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References

1. W. S. Fyfe, N. J. Price and A. B. Thompson, Fluids in the Earth's Crust, Elsevier Scientific Publishing Co., N. Y., 1978.
2. "Oceanography Related to Deep Sea Waste Disposal," Institute of Oceanographic Sciences Report No. 77, September 1978.
3. J. Crank, The Mathematics of Diffusion, Clarendon Press, Oxford 1975.
4. H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids, Oxford Press, N. Y., 1959.
5. A. J. Russo, "Prediction of the Migration of Several Radionuclides in Ocean Sediment with the Computer Code Ionmig: A Preliminary Report." SAND79-1666, May, 1980.
6. H. E. Nuttall, A. K. Ray and E. J. Davis, "An Analysis of Diffusional Ion Transport in Ocean Sediments: Subseafloor Disposal of Radioactive Waste," Department of Chemical and Nuclear Engineering, University of New Mexico, To Be Published.

NOMENCLATURE

c = Concentration
 D = Effective molecular diffusivity
 D_m = Molecular diffusivity
 K_d = Adsorption coefficient
 M = Instantaneous source density
 M' = Instantaneous source density per unit length
 M'' = Instantaneous source density per unit area
 m = Continuous source density
 m' = Continuous source density per unit length
 m'' = Continuous source density per unit area
 r = Distance from source
 t = Time
 t_m = Time of peak concentration
 $\bar{X}$ = Average distance traveled by ions in time t
 ϵ = Porosity
 ρ_B = Bulk density

The time for ions to migrate from a nuclear waste disposal canister, through the disposal media, to a mobile fluid is becoming a frequently discussed parameter for rough evaluations and comparisons of disposal processes. The usefulness of these approximations could be increased if definitions and methods of solution are standardized. As an example of the current inconsistencies, reference 1 developed a semi-empirical equation for the average distance traveled by ions as a function of time from an instantaneous planar source with one-dimensional flow. This equation is:

$$\bar{X} = (2Dt)^{1/2} \quad (1)$$

Reference 2 uses the equation

$$t = \frac{r^2}{D} \quad (2)$$

for the breakthrough time for subseabed nuclear waste repository which is more closely represented by a point source and three-dimensional flow. Using the exact analytical solutions for ion transport given in References 3 & 4, a D of 0.01 m²/yr and an r (or $\bar{X}$) of 30 m, equation 1 actually predicts the time of peak concentration rather than the average time of arrival. Assuming breakthrough to be 5% of the peak concentration, equation 2 predicts a breakthrough time 25 times later than that of the exact equation. Since these differences were caused by misinterpretation of definitions, there is definitely a need for standardization, even for approximations such as these.

There are three ion transport times that can be used for systems analyses and rough evaluations of repositories. These are:

1. Breakthrough time - The time after emplacement when the added isotope concentration in the sediment at the ocean interface equals the presently existing background level of that isotope, or the lowest detectable level, whichever is higher. This time includes the time the waste is completely contained by the canister and applies to both instantaneous or graduate leaching of the waste form.
2. Release duration - This is the time duration that the concentration at the ocean interface is above breakthrough levels.

3. Peak release time - The time of peak concentration at the ocean interface is easily found by differentiation of the instantaneous release transport equations or iterative solutions of the finite duration, gradual release, equations.

Equations for diffusion in an infinite media (Refs. 3 and 4) were checked against the finite element code IONMIG (Ref 5) and the analytic code TRION (Ref 6) and were found to be in good agreement over the range of input parameters expected in the SDP, provided the effective diffusivity is used, and therefore, can be used for estimating concentrations in the sediment. The equation for a point instantaneous source is

$$\frac{c}{M} = \frac{e^{-\frac{r^2}{4Dt}}}{8(\pi Dt)^{1.5}} \quad (3)$$

where the effective diffusivity is given by

$$D = \frac{D_m}{1 + \frac{K_d \rho_B}{\epsilon}} \quad (4)$$

For an instantaneous infinite line source

$$\frac{c}{M'} = \frac{e^{-\frac{r^2}{4Dt}}}{4\pi Dt} \quad (5)$$

and an instantaneous infinite plane source with ion transport from both sides of the plane

$$\frac{c}{M''} = \frac{e^{-\frac{r^2}{4Dt}}}{2(\pi Dt)^{0.5}} \quad (6)$$

For a continuous point source

$$\frac{c}{m} = \frac{\operatorname{erfc}\left(\frac{r}{\sqrt{4Dt}}\right)}{4\pi Dr} \quad (7)$$

a continuous infinite line source

$$\frac{c}{m'} = - \frac{\operatorname{Ei}\left(-\frac{r^2}{4Dt}\right)}{4\pi D} \quad (8)$$

and a continuous infinite plane source with ion transport from both sides of the plane

$$\frac{c}{m''} = \left(\frac{t}{\pi D}\right)^{1/2} e^{-\frac{r^2}{4Dt}} - \frac{r}{2D} \operatorname{erfc}\left(\frac{r}{2\sqrt{Dt}}\right) \quad (9)$$

To find the maximum for the instantaneous sources, equations 3-5 were differentiated and set equal to zero. The resulting peak times are

$$t_m = \frac{r^2}{6D} \quad (10)$$

for a point source,

$$t_m = \frac{r^2}{4D} \quad (11)$$

for a line source and

$$t_m = \frac{r^2}{2D} \quad (12)$$

for a plane source.

Normalized concentration curves for instantaneous sources are plotted in Figure 1. The peak concentration time for a point source is within 4% of the values published in References 5 and 6 for the same input conditions. The point source curve rises and decays much more rapidly than the plane source.

Figure 2 compares the normalized concentrations 30 metres from instantaneous and continuous point sources. Concentration changes for a specific ion with a D of 0.01 m²/yr from a slowly leaching waste form would be bracketed by these two curves. Similar curves will be generated to bracket the concentration changes of other ions.

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Figure 2

Appendix D

Titanium Alloy Suitability for
Subseabed Environment

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Titanium Alloy Suitability for Subseabed Environment*

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Abstract

Corrosion and stress corrosion examinations of TiCode-12 (ASTM Gr. 12) and commercial purity titanium (ASTM Gr. 2) have been conducted. The data from these experiments, many from severe overtests, continue to show that TiCode-12 still remains as a viable candidate material for long-term waste isolation.

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INTRODUCTION

Recent studies at Sandia National Laboratories have identified titanium alloys as the most promising candidates for a corrosion-resistant metallic canister overpack. [1]. A detailed review of the selection criteria and the available technical literature has been presented in the 1979 Subseabed Disposal Program Annual Report. [2]. The present discussion will therefore be limited to progress made in characterizing the performance of these alloys during calendar year 1980.

GENERAL CORROSION

Previous corrosion screening tests [1, 2] have identified TiCode-12* (ASTM Grade 12) and commercial purity titanium (ASTM Grade 2) as promising candidates for nuclear waste disposal overpack materials. While a number of screening tests are still being completed, greater emphasis is now being placed on obtaining an understanding of the detailed electrochemical interfacial properties (i.e. oxide film structure) of TiCode-12, titanium and related alloys. This approach is being pursued in the belief that these results will be essential in developing a model which will be capable of predicting long-term behavior in the anticipated environment.

EXPERIMENTAL

A. Materials and Environments

As noted above TiCode-12 and commercial purity titanium have been chosen for study. Test environments have included natural seawater, Brine A (a nearly saturated $\text{Na}^+/\text{Mg}^{+2}$ brine), 3-4% NaCl (a common one component synthetic seawater) and Brine Z (a $\text{Na}^+/\text{K}^+/\text{Mg}^{+2}/\text{Cl}^-$ synthetic seawater). Compositions of these solutions are listed in Table I. All solutions were deoxygenated prior to use to obtain maximum corrosion rates.

B. Sample Preparation

The sample preparation procedure, except as noted below, was the same as that previously described [2]. For the Raman, and Auger experiments the samples were polished with a series of aluminum oxides thru 0.05 μ . They were then cleaned with acetone.

C. Apparatus

The apparatus used in the general corrosion studies has been previously described [1,2] as has the Raman spectroscopic experimental method and apparatus [3,4]. The Auger spectrum was obtained using argon ion sputtering and a 3 KeV, 25 μA electron-beam current. The modulation voltage was 3V.

*Trademark of Titanium Metals Corp. of America.

RESULTS AND DISCUSSION

A. Uniform Corrosion

The corrosion of titanium in seawater is difficult to study on a short-term basis due to its good corrosion-resistance. For this reason, the testing method described previously [2] was modified to allow greater sensitivity. This was done by using titanium foil (99.7%) 0.25 mm thick which allowed samples of greater surface area to be studied.

Tests were conducted to determine the influence of temperature and pH on the corrosion rate of commercial purity titanium. Some results are given in Table II as a function of test temperature. These results show that the observed corrosion rate is a strong function of temperature as measured by conventional weight gain measurements. However it is important to note that preliminary results indicate a drastic reduction in corrosion rate with increasing exposure time, that is the corrosion rates presented in Table II are highly conservative.

Table III shows that the corrosion rate of commercial purity titanium is much greater in the lower pH sodium chloride solution than in the more neutral brines and seawater.

B. Localized Corrosion

Testing has been conducted with commercial purity titanium and TiCode-12 to determine conditions under which crevice corrosion can occur. Crevices were constructed using polished coupons separated with a suitable titanium shim, the later varying from 0.25 mm to 0.025 mm thick. These crevices showed no indications of more rapid corrosion than the exterior metal. When no shim was used, buildup of precipitate was noticed between the commercial purity titanium coupons. With the TiCode-12 specimens, some discoloration occurred, but there was no obvious enhancement of corrosion.

C. Surface Oxide Structure

1. Raman Spectroscopy

Raman spectroscopy has recently been used to examine the surface oxide structure of alloys [3-7]. This technique is sensitive to the outermost layers of the oxide film. The magnitude of the effect is dependent upon the raman scattering strength of the particular oxide form, as well as upon its concentration in the oxide film surface region.

Recently, examination of the raman spectra of two TiCode-12 samples have shown that when oxide films are formed by room temperature oxidation, no characteristic oxide peaks were seen. This is a result of the limitations imposed on this technique as, in general, oxide films with thicknesses greater than approximately 50 Å are necessary to observe raman scattering. It is likely that the film formed on TiCode-12 at room temperature is 20 Å or less.

On a heavily oxidized sample of TiCode-12 (600°C in air for 72 hours) a greyish film was formed. The raman spectrum of this oxide film showed peaks characteristic of TiO₂ (rutile). No peaks due to Ni or Mo oxides were observed, possibly due to the small concentrations of these elements in the alloy.

Further work is planned using this technique to examine surface oxides. Alloys of increasing Ni and Mo concentrations will be investigated to get some understanding of the oxide film interfacial properties. Also, in-situ electrochemical measurements will be taken.

2. Auger Electron Spectroscopy (AES)

Auger electron spectroscopy may also be used to examine an interfacial phenomena. An AES spectrum of TiCode-12 has recently been taken after this alloy was corroded in 250 g/l NaCl (pH=1.00) for three weeks at 200°C. The spectrum, as shown in Figure 1, shows a near surface enhancement of Ni (note that the Ni spectrum is magnified 25 times). This result is in agreement with previous studies of similar alloys [8-10], may be related to the corrosion resistance properties of this alloy. This apparent surface segregation is the subject of further examination.

STRESS CORROSION CRACKING

The susceptibility of TiCode-12 to stress corrosion cracking (SCC) being assessed using the slow strain rate technique. The effects of environmental variables such as pH, oxygen concentration, and temperature have been studied. In addition, the susceptibility of welded samples to cracking has been examined. In all cases, no macroscopic evidence of stress corrosion cracking has been observed. Parameters such as time to failure, ultimate tensile strength and reduction of area showed no degradation relative to that observed in an inert environment.

The apparatus and details of the slow strain rate test are found in Ref. [11]. In all cases the environment was synthetic seawater or a more concentrated brine characteristic of a salt repository. Experiments were done under static deoxygenated conditions as well as flowing, oxygen-saturated conditions.

In a stress-corrosion susceptible material one expects to see a decrease in some measure of ductility, such as elongation, when the material is strained to failure in the hostile environments. Typically, materials are susceptible only within certain regions of strain rate. In high strength titanium alloys, for example, susceptibility to cracking is observed at strain rates near 10^{-5} . At faster rates, cracking occurs so fast that the corrosive effect of the environment has little effect. At much slower rates, repassivation of the crack tip presumably occurs so that no environmentally enhanced cracking is observed.

Figure 2 shows the observed strain rate dependence of the ratio of the elongation of TiCode-12 in seawater to air at several temperatures. Although there is a large amount of scatter in the results, in no case does the ratio fall below one. These tests therefore suggest that TiCode-12 at temperatures below 250°C is not susceptible to stress corrosion cracking in seawater.

In order to simulate potential acidified conditions at a crack tip, experiments were also performed in synthetic seawater acidified to $\text{pH}=1$ and 3 with hydrochloric acid. These tests were performed in static deoxygenated and flowing oxygenated conditions at 200°C . Some of these data are shown in Figure 3 as the environment to air ratios of the elongation at failure. Once again, ratios near unity indicate no susceptibility to stress corrosion cracking. Similar results were observed for electron beam and TIG welded samples as shown in Figure 4.

Finally a limited set of experiments was also performed on commercial purity titanium samples in oxygenated acidified seawater. These tests also showed no susceptibility to stress corrosion cracking at temperatures to 200°C .

It should be pointed out that the slow strain rate test result reported here are not definitive in proving the absence of stress corrosion cracking. It is possible that stress corrosion cracking would be observed in thicker samples as well as in samples with preexisting flaws (cracks). It is also possible that environmentally assisted cracking would be observed at slower strain rates. In fact, there is limited fractographic evidence for some brittle fracture near the edges of samples fractured at strain rates of 10^{-7} , the slowest test to date [11].

REFERENCES

1. J. W. Braithwaite and M. A. Molecke, Nuclear & Chemical Waste Management, 1, 37 (1980).
2. J. W. Braithwaite, N. J. Magnani and L. Abrego in Subseabed Disposal Program Annual Report, 1979, and references therein.
3. R. L. Farrow and A. S. Nagelberg, SAND80-8606, 1980.
4. R. L. Farrow, P. L. Mattern and A. S. Nagelberg, Appl. Phys. Lett., 36, 212 (1980).
5. R. L. Farrow and P. L. Mattern, Bull. Am. Phys. Soc., 25, 165 (1980).
6. R. J. Thibau, et. al., Appl. Spectroscopy, 32, 532 (1978).
7. R. L. Farrow, P. L. Mattern, and A. S. Nagelberg, SAND79-8733 1979.
8. E. N. Paleolog, et. al., J. Electrochem. Soc., 125, 1410 (1978).
9. A. J. Sedriks, J. A. S. Green and D. L. Novak, Corrosion-NACE, 28, 137 (1972).
10. J. A. S. Green and P. S. Kotval, Corrosion-NACE, 28, 419 (1972).
11. L. Abrego and H. J. Rack, "The Slow Strain Rate Behavior of TiCode 12 (ASTM Gr. 12) in Aqueous Chloride Solutions," CORROSION 81.

TABLE I
Representative Solution Compositions

<u>Ion</u>	<u>Brine A</u> <u>(ppm)</u>	<u>Brine Z</u> <u>(ppm)</u>	<u>Seawater</u> <u>(ppm)</u>
Na ⁺	42,000	10,650	10,650
K ⁺	30,000	380	380
Mg ⁺²	35,000	1,270	1,270
Ca ⁺²	600		400
Sr ⁺²	5		10
Cl ⁻	190,000	20,500	18,980
SO ₄ ⁻²	3,500		880
I ⁻	10		50
HCO ₃ ⁻	700		150
Br ⁻	400		65
BO ₃ ⁻	1,200		
Total Dissolved Solids	297 g/l	33 g/l	35 g/l
pH	6.5	6.0	8.1

TABLE II
Corrosion Rate of Commercial Purity Titanium
in Brine Z at two Weeks

<u>Temperature (°C)</u>	<u>Corrosion Rate (µm/yr)</u>
30°C	0.008
70°C	0.016
150°C	0.457
250°C	0.501

TABLE III
Corrosion Rates of Commercial Purity Titanium
in Various Solutions*

<u>Solution</u>	<u>Temperature (°C)</u>	<u>Corrosion Rate (µm/yr)</u>
3½% NaCl pH 1	250	5.2
Seawater	30	4×10^{-3}
Brine A	30	5×10^{-3}
Brine Z	250	0.247

*Test duration: 4 wks.

Figure 1. AES surface profile of TiCode-12 corroded in 250 g/l NaCl, pH=1.00 for 3 weeks at 200°C. 70 minutes of sputtering corresponds to approximately 300 Å.

Figure 2. Influence of strain rate and temperature on the stress corrosion susceptibility of TiCode-12 represented as the ratio of total strain to failure. Environment is deoxygenated synthetic seawater.

Figure 3. Influence of strain rate and pH on the stress corrosion susceptibility of TiCode-12. Tests were performed at room temperature in an oxygen saturated environment. Similar results were obtained under deoxygenated conditions.

Figure 4. Influence of strain rate and weld practice of the stress corrosion susceptibility of TiCode-12 at 200°C in deoxygenated seawater.

Appendix E

Sediment-Seawater Interaction at 200° and 300°C,
500 Bars Pressure: Chemical Exchange and
Hydrothermal Alteration

W. E. Seyfried and E. C. Thornton

SEDIMENT-SEAWATER INTERACTION AT 200° AND 300°C, 500 BARS PRESSURE -
CHEMICAL EXCHANGE AND HYDROTHERMAL ALTERATION

by

W.E. Seyfried
and
E.C. Thornton

Annual Progress Report: January 1, 1981 through December 1980

Sandia Contract No. 0645-5968
0645-5717

Department of Geology and Geophysics
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February, 1981

ABSTRACT

The results of a series of experiments conducted at 200° and 300°C and 500 bars and at a water/rock mass ratio of 5 are reported and discussed in order to document chemical exchange and mineralogical modification between sediment and seawater during hydrothermal interaction. Sediments utilized were obtained from the MPG-I region in the North Pacific. Experimental conditions were chosen to simulate the near field chemical environment.

Changes in solution composition indicate similar modifications of major element chemistry in all experiments. Aqueous concentrations of Ca, Mg, Sr, and SO_4 decreased while SiO_2 , Na, Cl, B, K, and ΣCO_2 increased relative to initial seawater values. An acid pH developed due to the precipitation of Mg-bearing phases, primarily Mg-silicates (e.g., smectite) and possibly Mg-hydroxysulfate. Low pH values were maintained throughout the experiments though titrated slowly upwards with time by reaction of plagioclase, illite, and chlorite. In general, the concentrations of heavy metals in solution varied inversely with pH. Titanium, however, remained at very low concentrations (<0.01 ppm). This indicates that titanium remains immobile under acidic, oxidizing conditions and suggests that waste canisters constructed of titanium alloys would be relatively resistant to corrosion under the chemical conditions existing in the near field environment.

Redox reactions critically affected alteration processes. These typically involved reduction of MnO_2 components of the sediment by small but nevertheless significant amounts of organic carbon and ferrous iron. The acidic, oxidizing environment created by the MnO_2 -rich smectite sediments resulted in the dissolution of gold from the reaction cell as demonstrated by high concentrations of gold in solution. Quantification of the redox potential or f_{O_2} was accomplished utilizing the Au-AuCl_2^- couple and indicated that f_{O_2} ranges from 10^{-8} to 10^{-14} at 200°C and from 10^{-6} to 10^{-20} at 300°C.

Mineralogical changes for smectite-rich sediment involved the production of smectite at the expense of a mixed smectite-illite component and amorphous material. Clinoptilolite dissolved entirely while plagioclase and chlorite reacted to a moderate extent. Similarly, metalliferous sediment was found to produce smectite; this being a result of recrystallization of amorphous material. An increase in Cl content of the solutions obtained during these experiments indicates the uptake of water into the newly formed smectite. Anhydrite was an abundant reaction product of all experiments.

A program of development and testing of hydrothermal equipment designed for the study of the migration of radionuclides in a thermal gradient has demonstrated that a uniform and reproducible gradient can be maintained between 300° and 100°C at 500 bars. Details of operation are discussed and a proposed research program of radionuclide mobilization in the near- to far-field environment is outlined.

INTRODUCTION

Feasibility of subseabed disposal of high level radioactive waste requires assessment of the temperature dependent chemical reactivity of the sediment-seawater system. This system, defined in terms of the near field (the zone immediately adjacent to a waste canister) and far field (the zone relatively distant from the waste canister) must be rigorously characterized. To be sure, it is the far field which represents the primary barrier against radionuclide mobility (Erickson et al., 1980), but the near field is the initial barrier and the alteration processes operative here will affect significantly the flux of chemical species to the far field and the rate of canister corrosion. It has been our objective at the University of Minnesota to rigorously evaluate chemical exchange and sediment recrystallization reactions thought to occur in the near field by conducting an experimental program involving high-temperature sediment-seawater reactions at 500 bar pressures (Seyfried et al., 1980; Erickson et al., 1980).

Experiments conducted this last year have utilized sediments obtained from the MPG-I region in the North Pacific, an area currently being investigated for its suitability as a waste disposal site. The sediments were reacted with seawater at temperatures of 200° and 300°C at 500 bars pressure and at a water/rock ratio of 5. The resulting changes in fluid chemistry and sediment mineralogy were monitored and are reported here together with interpretations of the hydrothermal processes involved.

PROCEDURES

Experimental Equipment

Experiments were conducted in the hydrothermal apparatus described by Dickson et al. (1963) with modifications by Seyfried et al. (1979). This apparatus consists of a gold reaction cell enclosed in a pressure vessel and electric furnace. The furnace temperature is maintained within $\pm 2^\circ\text{C}$ by a proportioning controller. The reaction cell is sealed with a titanium top and solution samples are obtained through an internal gold filter and a titanium exit tube by opening a sampling valve. Constant hydrostatic pressure is maintained while sampling by pumping water into the pressure vessel around the reaction cell. The assembly is mounted on a rack and continuously rocked through 180° at 20 times per minute. Reaction kinetics are thus accelerated by suspending the sediment in seawater to insure a maximum surface area of reaction.

Sampling of the aqueous fluid can be accomplished at constant temperature and pressure at any time during the experiment. Quench fluid and reacted sediment is also obtained at the end of each experiment.

Analytical

Approximately 10 ml of solution was taken per sample. This consisted of about 1 ml for bleed, 0.35 ml in a glass gas-tight syringe for total dissolved CO_2 (ΣCO_2), and 8 ml for other components. ΣCO_2 was analyzed immediately after sampling with a total carbon analyzer (Oceanography International). The 8 ml sample was divided into three aliquots. The first consisted of a 1 ml

unfiltered sample for pH determination by selective ion electrode and SO_4 by ion chromatography (Dionex Corporation). A second 1 ml portion was filtered through a 1 μ membrane filter, acidified with ultrapure HNO_3 , and diluted for analysis of SiO_2 and major cations (K, Mg, Ca) utilizing plasma emission spectrometry (Spectrametrics, Inc.) and atomic absorption spectrophotometry (Perkin-Elmer Corp.). The remaining portion (approximately 5 ml) was also filtered and acidified but was not diluted. It was analyzed for chloride (potentiometrically) and for heavy metals and minor elements by plasma emission spectrometry. F was measured with a selective ion electrode in several experiments.

The following components have been routinely analyzed in the solution samples: Mg, Ca, K, SO_4 , SiO_2 , Cl, Sr, Fe, Mn, Zn, Al, Ni, Co, Cr, Ti, Au, Ba, B, pH, and ECO_2 . Na was calculated based on charge balance considerations. Uncertainties in reported concentrations are: $\pm 3\%$ for Na, Ca, K, Mg, ECO_2 , and SiO_2 ; $\pm 2\%$ for Cl and SO_4 ; $\pm 3\%$ for Fe and Mn at >10 ppm and $\pm 10\%$ at ≤ 10 ppm; and $\pm 10\%$ for Sr, Zn, Al, Ni, Cr, Ba, B, Au, and Ti. The reported pH values are accurate to 0.05 pH units.

Distribution of Aqueous Species

Computation of ion activities of aqueous species were performed utilizing "SOLVEQ", a computer program written by Reed (1977). SOLVEQ distributes element concentrations among aqueous species through a series of mass balance equations containing dissociation constants for complexes and by assuming electrical neutrality. The extended Debye-Huckle equation is utilized to compute activity coefficients (Helgeson, 1969). Activities were first computed at 25°C and 1 bar using the measured pH. From this initial distribution a hydrogen ion mass balance was computed for use in calculating activities at elevated temperatures and pressures. The activities calculated are reported in Addenda 1 for the solutions sampled for each experiment. Hydrolysis constants of minerals at the experimental conditions calculated from the data of Helgeson *et al.* (1978) were compared with the activity products to determine the extent of saturation of the solutions with respect to selected minerals (Addenda 2).

Sediments

Experiments were performed this year with smectite-rich sediments from the MPG-I region in the central North Pacific. Sediment of this type occurs below the surficial quartz-illite-chlorite assemblage as indicated by studies of the GPC-3 core (Hollister *et al.*, 1979).

X-ray diffraction results and chemical analyses of sediments from the MPG-I region are included in this report. Table 1 summarizes the chemical composition of three representative types. Sediment B is the surficial quartz-illite-chlorite sediment. The Pacific smectite is fairly representative of the smectite-rich sediments occurring at depths of 6 to 13 meters in the GPC-3 core. GPC3-13 was taken somewhat deeper in the core (approximately 16 meters) and is metalliferous in composition with significant amounts of plagioclase of probably volcanic origin. Figure 1 illustrates the relative amounts of pelagic clay and metalliferous fractions of these sediment types when the chemical components are partitioned by the technique of Bischoff *et al.* (1979). Experiments this year involved the GPC3-13 sediment and a smectite-rich sediment similar to the Pacific smectite.

Organic carbon and MnO₂ analyses were conducted on the sediments in order to evaluate their redox capabilities (see Discussion). Ferrous-ferric ratios are not readily determined in sediments of this type although they may be qualitatively evaluated using x-ray diffraction techniques.

RESULTS

Solution Chemistry

Seawater chemistry was significantly modified during these experiments (Figures 2-5; Tables 2-6). Smectite-rich sediment-seawater interaction at 200°C and 300°C showed a decrease of Mg, Ca, Sr, and SO₄ in solution during reaction and an increase in K, SiO₂(aq), Mn, Σ CO₂, B, Na, and Cl. Fe, Zn, Ba, Ni, Al, and Au were present at ppm levels and Ti, Co, and Cr were very low or below detection limits. F reached a maximum of about 6 ppm in the 300°C experiment. pH fell to a steady value of approximately 4.4 at 200°C. At 300°C, it fell to a minimum value of 2.3 but subsequently rose to greater than 4. The increase in pH was accompanied by an increase in Σ CO₂ and a decrease in SiO₂, Fe, and Mn.

Three experiments conducted with the metalliferous GPC3-13 sediment produced a modification of solution chemistry similar to that described for the smectite-rich sediment. At 200°C (Table 4), pH and Σ CO₂ were relatively constant at about 4 and 8 m molal, respectively. In the 300°C experiment (Table 6), Σ CO₂ rose sharply and pH fell to 2.4 and then slowly increased, ultimately attaining a value of 4. An increase in Mn (to a maximum of about 1100 ppm) accompanied the increase in Σ CO₂ while Fe concentration fell as pH rose. H₂S was detected in the second sample at 93 hours.

Another experiment conducted with the GPC3-13 sediment was run at 200°C for about 600 hours and then at 300°C for an additional 273 hours (Table 5). The 200°C portion was similar to the longer 200°C experiment, but some differences exist between the 300°C portion and the longer experiment at 300°C. At 300°C, less Σ CO₂ developed than in the longer experiment and correspondingly less Mn entered solution (see Discussion), suggesting that the amount of organic carbon differed somewhat in the two original samples. pH was fairly constant at about 2.5. Fe rose to a maximum value of 120 ppm and Zn, Ni, Co, Ba, Al, and Au also reached unusually high levels.

Alteration Products

Results of x-ray diffraction analysis of the "bulk" sediments before and after reaction are presented in Figures 6 and 7. Mineralogical changes for the smectite-rich sediment involved a transition from a mixed illite-smectite component to a product containing more smectite and less of the mixed-layer clay. Clinoptilolite dissolved entirely. A reduction in the intensity of the reflection of plagioclase and chlorite suggests that each underwent partial reaction.

Mineralogical modification of the metalliferous sediment primarily involved the formation of smectite following the reaction or recrystallization of amorphous components of the sediment. A substantial portion of the plagioclase appears to have also undergone reaction.

Anhydrite was commonly observed in the reaction products, both microscopically and in the x-ray diffractograms.

DISCUSSION

Mechanisms of Sediment-Seawater Interaction

Experiments in the sediment-seawater system have shown that Mg is removed while acidity develops due to the release of significant amounts of H⁺ into solution (Seyfried *et al.*, 1980). Bischoff and Seyfried (1978) have demonstrated that one mechanism for removal of Mg⁺⁺ involves the precipitation of magnesium-hydroxysulfate from seawater heated above 250°C at 500 bars by the reaction:

where $3 \leq n \leq 5$. This reaction is probably important during the first few hours of an experiment (Addenda 2). As SO₄ is removed from solution, however, the reaction of Mg and SiO₂ leads to the precipitation of smectite either as a distinct phase or as talc layers within existing chlorite or clay minerals. This mechanism for H⁺ generation may be written as:

The degree of acidity depends on the mineralogy of the sediment involved. Sedimentary components such as feldspar, volcanic glass, carbonate minerals, and zeolites titrate acidity and thus produce an increase in pH. Evaluation of these relations in terms of primary and alteration mineral stability can best be accomplished by use of cation-activity diagrams (Helgeson *et al.*, 1969). It is necessary to point out, however, that the thermochemical data base used for these constructions is limited and includes information pertinent to the stability of phases structurally analogous but chemically dissimilar to those identified in seabed sediments. Thus, reaction paths of aqueous species, which have been superimposed on these diagrams, provide only general information bearing on solution-mineral equilibrium. The difference in thermodynamic properties between the mineralogically complex phases in seabed sediments and those used to construct the activity diagrams must be appreciated.

Activities of aqueous species of solutions sampled from two of the experiments conducted at 300°C are plotted on three activity diagrams (Figures 8, 9, and 10). Reaction paths illustrate that pH changes are related to mineralogical reactions involving the exchange of H⁺ for Ca⁺⁺, Mg⁺⁺, and K⁺. Initially, these paths move to lower cation/H⁺ ratios as cations are incorporated into smectite and H⁺ is released due to the hydrolysis of water but subsequently they are reversed as H⁺ in solution reacts with primary silicate minerals.

Several reactions can be considered to illustrate how silicate minerals in the samples reduce the acidity of the solutions. The reaction paths in Figure 8, for example, indicate that the Mg⁺⁺ activity in solution increases relative to H⁺ with time and thus suggests that Mg-chlorite may be reacting and consuming acidity. Fe-chlorite would likewise reduce acidity by exchanging Fe⁺⁺ for H⁺. The increase in K⁺ relative to H⁺ in Figures 8 and 9 is probably due largely to the exchange of H⁺ for K⁺ in illite. Plagioclase is also very important in titrating acidity. Solution chemistry moves into the stability field of leonhardite, a Ca-zeolite, (Figures 9 and 10) and possibly suggests alteration of the anorthite component of the detrital plagioclase feldspar is occurring. The alteration of the albite component of this phase would likewise reduce aci-

dity by releasing Na^+ to the solution in exchange for H^+ . The data in Tables 3 and 6 show a steady increase of Na^+ in solution (normalized to seawater chlorinity) as pH rises.

Redox Reactions

In addition to the production of acidity as discussed above, sediment-seawater interaction controls the redox potential of the near field environment. Since redox reactions are important in controlling the degree of radionuclide mobility, consideration of the oxidizing and reducing agents present in sediment will undoubtedly play a role in site selection.

f_{O_2} -pH diagrams have been constructed at temperatures of 25°, 200°, and 300°C at 500 bars in order to illustrate redox relationships (Figures 12, 13, and 14). Among oxidizing agents, MnO_2 is the most important. Its reduction may be illustrated as:

Organic carbon is commonly the most important reducing agent and its oxidation may be written as:

In order to estimate f_{O_2} during these experiments, it was found convenient to make use of the observation that gold dissolved from the reaction cell containing the sediment-seawater mixture, and attained low, but nevertheless significant concentrations in solution. These data and information from Helgeson and Garrels (1968), which maintains AuCl_2^- to be the dominant form of gold in aqueous, hydrothermal solutions, permits assessment of f_{O_2} owing to the following equilibria:

Gold solubility as a function of temperature, pH and f_{O_2} is illustrated by figure 11.

Utilization of reaction 5 and solution data from the 200°C experiments indicate that pH and f_{O_2} varied within a fairly restricted range (Figure 13). pH (*in situ*) varied from 4.5 to 5.5 and f_{O_2} from 10^{-8} to 10^{-14} . Addenda 2 includes mineral saturation information for several Mn oxides which were obtained using thermodynamic data from Robie *et al.* (1978) and indicates that the manganese oxides (e.g., pyrolusite) are very near saturation at 200°C. Thus, f_{O_2} derived either by reactions 3 or 5 is essentially the same.

The range of f_{O_2} and pH observed in the 300°C experiments was much broader than at 200°C. pH (*in situ*) varied from 2.7 to 5.7 and f_{O_2} from 10^{-6} to 10^{-20} (Figure 14). Inspection of the solution data for the smectite-rich sediment at 300°C (Table 2 and Figure 3) suggests that sufficient organic carbon was present in the sediment to reduce a substantial portion of MnO_2 and thus maintain f_{O_2} at a moderate level (approximately 10^{-12}).

Experiments conducted at 300°C with metalliferous sediment (Tables 5 and 6, Figure 5) contain some degree of variation in ΣCO_2 and Mn concentrations in

solution, possibly due to differences in organic carbon content of the sediment. The first experiment at 300°C (GPC3B-200-5), was characterized by low Mn^{2+} concentrations in the solution which suggests a low organic carbon content. This resulted in a high f_{O_2} and the oxidation of gold. Fe^{2+} subsequently entered solution, possibly from the breakdown of volcanic debris under the acidic conditions generated, and the system became more reducing. That is,

Correspondingly, the gold content of the solution decreased as f_{O_2} was lowered.

GPC3-300-5, the second experiment at 300°C has higher Mn^{2+} contents in solution, suggesting the presence of more organic matter. This is consistent with the higher ΣCO_2 values (Table 6). Thus the f_{O_2} of this experiment was lower and less gold entered solution. A particularly interesting aspect of this experiment was the production of H_2S in solution at 93 hrs of reaction. This suggests that sulfate reduction occurred under the acidic, reducing conditions generated and is compatible with the f_{O_2} -pH diagram in Figure 14. Reducing agents probably included both organic carbon and Fe^{2+} .

Examination of the mineral saturation data at 300°C for the manganese oxides (Addenda 2) indicates undersaturation of these phases on the basis of the f_{O_2} calculated utilizing reaction 5. This indicates that a discrepancy exists either in the estimation of f_{O_2} at 300°C or in the thermodynamic data for the manganese oxides. Calculation of f_{O_2} based on reaction 3 would produce substantially higher values than those obtained from reaction 5 and indicates the need to conduct experiments with manganese oxides to better evaluate redox processes above 200°C. It may be desirable in the future to base f_{O_2} calculations on reaction 3 since part of the experiments will be conducted in a titanium-lined cell. In addition, Mn^{2+} in solution can be measured more accurately than Au.

The evidence from a number of experiments at 300°C, both this year and last, indicates that MnO_2 will generate oxidizing conditions unless reducing agents such as organic carbon or ferrous iron are present in excess. Knowledge of the relative abundance of these components in sediment will provide information pertinent to redox conditions in the near field environment and contribute information relevant to radionuclide solubility. Owing to the importance of redox conditions in the near field environment, attention has been given to investigating procedures for the measurement of concentrations of Mn^{2+} , MnO_2 , Fe^{2+}/Fe^{3+} , and organic carbon in sediments.

Measurement of ferrous iron in sediments containing MnO_2 or organic carbon by standard methods such as potassium dichromate titration (Peck, 1964) is generally considered inaccurate due to interference from the latter species (i.e., MnO_2 , C_{org}). X-ray diffraction is useful, however, in obtaining information regarding the abundances of Fe^{2+} -bearing silicate phases such as chlorite.

In most sediments, the relative amounts of MnO_2 and organic carbon are the critical parameters in establishing redox capacity. Measurement of MnO_2 content may be readily accomplished through the use of the ferrous sulfate method (Katz *et al.*, 1956). Measurements to date indicate that 90% or more of the manganese present in most sediments is in the tetravalent state (i.e.,

MnO₂). Thus, it is generally sufficient to simply analyze for Mn in order to evaluate the amount of MnO₂ present in a sediment.

Organic carbon may be measured by any of several instruments available commercially. We have utilized the total carbon analyzer manufactured by Oceanography International and obtained values of about 0.04% for several samples (Table 1). A very small amount of organic material may thus be sufficient in many cases to counterbalance the oxidizing characteristics of MnO₂.

Development and Testing of Gradient Furnace Equipment

A major portion of our research effort for the last year has been directed towards the development of gradient furnace equipment to study the migration of radionuclides in a thermal gradient. The reaction cell consists of a titanium-lined pressure vessel encased in steel (Figure 15) with a volume of approximately 70 ml.

Testing has indicated that the cell will function in a satisfactory manner when situated in a vertical position in its furnace. In order to achieve a maximum gradient, it was found necessary to suspend the cell by means of a steel collar and crossbar such that the capnut is actually situated outside of the top of the furnace and thus air-cooled. The furnace has been wound so that the maximum amount of heat is directed into the bottom end of the cell.

In order to accurately measure the internal temperature gradient of the cell, a probe assembly was constructed of titanium tubing with five miniature probes situated internally along its length. Testing of the probe assembly indicated very favorable response to temperature changes. The first test involved securing the assembly in the cell as shown in Figure 15. Sand was used to pack the cell because it is similar in thermal characteristics to seabed sediment; thus, its use permits us to conserve our sediment resources for future experiments. Subsequent to packing, the cell was filled with water, sealed, and an exit tube and sampling valve were attached to the closure piece. A very favorable thermal gradient developed and stabilized within about 6 hours after the cell was positioned in the furnace in the configuration described above. Temperatures of 300°C in the hot zone to 100°C in the cool zone were recorded. The gradient produced was found to be nearly linear and averaged approximately 17°C per inch.

In a second run, external thermocouples were implanted in the exterior steel casing of the cell and their temperatures compared with those of the internal probes. This run verified that the gradient could be reproduced easily and demonstrated an agreement of $\pm 5^\circ\text{C}$ between the internal and external probes located at identical positions along the length of the cell. Thus, it was verified that the external probes may be used to accurately obtain the internal temperature of the cell thereby removing the need to employ the internal probe assembly in future experiments and making available the entire cell volume for seawater sediment mixtures.

This equipment will be used to perform several experiments in the coming year involving sediment and the glass waste simulant. A perforated titanium container will be utilized to secure the waste simulant in the 300° zone and sediment will be packed into the remainder of the cell. Seawater will be added to sediment to produce a water/rock ratio of approximately 2. During these

experiments, solution samples will be periodically taken from the cool zone near the top of the cell and replaced with fresh seawater via a separator. Recovery of the sediment and waste simulant at the termination of the experiment will allow us to evaluate the integrity of the waste simulant in the near field environment and to assess the mobility of the radionuclide analogs as a function of temperature. Results of these experiments will be examined in terms of rates and mechanisms of radionuclide migration with particular regard being given to the roles of diffusional versus convective transport.

CONCLUSIONS

Five new experiments were conducted this year to study seawater-sediment interaction at 200° and 300°C at 500 bars. Conditions were chosen that are thought to be representative of the near field environment.

A decrease in pH was noted initially in each experiment and solutions remained acid although pH gradually increased with time. Similar modifications of major element chemistry was noted in all experiments. The concentrations of Ca, Mg, Sr, and SO₄ decreased with time while SiO₂(aq), K, Na, Cl, B, and ΣCO₂ increased. Heavy metal concentration in solution varied concomitantly with acidity.

Mn concentration was found to be primarily dependent upon the degree to which manganese oxides (e.g., MnO₂) are reduced by organic carbon and ferrous iron. The relative amounts of these components establish the redox potential or f_{O_2} of the system. Quantification of f_{O_2} utilizing the Au-AuCl₂⁻ redox couple was relatively successful and indicated that f_{O_2} ranged from 10⁻⁸ to 10⁻¹⁴ at 200°C and from 10⁻⁶ to 10⁻²⁰ at 300°C. The acidic, oxidizing environment generated during the 300°C experiments is potentially conducive to radionuclide mobility and requires more intensive investigation. This includes the accurate analysis of all redox components in the sediments. Titanium occurred in very low concentrations in solution from these experiments ($\leq$ 0.01 ppm), suggesting that this environment will not be unduly corrosive to waste canisters constructed of titanium alloys.

Mineralogical changes for the smectite-rich sediment involved the production of more smectite at the expense of a mixed smectite-illite component and amorphous material. Clinoptilolite dissolved entirely while plagioclase and chlorite appear to have partially reacted. The metalliferous sediment also produced smectite as plagioclase and amorphous material underwent reaction. An increase in Cl concentration of the solutions occurred as water was incorporated into the smectite phase produced. Anhydrite was an important alteration product.

FUTURE RESEARCH

Part of our research program for the coming year will involve further characterization of the near field chemical environment through sediment-seawater experiments. We anticipate conducting several experiments with sediment significantly more reducing than that used previously. An experiment will also be conducted with MnO₂ and seawater in order to obtain more information pertinent to the MnO₂-Mn⁺⁺ redox couple.

The most important work for the near future, however, involves experimental investigation of the behavior of radionuclide analogs in the near field environment and their solubility in the near to far field transition. Several experiments are to be conducted in the Dickson hydrothermal equipment with glass waste simulant in sediment and seawater at 300°C and 500 bars. The development of the gradient furnace equipment has progressed such that an experiment can be conducted shortly to evaluate radionuclide mobilization and adsorption in a thermal gradient from 300°C to 100°C.

REFERENCES

- Bischoff, J.L., Heath, G.R. and Leinen, M., (1979) Geochemistry of deep-sea sediments from the Pacific manganese nodule province: Domes sites A, B, and C. In: Bischoff, J.L. and Piper, D.Z., (eds.) Marine Geology and Oceanography of the Pacific Manganese Nodule Province. Plenum Press, 397-436.
- Bischoff, J.L. and Seyfried, W.E., (1978) Hydrothermal chemistry of seawater from 25° to 350°C. Am. J. Sci., 278, 838-860.
- Dickson, F.W., Blount, C.W. and Tunell, G., (1963) Use of hydrothermal solution equipment to determine the solubility of anhydrite in water from 100°C to 275°C and from 1 bar to 1000 bars pressure. Am. J. Sci., 261, 61-78.
- Erickson, K.L., Seyfried, W.E., Heath, G.R., Krumhausl, J.L. and Bowen, V.T., (1980) Geochemical studies supporting the U.S. seabed disposal program. Marine Technology, Sixteenth Annual Conf., Washington, D.C., 500-508.
- Heath, G.R., Moore, T.C., Jr. and Dauphin, J.P., (1980) Organic carbon in deep-sea sediments. In: Andersen, N.R. and Malahoff, A., (eds.) The Fate of Fossil Fuel CO₂ in the Oceans. Plenum Publishing Corp.
- Helgeson, H.C., Brown, T.H. and Leeper, R.H., (1969) Handbook of Theoretical Diagrams Depicting Chemical Equilibria in Geologic Systems Involving an Aqueous Phase at One Atm. and 0° to 300°C. Freeman Cooper and Co.
- Helgeson, H.C., Delany, J.M., Nesbitt, H.W. and Bird, D.K., (1978) Summary and critique of the thermodynamic properties of rock-forming minerals. Am. J. Sci., 278-A, 299pp.
- Helgeson, H.C. and Garrels, R.M., (1968) Hydrothermal transport and deposition of gold. Econ. Geol., 68, 622-635.
- Hollister, C.D., et al., (1978) Geological assessment of the MPG-I Region, central North Pacific, Part II: Seabed Disposal Annual Report, January to December 1978, Sandia Laboratories, Albuquerque, N.M.
- Katz, M.J., Clarke, R.C. and Nye, W.F., (1956) Available oxygen in manganese dioxide. Anal. Chem., 28, 507-508.
- Peck, L.C., (1964) Systematic analysis of silicates. U.S. Geol. Survey Bull. 1170, 89pp.
- Reed, M.H., (1977) Calculation of hydrothermal metasomatism and ore deposition in submarine volcanic rocks with special reference to the West Shasta district, California. Ph.D. Thesis, University of California, Berkeley, 107pp.
- Robie, R.A., Hemingway, B.S. and Fisher, J.R., (1978) Thermodynamic properties of minerals and related substances at 298.15 K and 1 bar (10⁵ pascals) pressure and at higher temperatures. U.S. Geol. Survey Bull. 1452, 456p.
- Seyfried, W.E., Gordon, P. and Dickson, F.W., (1979) A new reaction cell for hydrothermal solution equipment. Amer. Mineral., 64, 646-649.

Seyfried, W.E., Thornton, E.C. and Janecky, D.R., (1980) Seawater-sediment interaction at elevated temperatures and pressures: Implications for the near field chemical environment. Seabed Disposal Annual Report, January to December 1979, Sandia Laboratories, Albuquerque, N.M.

Seyfried, W.E., Thornton, E.C. and Janecky, D.R., (1980) Seawater-sediment interaction at 300°C, 500 bars: Implications for seabed disposal of nuclear wastes. Proc. 3rd Int. Sym. on Water-Rock Interaction, Edmonton, Canada, 135-137.

Thornton, E.C. and Seyfried, W.E., (1980) Seawater-sediment hydrothermal interaction: Implications for radionuclide mobility in the near field marine environment. Geol. Soc. Amer. (Abstracts with Programs), 12, 535.

TABLE 1. Chemical Composition of Sediments from MPG-I Region.*

<u>Wt % Component</u>	<u>Sediment B</u>	<u>Pacific Smectite</u>	<u>GPC3-13</u>
SiO ₂	53.46	51.72	39.82
Al ₂ O ₃	17.35	14.28	12.48
Fe ₂ O ₃ **	7.64	9.06	14.49
MgO	3.21	3.49	3.19
CaO	0.73	1.31	4.22
Na ₂ O	1.43	1.47	0.87
K ₂ O	4.24	3.79	2.18
MnO	0.47	1.26	4.82
TiO ₂	0.84	0.61	0.53
C _{inorg}	nil	0.01	0.05
C _{org}	0.04	0.04	0.04
H ₂ O ⁻	0.86	1.52	2.89
H ₂ O ⁺	<u>6.48</u>	<u>8.69</u>	<u>11.37</u>
Total	96.75	97.25	96.95

* Sediments dried at 40°C prior to analysis.

** Total Fe as Fe₂O₃.

TABLE 2. Change in Concentration of Aqueous Species (ppm), Total Dissolved CO₂ (millimoles/kg), and pH During Seawater-Smectite Sediment (SM2-200-5) Interaction at 200°C, 500 Bars and Water/Rock Ratio of 5.

<u>SAMPLE</u>	<u>HOURS</u>	<u>pH</u>	<u>Ct</u>	<u>Na⁺</u>	<u>K⁺</u>	<u>Ca⁺²</u>	<u>Mg⁺²</u>	<u>SiO₂</u>	<u>SO₄</u>	<u>Cl⁻</u>
SW*	0	7.90	2.33	10763	399	412	1297	4.2	2734	19375
1	5	4.86	4.38	10853	618	192	1238	217	2030	19822
2	101	4.47	13.19	10479	844	203	864	737	1300	19626
3	341	4.39	12.77	10404	975	271	717	754	851	19667
4	678	4.35	9.97	10685	797	295	659	785	936	19720
Q**	706	6.00	-	-	633	659	812	473	1781	-

<u>SAMPLE</u>	<u>HOURS</u>	<u>Fe²⁺</u>	<u>Mn²⁺</u>	<u>Zn²⁺</u>	<u>Ni</u>	<u>Co</u>	<u>Ba</u>	<u>Sr</u>	<u>Al</u>	<u>B</u>	<u>Au</u>	<u>Ti</u>
SW*	0	4.01	4.01	4.01	4.01	4.01	0.03	7.9	4.01	4.4	4.02	4.01
1	5	1.54	56.8	2.3	0.50	0.02	0.08	2.8	0.31	8.5	0.09	4.01
2	101	1.60	605	2.1	0.35	0.02	0.08	3.4	0.22	22.4	1.30	4.01
3	341	2.10	614	2.24	0.30	0.02	0.14	4.3	0.26	24.0	1.40	4.01
4	678	5.70	582	2.9	0.48	0.02	0.18	4.5	0.29	24.0	1.30	4.01
Q**	706	0.16	576	0.74	0.37	0.02	0.12	9.3	0.46	23.0	0.05	4.01

* Seawater (prior to reaction)

** Quench sample (25°C)

(-) Not analyzed

TABLE 3. Change in Concentration of Aqueous Species (ppm), Total Dissolved CO₂ (millimoles/kg), and pH During Seawater-Smectite Sediment (SM3-300-5) Interaction at 300°C, 500 Bars and Water/Rock Ratio of 5.

<u>SAMPLE</u>	<u>HOURS</u>	<u>pH</u>	<u>Ct</u>	<u>Na⁺</u>	<u>K⁺</u>	<u>Ca⁺²</u>	<u>Mg⁺²</u>	<u>SiO₂</u>	<u>SO₄</u>	<u>Cl⁻</u>
SW*	0	7.90	2.33	10763	399	412	1297	4.2	2734	19375
1	2.0	2.71	7.98	10871	1044	109	562	2064	577	19904
2	79.0	2.34	7.31	10681	1202	184	272	2004	185	19760
3	261.5	2.73	8.00	10884	1281	176	255	1918	161	19998
4	575.3	3.02	7.66	10949	1380	181	208	1981	168	20051
5	1347.0	4.08	14.06	10874	1538	154	137	1246	146	19654
6	2811.0	4.17	12.15	10947	1314	135	114	1239	186	19376

<u>SAMPLE</u>	<u>HOURS</u>	<u>Fe²⁺</u>	<u>Mn²⁺</u>	<u>Zn²⁺</u>	<u>Ni</u>	<u>Cr</u>	<u>Co</u>	<u>Ba</u>	<u>Sr</u>	<u>Al</u>	<u>B</u>	<u>F</u>	<u>Ti</u>	<u>Au</u>
SW*	0	4.01	4.01	4.01	4.01	4.01	4.01	0.03	7.9	4.01	4.4	1.3	4.01	4.03
1	2.0	5.9	520	9.6	0.25	0.04	0.24	0.22	1.3	0.12	17.5	5.0	.01	1.20
2	79.0	6.7	756	16.2	0.43	0.04	0.09	0.38	2.0	0.12	22.6	6.1	4.01	1.70
3	261.5	4.2	777	16.4	0.40	0.05	0.09	0.49	2.3	0.17	23.0	3.7	4.01	1.70
4	575.3	1.3	807	19.0	0.50	0.07	0.06	0.42	2.8	0.17	23.1	3.0	4.01	1.80
5	1347.0	0.2	700	17.6	0.45	0.01	0.03	0.41	2.9	0.21	23.8	2.2	4.01	1.66
6	2811.0	0.2	657	17.4	0.54	0.01	0.02	0.44	2.4	0.18	24.2	1.1	4.01	1.60

* Seawater (prior to reaction)

TABLE 4. Change in Concentration of Aqueous Species (ppm), Total Dissolved CO₂ (millimoles/kg), and pH During Seawater-Metalliferous Sediment (GPC3C-200-5) Interaction at 200°C, 500 Bars and Water/Rock Ratio of 5.

<u>SAMPLE</u>	<u>HOURS</u>	<u>pH</u>	<u>Ct</u>	<u>Na⁺</u>	<u>K⁺</u>	<u>Ca⁺²</u>	<u>Mg⁺²</u>	<u>SiO₂</u>	<u>SO₄</u>	<u>Cl⁻</u>
SW*	0	7.90	2.33	10763	399	412	1297	4.2	2734	19375
1	1.0	5.07	5.44	11261	741	219	1040	417	1868	20102
2	123.2	4.00	8.29	11105	745	181	935	637	1449	19853
3	292.0	3.91	7.57	11071	870	190	921	625	1451	19897
4	674.0	4.74	7.46	11044	729	202	904	605	1402	19735
5	1389.0	4.05	8.10	11268	755	186	875	588	1411	19996
Q**	1396.5	6.50	-	11580	571	550	1040	315	2692	20364

<u>SAMPLE</u>	<u>HOURS</u>	<u>Fe²⁺</u>	<u>Mn²⁺</u>	<u>Zn²⁺</u>	<u>Ni</u>	<u>Cr</u>	<u>Co</u>	<u>Ba</u>	<u>Sr</u>	<u>Al</u>	<u>B</u>	<u>Ti</u>	<u>Au</u>
SW*	0	4.01	4.01	4.01	4.01	4.01	4.01	0.03	7.9	4.01	4.4	4.01	4.03
1	1.0	0.50	25.8	0.8	0.10	0.04	0.02	0.17	4.0	0.25	14.3	4.01	0.05
2	123.2	0.80	50.0	1.50	0.28	0.17	0.06	0.15	3.4	0.17	19.2	4.01	0.14
3	292.0	0.60	56.2	1.45	0.12	0.09	0.03	0.10	3.7	0.17	19.6	4.01	0.13
4	674.0	0.17	69.3	-	-	-	0.03	0.13	3.5	0.49	20.3	4.01	0.11
5	1389.0	4.01	67.2	1.90	0.06	0.01	0.02	0.25	3.4	0.18	19.6	4.01	0.09
Q**	1396.5	4.01	62.9	4.01	0.01	-	0.01	0.20	9.4	0.42	19.9	4.01	0.06

* Seawater (prior to reaction)

** Quench sample (25°C)

(-) Not analyzed

TABLE 5. Change in Concentration of Aqueous Species (ppm), Total Dissolved CO₂ (millimoles/kg), and pH During Seawater-Metalliferous Sediment (GPC3B-200-5) Interaction. Samples 1, 2, 3, and 4 were taken at 200°C and 5, 6, and 7 at 300°C, 500 Bars and Water/Rock Ratio of 5.

SAMPLE	HOURS	pH	Ct	Na ⁺	K ⁺	Ca ⁺²	Mg ⁺²	SiO ₂	SO ₄	Cl ⁻
SW*	0	7.90	2.33	10763	399	412	1297	4.2	2734	19375
1	3.0	4.80	4.54	9745	647	324	1128	355	1402	18444
2	74.5	5.10	6.67	9439	677	281	981	563	842	17894
3	267.5	4.60	6.77	9737	706	265	932	606	797	18262
4	602.5	4.30	7.44	10079	687	277	869	533	807	18613
5	648.0	2.94	6.86	10156	749	214	596	1165	295	18406
6	743.5	2.59	8.11	10280	1343	216	404	1501	230	18831
7	1017.5	2.50	6.10	9912	1408	212	365	1568	196	18330
Q**	1056.0	6.30	-	10947	340	540	884	149	2553	18837

SAMPLE	HOURS	Fe	Mn	Zn	Ni	Cr	Co	Ba	Sr	Al	B	F	Au	Ti
SW*	0	4.01	4.01	4.01	4.01	4.01	4.01	0.03	7.9	4.01	4.4	1.3	4.02	4.01
1	3.0	0.30	1.15	1.5	0.52	0.01	0.01	0.11	4.8	0.28	10.1	0.70	4.02	0.01
2	74.5	0.30	4.00	0.59	0.48	-	0.02	0.03	3.1	0.26	-	0.54	4.10	4.01
3	267.5	1.15	4.20	1.8	0.45	0.21	0.04	0.13	3.9	0.24	11.0	0.44	4.10	0.01
4	602.5	2.90	5.80	2.4	0.75	0.45	0.06	0.27	4.1	0.19	10.6	1.8	0.07	4.01
5	648.0	4.00	61.0	9.9	2.20	-	.30	-	4.5	1.00	-	1.7	17.5	4.01
6	743.5	67.0	42.6	33	8	0.5	0.92	.60	6.1	0.32	13.5	0.56	52.5	0.01
7	1017.5	120	43.3	38	11	20	0.85	0.11	5.2	0.27	13.9	2.3	0.20	4.01
Q**	1056.0	0.16	1.45	0.61	0.60	0.16	0.10	4.01	10.0	0.48	12.5	7.5	0.02	4.01

* Seawater (prior to reaction)

** Quench sample (25°C)

(-) Not analyzed

TABLE 6. Change in Concentration of Aqueous Species (ppm), Total Dissolved CO₂ (millimoles/kg), and pH During Seawater-Metalliferous Sediment (GPC3-300-5) Interaction at 300°C, 500 Bars and Water/Rock Ratio of 5.

<u>SAMPLE</u>	<u>HOURS</u>	<u>pH</u>	<u>Ct</u>	<u>Na⁺</u>	<u>K⁺</u>	<u>Ca⁺²</u>	<u>Mg⁺²</u>	<u>SiO₂</u>	<u>SO₄</u>	<u>Cl⁻</u>
SW*	0	7.90	2.33	10763	399	412	1297	4.2	2734	19375
1	3.0	3.35	12.17	10763	866	166	536	723	464	19967
2	93.0	2.38	12.31	10525	853	342	86.0	1121	54	19512
3	310.5	2.65	15.39	10512	1001	314	50.1	1262	54	19329
4	625.0	3.52	15.06	10584	961	322	49.1	1238	49	19352
5	1508.0	4.02	24.13	10289	880	356	50.8	1085	86	18785
6	3026.5	4.54	-	10681	879	341	67.0	915	133	19423
Q**	3045.5	5.90	4.92	-	-	-	145	159	2203	19010

<u>SAMPLE</u>	<u>HOURS</u>	<u>Fe²⁺</u>	<u>Mn²⁺</u>	<u>Zn²⁺</u>	<u>Ni</u>	<u>Cr</u>	<u>Co</u>	<u>Ba</u>	<u>Sr</u>	<u>Al</u>	<u>B</u>	<u>F</u>	<u>Ti</u>	<u>Au</u>
SW*	0	4.01	4.01	4.01	4.01	4.01	4.01	0.03	7.9	4.01	4.4	1.3	4.01	4.03
1	3.0	5.30	807	13.0	0.75	0.08	0.20	0.23	3.1	0.29	10.7	5.0	.01	1.90
2	93.0	24.0	1113	13.6	0.50	0.16	0.12	0.85	6.8	0.34	13.2	3.9	4.01	2.70
3	310.5	2.70	1100	14.0	0.66	0.02	0.07	1.12	6.8	0.31	14.3	2.8	4.01	2.60
4	625.0	2.15	1117	14.0	0.55	-	0.06	1.00	6.9	0.36	14.2	-	4.01	-
5	1508.0	1.00	1072	13.4	0.70	0.02	0.06	0.91	7.1	0.33	13.8	2.2	4.01	2.50
6	3026.5	-	1125	-	-	-	-	-	-	-	-	-	-	-
Q**	3045.5	-	-	-	0.08	0.03	0.07	0.23	10.0	0.61	12.0	-	-	2.40

* Seawater (prior to reaction)

** Quench sample (25°C)

(-) Not analyzed

FIGURE CAPTIONS

- Figure 1. Relative proportions of pelagic clay, biogenic silica, and metalliferous sediment in samples from the MPG-I region.
- Figure 2. Change in concentration of major aqueous species (K, SiO₂, Mg, Ca) and pH during smectite-rich sediment-seawater interaction at 300°C, 500 bars (SM3-300-5).
- Figure 3. Change in concentration of Mn, ΣCO₂, and Fe during the SM3-300-5 experiment.
- Figure 4. Change in concentration of major aqueous species (K, SiO₂, Mg, Ca) and pH during metalliferous sediment-seawater interaction at 200° and 300°C, 500 bars. The solid symbols present the data from the GPC3B-200-5 experiment while the open symbols are the fourth and fifth samples from the GPC3-300-5 experiment.
- Figure 5. Change in concentration of aqueous Mn, ΣCO₂, Fe, and Au during the GPC3B-200-5 experiment.
- Figure 6. Mineralogical composition of smectite-rich sediment before and after reaction of 300°C, 500 bars based on x-ray diffraction analysis. The arrows indicate the change in abundance of mineral phases based on the amplitude of reflection relative to the 3.34 Å quartz peak (CuKα).
- Figure 7. Mineralogical composition of metalliferous sediment before and after reaction at 300°C, 500 bars.
- Figure 8. Mineral activity diagram for the HCl-H₂O-Al₂O₃-CO₂-K₂O-MgO-SiO₂ system at 300°C, 1 bar, and quartz saturation (Helgeson *et al.*, 1969). Data for solution samples from the GPC3-300-5 experiment are indicated by an x with the corresponding sample number and SM3-300-5 samples are indicated by an o.
- Figure 9. Mineral activity diagram for the HCl-H₂O-Al₂O₃-CaO-CO₂-K₂O-SiO₂ system at 300°C, 1 bar, and quartz saturation.
- Figure 10. Mineral activity diagram for the HCl-H₂O-Al₂O₃-CaO-CO₂-MgO-SiO₂ system at 300°C, 1 bar, and quartz saturation.
- Figure 11. Solubility of gold in seawater as a function of f_{O₂} and pH at 300°C, 500 bars.
- Figure 12. Relationship of redox couples as a function of f_{O₂} and pH at 25°C, 500 bars. Boundaries drawn assuming an activity of 10⁻⁶ for aqueous species and log f_{O₂} = 0 for H₂O-O₂ couple.
- Figure 13. Relationship of redox couples as a function of f_{O₂} and pH at 200°C, 500 bars.
- Figure 14. Relationship of redox couples as a function of f_{O₂} and pH at 300°C, 500 bars.
- Figure 15. Schematic illustration of titanium-lined reaction vessel and thermocouple probe assembly for gradient experiments.

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

FIGURE 7

FIGURE 8

FIGURE 9

FIGURE 10

FIGURE 11

FIGURE 12

FIGURE 13

FIGURE 14

FIGURE 15

Addenda 1

Distribution of Aqueous Species of Solution Samples.

<u>Experiment</u>	<u>Code</u>
smectite-rich sediment - 200°C	SM2-200-5 (4 samples)
smectite-rich sediment - 300°C	SM3-300-5 (6 samples)
metalliferous sediment - 200°C	GPC3C-200-5 (5 samples)
metalliferous sediment - a) 200°C	GPC3B-200-5 (samples 1,2,3,4)
b) 300°C	GPC3B-200-5 (samples 5,6,7)
metalliferous sediment - 300°C	GPC3-300-5 (6 samples)

SM2-200-5-1 HOURS = 5.00 PH(25) = 4.86
200 DEGREES C AT 500 BARS AND W/P = F
81/02/17.

WATER 1.0000(KG.LIQ.) 55.5081(MOLES LIQ.) 55.5083(MOLES TOTAL)
STOICHIOMETRIC IONIC STRENGTH=.6816779E+00 OSMOTIC COEF.= .8362
IONIC STRENGTH=.5739304E+00 ACTIVITY=.9831

EQ2 INPUT AS REDOX CONTROL

LOG EQ2=-10.10 LOG FH2=-18.14 LOG FH2O= 1.25 LOG FCO2= -.06
LOG FH2S= N LOG FS2= N
CALCULATED ACTIVITY HS- = .4045E-12M LOG FH2S=-58.79 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG EQ2
H2(AQ) CM	.7391E-21	.8323E-21 .1126E+01	.1490E-17	.1656E-19	-18.1377
O2(AQ) CM	.8551E-13	.9630E-13 .1126E+01	.2734E-08	.1915E-11	

CM - MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))Z	LOG(A/(AH)Z)
1 H+	.1274E-04	-5.0436	.4165E-02	.1000E+01	0
2 H2O		-.0074	.5551E+02		
3 F02		-10.1024ATM			
4 CL-	.5207E+00	-.5916	.5591E+00	.2317E-05	-5.6352
5 SO4--	.2962E-02	-3.5942	.2113E-01	.2063E-13	-13.6814
6 HCO3-	.8431E-04	-4.3203	.4380E-02	.4326E-09	-9.3639
7 SiO2(AQ)	.3611E-02	-2.3908	.3611E-02	.4067E-02	-2.3908
8 AL+++	.7011E-14	-15.7086	.1149E-04	.2643E+00	-5.5779
9 CA++	.4493E-02	-3.2436	.4790E-02	.6975E+07	6.8435
10 MG++	.3588E-01	-2.1815	.5092E-01	.8047E+08	7.9056
11 FE++	.7425E-05	-6.0245	.2757E-04	.1155E+05	4.0626
12 K+	.1505E-01	-2.1307	.1580E-01	.8182E+03	2.9128
13 NA+	.4318E+00	-.6289	.4721E+00	.2598E+05	4.4147
14 MN++	.9068E-03	-4.1800	.1034E-02	.8074E+06	5.9071
15 ZN++	.6111E-07	-8.3514	.3518E-04	.5442E+02	1.7358
16 BA++	.5582E-06	-7.2555	.5816E-06	.6787E+03	2.8316
17 SP++	.2681E-04	-5.5740	.3196E-04	.3260E+05	4.5132
18 AU+	.4076E-11	-11.7254	.4569E-06	.2060E-06	-6.6818

SM2-200-5-1 HOURS = 5.00 PH(25) = 4.86
 200 DEGREES C AT 500 BARS AND W/P = F
 81/02/77.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.1274E-04	-4.8948	.9045E-05	-5.0436	.7100E+00
2 H2O			.9831E+00	-.0074	.9831E+00
3 F02			.7900E-10ATM	-10.1024	
4 CL-	.5207E+00	-.2834	.2561E+00	-.5916	.4918E+00
5 SO4--	.2962E-02	-2.5285	.2546E-03	-3.5942	.8595E-01
6 HCO3-	.8431E-04	-4.0741	.4783E-04	-4.3203	.5673E+00
7 SiO2(AQ)	.3611E-02	-2.4424	.4067E-02	-2.3908	.1126E+01
8 AL++	.7011E-14	-14.1542	.1956E-15	-15.7066	.2790E-01
9 CA++	.4482E-02	-2.3484	.5707E-03	-3.2436	.1273E+00
10 MG++	.3588E-01	-1.4451	.6584E-02	-2.1815	.1835E+00
11 FE++	.7425E-05	-5.1293	.9451E-06	-6.0245	.1273E+00
12 K+	.1505E-01	-1.8225	.7401E-02	-2.1307	.4918E+00
13 NA+	.4318E+00	-.3647	.2350E+00	-.6289	.5443E+00
14 MN++	.9068E-03	-3.0425	.6607E-04	-4.1800	.7286E-01
15 ZN++	.6111E-07	-7.2139	.4452E-08	-8.3514	.7286E-01
16 BA++	.5582E-06	-6.2532	.5553E-07	-7.2555	.9947E-01
17 SR++	.2681E-04	-4.5717	.2667E-05	-5.5740	.9947E-01
18 AU+	.4076E-11	-11.3898	.1882E-11	-11.7254	.4617E+00
19 AM+++	.2809E-34	-34.5514	.7169E-37	-37.1445	.2552E-02
20 AUCL2-	.4545E-06	-6.3425	.2474E-06	-6.6066	.5443E+00
21 AUCL4-	.2406E-08	-8.6188	.1209E-08	-8.8629	.5443E+00
22 FE+++	.1266E-10	-10.8977	.3531E-12	-12.4521	.2790E-01
23 OH-	.1177E-05	-5.9292	.6112E-06	-6.2138	.5193E+00
24 H3SiO4-	.3605E-06	-6.4431	.1962E-06	-6.7072	.5443E+00
25 H2SiO4--	.2978E-11	-11.5261	.2170E-12	-12.6636	.7286E-01
26 KSO4-	.3309E-03	-3.4803	.1718E-03	-3.7649	.5193E+00
27 FES04	.1618E-05	-5.7403	.2048E-05	-5.6887	.1126E+01
28 HCL	.1792E-05	-5.7468	.2018E-05	-5.6952	.1126E+01
29 HSO4-	.7251E-04	-4.1336	.4001E-04	-4.3978	.5443E+00
30 CADH+	.2997E-06	-6.5233	.1631E-06	-6.7874	.5443E+00
31 MGDH+	.9095E-04	-4.0412	.4951E-04	-4.3053	.5443E+00
32 FECL+	.1770E-04	-4.7520	.9636E-05	-5.0161	.5443E+00
33 FECL++	.7831E-08	-8.1062	.5706E-09	-9.2437	.7286E-01
34 FECL4-	.2085E-08	-8.6810	.1519E-09	-9.8185	.7286E-01
35 FECL3	.3322E-08	-8.4785	.3742E-08	-8.4269	.1126E+01
36 FECL2+	.3880E-08	-8.4111	.2112E-08	-8.6753	.5443E+00
37 FES04+	.5996E-09	-9.2222	.3264E-09	-9.4863	.5443E+00
38 ZNCL+	.1178E-06	-6.9288	.6413E-07	-7.1930	.5443E+00
39 ZNCL2	.4829E-07	-7.3162	.5438E-07	-7.2646	.1126E+01
40 ZNCL2-	.8669E-05	-5.0620	.4719E-05	-5.3262	.5443E+00
41 ZNCL4--	.2629E-04	-4.5802	.1915E-05	-5.7178	.7286E-01
42 ALS04+	.4087E-14	-14.3896	.2224E-14	-14.6528	.5443E+00
43 CO3--	.1285E-08	-8.8910	.1105E-09	-9.9568	.8595E-01
44 H2CO3	.4212E-02	-2.3755	.4744E-02	-2.3239	.1126E+01

SM2-200-5-1 HQUFS = 5.00 PH(25) = 4.86
 200 DEGREES C AT 500 BARS AND W/F = F
 91/02/17.
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 AL(OH)4-	.1149E-04	-4.9397	.6254E-05	-5.2039	.5443E+00
46 FE(OH)++	.1764E-13	-13.7534	.1286E-14	-14.8909	.7286E-01
47 FE(OH)+	.6107E-06	-6.2142	.3324E-06	-6.4783	.5443E+00
48 AL(OH)++	.1183E-08	-8.9272	.1505E-09	-9.8224	.1273E+00
49 NaCl	.3784E-01	-1.4221	.4261E-01	-1.3705	.1126E+01
50 KCl	.4227E-03	-3.3739	.4761E-03	-3.3223	.1126E+01
51 KHSO4	.3980E-05	-5.4001	.4482E-05	-5.3485	.1126E+01
52 CaCO3	.6427E-08	-8.1920	.7238E-08	-8.1404	.1126E+01
53 MnSO4	.1271E-03	-3.8958	.1431E-03	-3.8442	.1126E+01
54 NaSO4-	.2455E-02	-2.6100	.1371E-02	-2.8631	.5583E+00
55 MgSO4	.1488E-01	-1.8273	.1676E-01	-1.7757	.1126E+01
56 CaSO4	.2955E-03	-3.5294	.3328E-03	-3.4778	.1126E+01
57 NaCO3-	.3146E-08	-8.5023	.1838E-08	-8.7357	.5843E+00
58 MgHCO3+	.6797E-04	-4.1677	.3700E-04	-4.4318	.5443E+00
59 CaHCO3+	.1149E-04	-4.9398	.6252E-05	-5.2040	.5443E+00
60 MgCO3	.2648E-17	-17.5770	.2983E-17	-17.5254	.1126E+01
61 BaCO3	.2168E-13	-13.6639	.2442E-13	-13.6123	.1126E+01
62 BaHCO3+	.2034E-07	-7.6917	.1107E-07	-7.9558	.5443E+00
63 BaOH+	.8730E-10	-10.0590	.5197E-10	-10.2863	.5884E+00
64 BaSO4	.3011E-08	-8.5213	.3391E-08	-8.4697	.1126E+01
65 SrOH+	.8761E-10	-10.0575	.5155E-10	-10.2878	.5884E+00
66 SrCO3	.2616E-11	-11.5923	.2946E-11	-11.5307	.1126E+01
67 SrHCO3+	.4072E-05	-5.3901	.2217E-05	-5.6543	.5443E+00
68 SrSO4	.1072E-05	-5.9698	.1207E-05	-5.9182	.1126E+01

SM2-200-5-2 HOURS = 101.00 PH(25) = 4.47
 200 DEGREES C AT 500 BARS AND W/P = F
 91/02/17.

WATER 1.0000(KG.LIG.) 55.5082(MOLES LIO.) 55.5083(MOLES TOTAL)
 STOICHIOMETRIC IONIC STRENGTH=.6526268E+00 OSMOTIC COEF.= .8456
 IONIC STRENGTH=.5671954E+00 ACTIVITY=.9832

FD2 INPUT AS PFDXX CONTROL

LOG FD2=-10.49 LOG FH2=-17.94 LOG FH2O= 1.25 LOG FCO2= .43
 LOG FH2S= N LOG FS2= N
 CALCULATED ACTIVITY HS- = .2993E-61M LOG FH2S=-57.69 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PDM	CC/G	LOG F CALC LOG FD2
H2(AQ) CM	.1143E-20	.1308E-20 .1125E+01	.2345E-17	.2605E-19	-17.9414
O2(AQ) CM	.3469E-13	.3901E-13 .1125E+01	.1110E-08	.7770E-12	

CM - MOLALITY CALCULATED FROM PFDXX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))Z	LOG(A/(AH)Z)
1 H+	.2174E-04	-4.8116	.1296E-01	.1000E+01	0
2 H2O		-.0074	.5551E+02		
3 FD2		-10.4949ATM			
4 CL-	.5164E+00	-.5944	.5536E+00	.3926E-05	-5.4060
5 SO4--	.2095E-02	-3.7420	.1353E-01	.4314E-13	-13.3651
6 HCO3-	.1512E-03	-4.0663	.1319E-01	.1325E-08	-8.8779
7 STO2(AQ)	.1226E-01	-1.8604	.1227E-01	.1379E-01	-1.8604
8 AL+++	.4194E-13	-14.9293	.8154E-05	.3202E+00	-4.946
9 CA++	.4815E-02	-3.2108	.5065E-02	.2584E+07	6.4123
10 MG++	.2731E-01	-2.2989	.3554E-01	.2110E+08	7.3242
11 FE++	.7953E-05	-5.9929	.2865E-04	.4268E+04	3.6302
12 K+	.2068E-01	-1.9920	.2158E-01	.6601E+03	2.8196
13 NA+	.4177E+00	-.6478	.4558E+00	.1475E+05	4.1688
14 MN++	.1001E-01	-3.1347	.1101E-01	.3082E+07	6.4888
15 ZN++	.5710E-07	-8.3779	.3212E-04	.1759E+02	1.2452
16 BA++	.5438E-06	-7.2646	.5816E-06	.2283E+03	2.3585
17 SR++	.2980E-04	-5.5259	.3880E-04	.1251E+05	4.0972
18 AU+	.5932E-10	-10.5614	.6600E-05	.1779E-05	-5.7498

SM2-200-F-2 HOURS = 101.00 PH(25) = 4.47
 200 DEGREES C AT 500 BARS AND W/P = F
 81/02/17.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.2174E-04	-4.6628	.1543E-04	-4.8116	.7100E+00
2 H2O			.9832E+00	-.0074	.9832E+00
3 F02			.3200E-10ATM	-10.4949	
4 CL-	.5164E+00	-.2870	.2544E+00	-.5944	.4927E+00
5 SO4--	.2095E-02	-2.6788	.1811E-03	-3.7420	.8646E-01
6 HCO3-	.1512E-03	-3.8205	.8584E-04	-4.0663	.5678E+00
7 SiO2(AQ)	.1226E-01	-1.9114	.1379E-01	-1.8604	.1125E+01
8 AL+++	.4194E-13	-13.3773	.1177E-14	-14.9293	.2805E-01
9 CA++	.4815E-02	-2.3174	.6154E-03	-3.2108	.1278E+00
10 MG++	.2731E-01	-1.5637	.5024E-02	-2.2989	.1840E+00
11 FF++	.7953E-05	-5.0995	.1016E-05	-5.9929	.1278E+00
12 K+	.2048E-01	-1.6845	.1019E-01	-1.9920	.4927E+00
13 NA+	.4177E+00	-.3792	.2276E+00	-.6428	.5449E+00
14 MN++	.1001E-01	-1.9997	.7340E-03	-3.1343	.7335E-01
15 ZN++	.5710E-07	-7.2434	.4188E-08	-8.3779	.7335E-01
16 BA++	.5438E-06	-6.2646	.5437E-07	-7.2646	.9999E-01
17 SR++	.2980E-04	-4.5258	.2979E-05	-5.5259	.9999E-01
18 AM+	.5933E-10	-10.2268	.2745E-10	-10.5614	.4627E+00
19 AU+++	.7464E-32	-33.1270	.1936E-35	-35.7121	.2594E-02
20 AUCL2-	.6537E-05	-5.1846	.3562E-05	-5.4483	.5449E+00
21 AUCL4-	.6321E-07	-7.1992	.3444E-07	-7.4629	.5449E+00
22 FF+++	.1842E-10	-10.7348	.5167E-12	-12.2868	.2805E-01
23 OH-	.6890E-06	-6.1618	.3583E-06	-6.4458	.5200E+00
24 H2SiO4-	.7159E-06	-6.1451	.3901E-06	-6.4088	.5449E+00
25 H2SiO4--	.3446E-11	-11.4626	.2528E-12	-12.5972	.7335E-01
26 KSO4-	.3236E-03	-3.4899	.1683E-03	-3.7739	.5200E+00
27 FFSO4	.1393E-02	-5.8559	.1567E-05	-5.8049	.1125E+01
28 HCL	.3041E-05	-5.5170	.3420E-05	-5.4660	.1125E+01
29 HSO4-	.8915E-04	-4.0499	.4858E-04	-4.3135	.5449E+00
30 CADH+	.1892E-06	-6.7230	.1031E-06	-6.9866	.5449E+00
31 MGPH+	.4064E-04	-4.3911	.2215E-04	-4.6547	.5449E+00
32 FECL+	.1889E-04	-4.7237	.1029E-04	-4.9874	.5449E+00
33 FECL++	.1131E-07	-7.9467	.8294E-09	-9.0812	.7335E-01
34 FECL4-	.2951E-08	-8.5200	.2165E-09	-9.6646	.7335E-01
35 FFCL3	.4774E-08	-8.3211	.5369E-08	-8.2701	.1125E+01
36 FECL2+	.5597E-08	-8.2520	.3050E-08	-8.5157	.5449E+00
37 FFSO4+	.6236E-09	-9.2051	.3398E-09	-9.4688	.5449E+00
38 ZNCL+	.1100E-06	-6.9567	.5993E-07	-7.2224	.5449E+00
39 ZNCL2	.4489E-07	-7.3478	.5049E-07	-7.2968	.1125E+01
40 ZNCL3-	.7987E-05	-5.0976	.4352E-05	-5.3613	.5449E+00
41 ZNCL4--	.2392E-04	-4.6211	.1755E-05	-5.7557	.7335E-01
42 ALSD4+	.1747E-13	-13.7577	.9521E-14	-14.0213	.5449E+00
43 CO3--	.1344E-08	-8.8716	.1162E-09	-9.9348	.8646E-01
44 H2CO3	.1292E-01	-1.8889	.1452E-01	-1.8379	.1125E+01

SM2-200-5-2 WOLPS = 101.00 PH(25) = 4.47
 200 DEGREES C AT 500 BARS AND W/P = 5
 81/02/17.
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 AL(OH)4-	.8150E-05	-5.0888	.4441E-05	-5.3525	.5449E+00
46 FEOH++	.1503E-13	-13.8230	.1103E-14	-14.9576	.7335E-01
47 FEOH+	.3845E-06	-6.4151	.2095E-06	-6.6787	.5449E+00
48 AL(OH)++	.4153E-08	-8.3817	.5307E-09	-9.2751	.1278E+00
49 NaCl	.3646E-01	-1.4382	.4100E-01	-1.3872	.1125E+01
50 KCl	.5789E-03	-3.2374	.6510E-03	-3.1864	.1125E+01
51 KHSO4	.6660E-05	-5.1765	.7490E-05	-5.1255	.1125E+01
52 CaCO3	.7301E-08	-8.1366	.8211E-08	-8.0856	.1125E+01
53 MnSO4	.1006E-02	-2.9973	.1132E-02	-2.9463	.1125E+01
54 NaSO4-	.1690E-02	-2.7721	.9445E-03	-3.0248	.5589E+00
55 MgSO4	.8092E-02	-2.0919	.9101E-02	-2.0409	.1125E+01
56 CaSO4	.2271E-03	-3.6438	.2554E-03	-3.5928	.1125E+01
57 NaCO3-	.3202E-08	-8.4945	.1873E-08	-8.7276	.5848E+00
58 MgHCO3+	.9298E-04	-4.0316	.5067E-04	-4.2953	.5449E+00
59 CaHCO3+	.2221E-04	-4.6535	.1210E-04	-4.9172	.5449E+00
60 MgCO3	.6197E-17	-17.2078	.6969E-17	-17.1568	.1125E+01
61 BaCO3	.2237E-13	-13.6504	.2515E-13	-13.5994	.1125E+01
62 BaHCO3+	.3570E-07	-7.4473	.1946E-07	-7.7109	.5449E+00
63 BaOH+	.5007E-10	-10.3004	.2948E-10	-10.5304	.5888E+00
64 BaSO4	.2101E-08	-8.6776	.2363E-08	-8.6266	.1125E+01
65 SrOH+	.5732E-10	-10.2417	.3375E-10	-10.4717	.5888E+00
66 SrCO3	.3079E-11	-11.5117	.3462E-11	-11.4607	.1125E+01
67 SrHCO3+	.8155E-05	-5.0886	.4444E-05	-5.3522	.5449E+00
68 SrSO4	.8533E-06	-6.0689	.9597E-06	-6.0179	.1125E+01

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SM2-200-5-2 HOURS = 341.00 PH(25) = 4.39
 200 DEGREES C AT 500 BARS AND W/O = 5
 81/02/18.

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WATER 1.0000(KG.LIQ.) 55.5082(MOLES LIQ.) 55.5083(MOLES TOTAL)
 STOICHIOMETRIC IONIC STRENGTH=.6353506E+00 OSMOTIC COEF.= .8502
 IONIC STRENGTH=.5650072E+00 ACTIVITY=.9822

FO2 INPUT AS REDOX CONTROL

LOG FO2=-10.70 LOG FH2=-17.84 LOG FH2O= 1.25 LOG FCO2= .42
 LOG FH2S= N LOG FS2= N
 CALCULATED ACTIVITY HS- = .6993E-61M LOG FH2S=-57.19 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FO2
H2(AQ) CM	.1472E-20	.1654E-20 .1124E+01	.2967E-17	.3297E-19	-17.8394
O2(AQ) CM	.2169E-13	.2438E-13 .1124E+01	.6940E-09	.4856E-12	

CM = MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))Z	LOG(A/(AH)Z)
1 H+	.2885E-04	-4.6886	.1262E-01	.1000E+01	0
2 H2O		-0.0074	.5551E+02		
3 FO2		-10.6990ATM			
4 CL-	.5175E+00	-5.932	.5547E+00	.5226E-05	-5.2818
5 SO4--	.1438E-02	-2.9047	.8859E-02	.5226E-13	-13.2819
6 HCO3-	.1107E-03	-4.2014	.1277E-01	.1288E-08	-8.8899
7 SIO2(AQ)	.1255E-01	-1.8506	.1255E-01	.1410E-01	-1.8506
8 AL+++	.1526E-12	-14.2650	.9637E-05	.5021E+00	-2.992
9 CA++	.6527E-02	-3.0782	.6761E-02	.1991E+07	6.2990
10 MG++	.2442E-01	-2.3471	.2949E-01	.1072E+08	7.0300
11 FE++	.1061E-04	-5.8673	.2760E-04	.3235E+04	3.5098
12 K+	.2400E-01	-1.9270	.2493E-01	.5775E+03	2.7615
13 NA+	.4150E+00	-6.454	.4525E+00	.1104E+05	4.0432
14 MN++	.1045E-01	-3.1144	.1118E-01	.1831E+07	6.2627
15 ZN++	.6025E-07	-8.3537	.3427E-04	.1056E+02	1.0225
16 BA++	.9686E-06	-7.0132	.1018E-05	.2312E+03	2.3640
17 SR++	.4021E-04	-5.3950	.4908E-04	.9597E+04	3.9821
18 AU+	.6327E-10	-10.5331	.7108E-05	.1430E-05	-5.8446

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SM2-200-F-2 H2OFS = 341.00 PH(25) = 4.39
 200 DEGREES C AT 500 BARS AND W/P = 5
 81/02/18.

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SPECTES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.2885E-04	-4.5398	.2048E-04	-4.6886	.7100E+00
2 H2O			.9832E+00	-.0074	.9832E+00
3 F02			.2000E-10ATM	-10.6990	
4 CL-	.5175E+00	-.2861	.2551E+00	-.5932	.4930E+00
5 SO4--	.1438E-02	-2.8424	.1245E-03	-3.9047	.8663E-01
6 HCO3-	.1107E-03	-3.9557	.6290E-04	-4.2014	.5680E+00
7 SiO2(AQ)	.1255E-01	-1.9014	.1410E-01	-1.8506	.1124E+01
8 AL+++	.1536E-12	-12.8137	.4316E-14	-14.3650	.2811E-01
9 CA++	.6527E-02	-2.1853	.8353E-03	-3.0782	.1280E+00
10 MG++	.2442E-01	-1.6122	.4496E-02	-2.3471	.1841E+00
11 FE++	.1061E-04	-4.9744	.1357E-05	-5.8673	.1280E+00
12 K+	.2400E-01	-1.6199	.1182E-01	-1.9270	.4930E+00
13 NA+	.4150E+00	-.3819	.2262E+00	-.6454	.5451E+00
14 MN++	.1045E-01	-1.9808	.7684E-03	-3.1144	.7352E-01
15 ZN++	.6025E-07	-7.2201	.4429E-08	-8.3537	.7352E-01
16 BA++	.0686E-06	-6.0139	.9701E-07	-7.0132	.1002E+00
17 SP++	.4021E-04	-4.3957	.4027E-05	-5.3950	.1002E+00
18 AU+	.6327E-10	-10.1988	.2930E-10	-10.5331	.4631E+00
19 AU+++	.1103E-32	-32.9572	.2877E-35	-35.5410	.2607E-02
20 AUCL2-	.7013E-05	-5.1541	.3823E-05	-5.4176	.5451E+00
21 AUCL4-	.9496E-07	-7.0225	.5177E-07	-7.2859	.5451E+00
22 FE+++	.2897E-10	-10.5381	.8142E-12	-12.0893	.2811E-01
23 OH-	.5188E-06	-6.2850	.7699E-06	-6.5688	.5202E+00
24 H3SiO4-	.5513E-06	-6.2586	.3006E-06	-6.5221	.5451E+00
25 H2SiO4--	.1996E-11	-11.6999	.1467E-12	-12.8335	.7352E-01
26 KSO4-	.2583E-03	-3.5879	.1344E-03	-3.8717	.5202E+00
27 FES04	.1280E-05	-5.8928	.1439E-05	-5.8420	.1124E+01
28 HCL	.4049E-05	-5.3926	.4552E-05	-5.3418	.1124E+01
29 HSO4-	.8132E-04	-4.0898	.4433E-04	-4.3533	.5451E+00
30 CADPH+	.1934E-06	-6.7135	.1054E-06	-6.9770	.5451E+00
31 MGPH+	.2739E-04	-4.5624	.1493E-04	-4.8259	.5451E+00
32 FECL+	.2575E+04	-4.5971	.1379E-04	-4.8606	.5451E+00
33 FECL++	.1783E-07	-7.7489	.1311E-08	-8.8825	.7352E-01
34 FECL4-	.4693E-08	-8.3286	.3450E-09	-9.4622	.7352E-01
35 FECL2	.7590E-08	-8.1198	.8532E-08	-8.0690	.1124E+01
36 FECL2+	.8866E-08	-8.0523	.4834E-08	-8.3157	.5451E+00
37 FES04+	.6753E-09	-9.1705	.3681E-09	-9.4340	.5451E+00
38 ZNCL+	.1166E-06	-6.9334	.6355E-07	-7.1969	.5451E+00
39 ZNCL2	.4776E-07	-7.3209	.5369E-07	-7.2701	.1124E+01
40 ZNCL3-	.8514E-05	-5.0699	.4641E-05	-5.3334	.5451E+00
41 ZNCL4--	.2553E-04	-4.5930	.1877E-05	-5.7286	.7352E-01
42 ALS04+	.4404E-13	-13.3562	.2401E-13	-13.6197	.5451E+00
43 CO3--	.7406E-09	-9.1304	.6415E-10	-10.1928	.8663E-01
44 H2CO3	.1257E-01	-1.9007	.1413E-01	-1.8499	.1124E+01

SM2-200-F-3 MOLES = 341.00 PH(25) = 4.39
 200 DEGREES C AT 500 BARS AND W/R = 5
 R1/02/18.
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 AL(OH)4-	.0625E-05	-5.0166	.5247E-05	-5.2801	.5451E+00
46 FE(OH)3	.1780E-13	-13.7495	.1309E-14	-14.8831	.7352E-01
47 FE(OH)2	.3867E-06	-6.4126	.2108E-06	-6.6761	.5451E+00
48 AL(OH)3	.1146E-07	-7.9408	.1466E-08	-8.6337	.1280E+00
49 NaCl	.3635E-01	-1.4394	.4087E-01	-1.3886	.1124E+01
50 KCl	.6744E-03	-3.1711	.7581E-03	-3.1203	.1124E+01
51 KHSO4	.7061E-05	-5.1511	.7937E-05	-5.1003	.1124E+01
52 CaCO3	.5473E-08	-8.2617	.6153E-08	-8.2109	.1124E+01
53 MnSO4	.7245E-03	-3.1399	.8144E-03	-3.0891	.1124E+01
54 NaSO4-	.1155E-02	-2.9376	.6455E-03	-3.1901	.5591E+00
55 MgSO4	.4982E-02	-2.2026	.5600E-02	-2.2518	.1124E+01
56 CaSO4	.2120E-02	-3.6737	.2283E-03	-3.6229	.1124E+01
57 NaCO3-	.1757E-08	-8.7553	.1028E-08	-8.9882	.5849E+00
58 MgHCO3+	.6095E-04	-4.2150	.3323E-04	-4.4785	.5451E+00
59 CaHCO3+	.2208E-04	-4.6560	.1204E-04	-4.9195	.5451E+00
60 MgCO3	.5397E-17	-17.2679	.6066E-17	-17.2171	.1124E+01
61 BaCO3	.2204E-13	-13.6568	.2478E-13	-13.6060	.1124E+01
62 BaHCO3+	.4666E-07	-7.3311	.2544E-07	-7.5945	.5451E+00
63 BaOH+	.6729E-10	-10.1721	.2963E-10	-10.4020	.5890E+00
64 BaSO4	.2578E-08	-8.5887	.2898E-08	-8.5379	.1124E+01
65 SP(OH)3	.5836E-10	-10.2329	.3437E-10	-10.4638	.5890E+00
66 SRCO3	.2298E-11	-11.6386	.2584E-11	-11.5878	.1124E+01
67 SPHCO3+	.8075E-05	-5.0929	.4402E-05	-5.3564	.5451E+00
68 SPSC4	.7934E-06	-6.1005	.6918E-06	-6.0497	.1124E+01

SM2-200-5-4 HOURS = 478.00 PH(25) = 4.35
 200 DEGREES C AT 500 BARS AND W/P = 5
 81/02/18.

WATER 1.0000(KG.LIO.) 55.5082(MOLFS LIO.) 55.5083(MOLES TOTAL)
 STOICHIOMETRIC IONIC STRENGTH=.6357398E+00 OSMOTIC COEF.= .8509
 IONIC STRENGTH=.5638269E+00 ACTIVITY=.9831

FO2 INPUT AS REDOX CONTROL

LOG FO2=-10.89 LOG FH2=-17.75 LOG FH2O= 1.25 LOG FCO2= .31
 LOG FH2S= N LOG FS2= N
 CALCULATED ACTIVITY HS- = .2538E-60M LOG FH2S=-56.52 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FO2
H2(AQ) CM	.1826E-20	.2052E-20 .1124E+01	.3681E-17	.4089E-19	-17.7459
O2(AQ) CM	.1410E-13	.1585E-13 .1124E+01	.4512E-09	.3159E-12	

CM - MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))2	LOG(A/(AH)2)
1 H+	.3777E-04	-4.5716	.9965E-02	.1000E+01	0
2 H2O		-.0074	.5551E+02		
3 FO2		-10.8861ATM			
4 CL-	.5180E+00	-.5927	.5562E+00	.6850E-05	-5.1643
5 SO4--	.1682E-02	-3.8359	.9744E-02	.1049E-12	-12.9792
6 HCO3-	.6628E-04	-4.4242	.9970E-02	.1010E-08	-8.9958
7 SiO2(AQ)	.1306E-01	-1.8332	.1306E-01	.1468E-01	-1.8332
8 AL+++	.5021E-12	-13.8500	.1075E-04	.7325E+00	-1.1252
9 CA++	.7076E-02	-3.0428	.7360E-02	.1260E+07	6.1004
10 MG++	.2183E-01	-2.3956	.2711E-01	.5593E+07	6.7476
11 FE++	.2565E-04	-5.4356	.1021E-03	.5102E+04	3.7078
12 K+	.1858E-01	-2.0152	.2038E-01	.3600E+03	2.5563
13 NA+	.4260E+00	-.6340	.4648E+00	.8662E+04	3.9376
14 MN++	.9797E-02	-3.1420	.1050E-01	.1003E+07	6.0012
15 ZN++	.7760E-07	-8.2432	.4436E-04	.7944E+01	.9000
16 BA++	.1268E-05	-6.8958	.1309E-05	.1768E+03	2.2475
17 SP++	.4492E-04	-5.3465	.5136E-04	.6262E+04	3.7967
18 AM+	.5820E-10	-10.5666	.6600E-05	.1007E-05	-5.9970

+++++

SM2-200-5-4 HQUPS = 678.00 PH(25) = 4.35
 200 DEGREES C AT 500 PARS AND W/P = F
 91/02/18.

+++++

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.3777E-04	-4.4229	.2682E-04	-4.5716	.7100E+00
2 H2O			.9831E+00	-.0074	.9831E+00
3 F02			.1300E-10 ATM	-10.8861	
4 CL-	.5190E+00	-.2856	.2555E+00	-.5927	.4931E+00
5 SO4--	.1682E-02	-2.7741	.1459E-03	-3.8359	.8672E-01
6 HCO3-	.6628E-04	-4.1786	.3765E-04	-4.4242	.5681E+00
7 SiO2(AQ)	.1304E-01	-1.8839	.1468E-01	-1.8332	.1124E+01
8 AL+++	.5021E-12	-12.2992	.1412E-13	-13.8500	.2813E-01
9 CA++	.7076E-02	-2.1502	.9062E-03	-3.0428	.1261E+00
10 MG++	.2183E-01	-1.6609	.4022E-02	-2.3956	.1842E+00
11 FE++	.2965E-04	-4.5429	.3669E-05	-5.4355	.1281E+00
12 K+	.1958E-01	-1.7083	.9654E-02	-2.0153	.4931E+00
13 NA+	.4260E+00	-.3706	.2223E+00	-.6340	.5453E+00
14 MN++	.9797E-02	-2.0089	.7211E-03	-3.1420	.7361E-01
15 ZN++	.7760E-07	-7.1101	.5712E-08	-8.2432	.7361E-01
16 BA++	.1268E-05	-5.8968	.1271E-06	-6.8958	.1002E+00
17 SP++	.4492E-04	-4.3476	.4503E-05	-5.3465	.1002E+00
18 AU+	.5829E-10	-10.2344	.2700E-10	-10.5686	.4623E+00
19 AU+++	.1401E-32	-32.8535	.3664E-35	-35.4361	.2615E-02
20 AUCL2-	.6478E-05	-5.1885	.3532E-05	-5.4519	.5453E+00
21 AUCL4-	.1215E-06	-6.9154	.6426E-07	-7.1788	.5452E+00
22 FE+++	.9195E-10	-10.0364	.2587E-11	-11.5872	.2813E-01
23 OH-	.3962E-06	-6.4021	.2062E-06	-6.6858	.5204E+00
24 H2SiO4-	.4383E-06	-6.3582	.2390E-06	-6.6216	.5453E+00
25 H2SiO4--	.1211E-11	-11.9169	.8912E-13	-13.0500	.7361E-01
26 KSO4-	.2468E-03	-3.6076	.1285E-03	-3.8913	.5204E+00
27 FES04	.4054E-05	-5.3921	.4556E-05	-5.3414	.1124E+01
28 HCL	.5309E-05	-5.2750	.5966E-05	-5.2243	.1124E+01
29 HSO4-	.1247E-03	-2.9042	.6799E-04	-4.1676	.5453E+00
30 CAOH+	.1603E-06	-6.7952	.8738E-07	-7.0586	.5453E+00
31 MGOH+	.1871E-04	-4.7280	.1020E-04	-4.9914	.5453E+00
32 FECL+	.6843E-04	-4.1647	.3731E-04	-4.4281	.5453E+00
33 FECL++	.5665E-07	-7.2468	.4170E-08	-8.3799	.7361E-01
34 FECL4-	.1497E-07	-7.8248	.1102E-08	-8.9579	.7361E-01
35 FECL3	.2422E-07	-7.6159	.2721E-07	-7.5652	.1124E+01
36 FECL2+	.2824E-07	-7.5492	.1540E-07	-7.8126	.5452E+00
37 FES04+	.2513E-08	-8.5998	.1370E-08	-8.8632	.5453E+00
38 ZNCL+	.1505E-06	-6.8225	.8206E-07	-7.0859	.5453E+00
39 ZNCL2	.6177E-07	-7.2092	.6942E-07	-7.1585	.1124E+01
40 ZNCL3-	.1102E-04	-4.9578	.6009E-05	-5.2212	.5453E+00
41 ZNCL4--	.3305E-04	-4.4808	.2433E-05	-5.6139	.7361E-01
42 ALSO4+	.1688E-12	-12.7726	.9205E-12	-13.0360	.5453E+00
43 CO3--	.3383E-09	-9.4707	.2934E-10	-10.5326	.8672E-01
44 H2CO3	.9851E-02	-2.0065	.1107E-01	-1.9558	.1124E+01

SM2-200-5-4 HOURS = 678.00 PH(25) = 4.35
 200 DEGREES C AT 500 BARS AND W/P = 5
 P1/02/18.
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 AL(OH)4-	.1072E-04	-4.9600	.5844E-05	-5.2333	.5453E+00
46 FECH++	.4316E-13	-13.3640	.3177E-14	-14.4980	.7361E-01
47 FECH+	.7082E-06	-6.0979	.4352E-06	-6.3613	.5453E+00
48 ALOH++	.2863E-07	-7.5432	.3666E-08	-8.4358	.1281E+00
49 NaCl	.2738E-01	-1.4273	.4201E-01	-1.3766	.1124E+01
50 KCl	.5512E-03	-3.2587	.6195E-03	-3.2060	.1124E+01
51 KHSO4	.8840E-05	-5.0536	.9934E-05	-5.0029	.1124E+01
52 CaCO3	.2716E-08	-8.5661	.3052E-08	-8.5154	.1124E+01
53 MnSO4	.7968E-03	-3.0986	.8955E-03	-3.0480	.1124E+01
54 NaSO4-	.1388E-02	-2.8575	.7764E-03	-3.1099	.5592E+00
55 MgSO4	.5221E-02	-2.2822	.5867E-02	-2.2315	.1124E+01
56 CaSO4	.2695E-03	-3.5694	.3029E-03	-3.5187	.1124E+01
57 NaCO2-	.8247E-09	-9.0837	.4824E-09	-9.3166	.5850E+00
58 MgHCO3+	.3263E-04	-4.4864	.1779E-04	-4.7498	.5453E+00
59 CaHCO3+	.1434E-04	-4.8436	.7816E-05	-5.1070	.5453E+00
60 MgCO3	.3783E-17	-17.4221	.4252E-17	-17.3714	.1124E+01
61 BaCO3	.1321E-13	-13.8791	.1455E-13	-13.8284	.1124E+01
62 BaHCO3+	.3650E-07	-7.4366	.1995E-07	-7.7000	.5453E+00
63 BaOH+	.6734E-10	-10.1717	.3967E-10	-10.4016	.5890E+00
64 BaSO4	.3959E-08	-8.4024	.4449E-08	-8.3517	.1124E+01
65 SrOH+	.4983E-10	-10.3025	.2935E-10	-10.5323	.5890E+00
66 SrCO3	.1175E-11	-11.9208	.1321E-11	-11.8791	.1124E+01
67 SrHCO3+	.5403E-05	-5.2673	.2946E-05	-5.5307	.5453E+00
68 SrSO4	.1040E-05	-5.9832	.1168E-05	-5.9325	.1124E+01

SM3-300-E-1 HOURS = 2.0 PH(25) = 2.71
 300 DEGREES C AT 500 PARS AND W/R = F
 91/02/19.

WATER 1.0000(KG.LIG.) = .5082(MOLES LIG.) 5.5083(MOLES TOTAL)
 STICHIOMETRIC IONIC STRENGTH=.6176531E+00 OSMOTIC COEF.= .7372
 IONIC STRENGTH=.4552824E+00 ACTIVITY=.9853

FO2 INPUT AS PEOOX CONTROL

LOG FO2=-15.60 LOG FH2=-10.01 LOG FH2O= 1.01 LOG FCO2= -.81
 LOG FH2S= N LOG FS2= N
 CALCULATED ACTIVITY HS- = .3100E-32M LOG FH2S=-27.75 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FO2
H2(AQ) CM	.2930E-12	.3524E-12 .1202E+01	.5907E-09	.6564E-11	-10.0129
O2(AQ) CM	.8087E-18	.9726E-18 .1203E+01	.2588E-13	.1811E-16	

CM - MOLALITY CALCULATED FROM PEOOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))Z	LOG(A/(AH)Z)
1 H+	.3781E-03	-3.6709	.1070E-01	.1000E+01	0
2 H2O		-.0064	.5551E+02		
3 FCO2		-15.6021ATM			
4 CL-	.4193E+00	-.8475	.5614E+00	.3031E-04	-4.5184
5 SC4--	.2268E-03	-5.1818	.6007E-02	.2994E-12	-12.5237
6 HCO3-	.7541E-07	-7.5070	.7980E-02	.6639E-11	-11.1779
7 SiO2(AQ)	.3435E-01	-1.3830	.3435E-01	.4131E-01	-1.3839
8 AL+++	.0004E-20	-22.2790	.4448E-05	.5417E-11	-11.2662
9 CA++	.2702E-02	-3.8690	.2720E-02	.2971E+04	3.4728
10 MG++	.2143E-01	-2.7481	.2312E-01	.3925E+05	4.5938
11 FE++	.1076E-04	-6.0049	.1056E-03	.2173E+02	1.3370
12 V+	.2262E-01	-2.1155	.2670E-01	.3593E+02	1.5555
13 NA+	.3250E+00	-.8842	.4729E+00	.6120E+03	2.7867
14 MN++	.8115E-02	-3.7276	.0465E-02	.4114E+04	3.6143
15 ZN++	.1625E-09	-10.4234	.1469E-03	.8289E-03	-3.0815
16 BA++	.1597E-05	-7.2462	.1600E-05	.1246E+01	.0957
17 SR++	.1425E-04	-6.2956	.1484E-04	.1112E+02	1.0463
18 AU+	.1892E-09	-10.2308	.6002E-05	.2755E-06	-6.5599

SM2-300-5-1 HOURS = 2.0 PH(25) = 2.71
 300 DEGREES C AT 500 BARS AND W/P = F
 81/02/10.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.3781E-03	-3.4223	.2133E-03	-3.6709	.5642E+00
2 H2O			.9853E+00	-.0064	.9853E+00
3 FCO			.2500E-15 ATM	-15.6021	
4 CL-	.4193E+00	-.3775	.1421E+00	-.6475	.3389E+00
5 SO4--	.2268E-03	-3.6443	.6579E-05	-5.1818	.2901E-01
6 HCO3-	.7541E-07	-7.1226	.3112E-07	-7.5070	.4127E+00
7 SiO2(AQ)	.3435E-01	-1.4641	.4131E-01	-1.3839	.1203E+01
8 AL+++	.9084E-20	-20.0417	.5260E-22	-22.2790	.5790E-02
9 CA++	.2702E-02	-2.5693	.1352E-03	-3.8690	.5004E-01
10 MG++	.2143E-01	-1.6690	.1786E-02	-2.7481	.8336E-01
11 FE++	.1976E-04	-4.7042	.9889E-06	-6.0049	.5004E-01
12 K+	.2262E-01	-1.6455	.7666E-02	-2.1155	.3389E+00
13 NA+	.3350E+00	-.4750	.1306E+00	-.8842	.3897E+00
14 MN++	.8115E-02	-2.0907	.1872E-03	-3.7276	.2307E-01
15 NH4+	.1635E-05	-5.7865	.2772E-10	-10.4234	.2307E-01
16 BA++	.1597E-05	-5.7966	.5673E-07	-7.2462	.2552E-01
17 SP++	.1425E-04	-4.8461	.5063E-06	-6.2956	.3552E-01
18 AU+	.1892E-09	-9.7232	.5878E-10	-10.2308	.3107E+00
19 AU+++	.2343E-22	-23.6302	.4862E-37	-37.3132	.2075E-03
20 AUCL2-	.6074E-05	-5.2165	.2367E-05	-5.6258	.3897E+00
21 AUCL4-	.1829E-07	-7.7379	.7127E-08	-8.1471	.3697E+00
22 FE+++	.3599E-12	-12.4438	.2084E-14	-14.6811	.5790E-02
23 OH-	.1180E-06	-6.9280	.4310E-07	-7.3655	.2652E+00
24 H2SiO4-	.3135E-07	-7.5038	.1222E-07	-7.9130	.3897E+00
25 H2SiO4--	.2482E-14	-14.6052	.5727E-16	-16.2420	.2307E-01
26 KSO4-	.3717E-03	-3.4298	.1357E-03	-3.8673	.3652E+00
27 FESO4	.7131E-05	-5.1469	.8576E-05	-5.0667	.1203E+01
28 HCL	.4379E-03	-3.3586	.5267E-03	-3.2784	.1203E+01
29 HSO4-	.1847E-02	-2.7335	.7198E-03	-3.1428	.3897E+00
30 CADH+	.6378E-06	-6.1953	.2486E-06	-6.6045	.3897E+00
31 MGCH+	.2727E-04	-4.5644	.1063E-04	-4.9736	.3897E+00
32 FECL+	.7192E-04	-4.1431	.2803E-04	-4.5522	.3697E+00
33 FECL2	.5607E-05	-5.2500	.7947E-05	-5.0998	.1203E+01
34 FECL++	.1776E-07	-7.7507	.4097E-09	-9.3875	.2307E-01
35 FECL4-	.3605E-08	-8.4431	.8318E-10	-10.0800	.2307E-01
36 FECL3	.9492E-09	-9.0227	.1142E-08	-8.9425	.1203E+01
37 FECL2+	.1322E-07	-7.8788	.5152E-08	-8.2880	.3897E+00
38 FESO4+	.7151E-10	-10.1457	.2767E-10	-10.5549	.3897E+00
39 NHCL+	.1813E-07	-7.7410	.7065E-08	-8.1505	.3897E+00
40 NHCL2	.6620E-08	-8.1785	.7974E-08	-8.0983	.1203E+01
41 NHCL2-	.1391E-04	-4.8566	.5422E-05	-5.2658	.3897E+00
42 NHCL4--	.1225E-03	-3.8764	.3067E-05	-5.5138	.2307E-01
43 ALSO4+	.8286E-20	-20.0816	.3230E-20	-20.4909	.3897E+00
44 CO3--	.2097E-15	-15.6785	.6081E-17	-17.2160	.2901E-01

SM3-300-E-1 MQUPS = 2.0 PH(25) = 2.71

300 DEGREES C AT 500 BARS AND W/P = 5

#1/02718.

(CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 H2CO2	.7970E-02	-2.0981	.9506E-02	-2.0179	.1203E+01
46 AL(OH)4-	.4448E-08	-5.3519	.1733E-05	-5.7611	.3897E+00
47 FEOH++	.3534E-11	-11.4517	.8155E-13	-13.0886	.2307E-01
48 FEOH+	.1P15E-06	-6.7412	.7073E-07	-7.1504	.3897E+00
49 AL(OH)++	.6111E-11	-11.2139	.3058E-12	-12.5145	.5004E-01
50 NaCl	.1375E+00	-.8619	.1653E+00	-.7817	.1203E+01
51 KCl	.3605E-02	-2.4431	.4336E-02	-2.3629	.1203E+01
52 KHSO4	.1027E-02	-3.9884	.1235E-03	-3.9082	.1203E+01
53 CaSO3	.5818E-13	-13.2352	.6998E-13	-13.1550	.1203E+01
54 MnSO4	.1250E-02	-2.8696	.1624E-02	-2.7894	.1203E+01
55 NaSO4-	.4245E-03	-3.3721	.1714E-03	-3.7660	.4037E+00
56 MgSO4	.1650E-02	-2.7801	.1996E-02	-2.6999	.1203E+01
57 CaSO4	.1694E-04	-4.7710	.2038E-04	-4.6900	.1203E+01
58 NaCO3-	.3200E-14	-14.4936	.1380E-14	-14.8602	.4300E+00
59 MgHCO3+	.5946E-06	-6.2258	.2317E-06	-6.6350	.3897E+00
60 CaHCO3+	.1423E-06	-6.8468	.5546E-07	-7.2560	.3897E+00
61 MgCO3	.1057E-10	-19.9761	.1271E-19	-19.8960	.1203E+01
62 BaCO3	.1438E-10	-19.8424	.1729E-19	-19.7622	.1203E+01
63 BaHCO3+	.1803E-08	-8.7429	.7028E-09	-9.1521	.3897E+00
64 BaOH+	.2450E-09	-9.6093	.1087E-09	-9.9717	.4341E+00
65 BaSO4	.3175E-09	-9.4082	.3819E-09	-9.4180	.1203E+01
66 SPCH+	.1125E-10	-10.9487	.4685E-11	-11.3111	.4341E+00
67 SPCH2	.3222E-18	-18.4918	.3875E-18	-18.4116	.1203E+01
68 SPHCO3+	.4042E-06	-6.3934	.1576E-06	-6.8026	.3897E+00
69 SPSC4	.1788E-06	-6.7476	.2151E-06	-6.6674	.1203E+01

SM3-300-5-2 HOURS = 79.0 PH(25) = 2.34
300 DEGREES C AT 500 RAPS AND W/P = 5
81/02/1P.

WATER 1.0000(KG.LIQ.) 55.5082(MOLES LIQ.) 55.5083(MOLES TOTAL)
STOICHIOMETRIC IONIC STRENGTH=.5937527E+00 OSMOTIC COEF.= .7477
IONIC STRENGTH=.4455072E+00 ACTIVITY=.9852

FO2 INPUT AS REDOX CONTROL

LOG FO2=-16.60 LOG FH2=-9.51 LOG FH2O= 1.91 LOG FCC2= -.85
LOG FH2S= N LOG FS2= N
CALCULATED ACTIVITY HS- = .2198E-31M LOG FH2S=-25.15 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FO2
H2(AQ) CM	.9302E-12	.1114E-11 .1198E+01	.1875E-08	.2084E-10	-9.513C
O2(AQ) CM	.8119E-19	.9776E-19 .1198E+01	.2598E-14	.1619E-17	

CM - MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))Z	LOG(A/(AH)Z)
1 H+	.2131E-02	-2.9192	.1328E-01	.1000E+01	0
2 H2O		-.0065	.5551E+02		
3 FO2		-16.6021ATM			
4 Cl-	.4141E+00	-.8500	.5574E+00	.1701E-03	-3.7692
5 SO4--	.2790E-04	-6.0829	.1926E-02	.1198E-11	-11.9214
6 HCO3-	.1214E-07	-8.2984	.7310E-02	.6058E-11	-11.2176
7 SiO2(AQ)	.3235E-01	-1.3984	.3335E-01	.3995E-01	-1.3984
8 AL+++	.9122E-17	-19.2701	.4448E-05	.3074E-10	-10.5123
9 CA++	.4587E-02	-3.6337	.4591E-02	.1602E+03	2.2047
10 MG++	.1110E-01	-2.0309	.1119E-01	.6420E+03	2.8076
11 FE++	.2382E-04	-5.9182	.1200E-02	.8323E+00	-.0797
12 K+	.2638E-01	-2.0459	.3074E-01	.7470E+01	.8733
13 NA+	.3291E+00	-.8897	.4646E+00	.1070E+03	2.0295
14 MN++	.1347E-01	-3.4989	.1376E-01	.2186E+03	2.3396
15 ZN++	.2818E-08	-10.1783	.2478E-02	.4573E-04	-4.3398
16 BA++	.2762E-05	-7.0016	.2763E-05	.6870E-01	-1.1631
17 SP++	.2268E-04	-6.0971	.2283E-04	.5642E+00	-.2486
18 AM+	.2632E-09	-10.0838	.8631E-05	.6845E-07	-7.1646

SM3-300-F-2 HOURS = 70.0 PH(25) = 2.34
 300 DEGREES C AT 500 BARS AND W/P = 5
 91/02/18.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.2121E-02	-2.6714	.1204E-02	-2.9192	.5652E+00
2 H2O			.9852E+00	-1.0065	.9852E+00
3 H2O			.2500E-16ATM	-16.6021	
4 CL-	.4141E+00	-3.3829	.1413E+00	-1.8500	.3411E+00
5 SO4--	.2709E-04	-4.5629	.8263E-06	-6.0829	.2952E-01
6 HCO3-	.1214E-07	-7.9159	.5020E-08	-8.2984	.4145E+00
7 SiO2(AQ)	.3325E-01	-1.4769	.2995E-01	-1.3984	.1198E+01
8 AL+++	.9122E-17	-17.0399	.5370E-19	-19.2701	.5886E-02
9 CA++	.4587E-02	-2.3385	.2324E-03	-3.6337	.5067E-01
10 MG++	.1108E-01	-1.9556	.9313E-03	-3.0309	.8408E-01
11 FE++	.2282E-04	-4.6230	.1207E-05	-5.9182	.5067E-01
12 K+	.2638E-01	-1.5758	.8997E-02	-2.0459	.2411E+00
13 NA+	.3291E+00	-1.4827	.1289E+00	-1.8897	.3917E+00
14 MN++	.1347E-01	-1.8706	.2171E-03	-3.4989	.2353E-01
15 ZN++	.2818E-05	-5.5500	.6632E-10	-10.1763	.2353E-01
16 RA++	.2762E-05	-5.5597	.9964E-07	-7.0016	.3607E-01
17 SP++	.2248E-04	-4.6443	.8183E-06	-6.0871	.3607E-01
18 AU+	.2632E-05	-5.5794	.8244E-10	-10.0839	.3131E+00
19 AI+++	.2162E-22	-32.5000	.6840E-36	-36.1636	.2169E-02
20 AUCL2-	.8380E-05	-5.0768	.3282E-05	-5.4838	.3917E+00
21 AUCL2-	.2509E-06	-6.6006	.9825E-07	-7.0077	.3917E+00
22 FE+++	.1371E-11	-11.8630	.8070E-14	-14.0931	.5886E-02
23 OH-	.2079E-07	-7.6822	.7634E-08	-8.1172	.3673E+00
24 H3SiO4-	.5344E-08	-8.2721	.2093E-09	-8.6792	.3917E+00
25 H2SiO4--	.7385E-16	-16.1217	.1738E-17	-17.7600	.2353E-01
26 KSO4-	.5448E-04	-4.2632	.2001E-04	-4.6988	.3673E+00
27 FE2O4	.1098E-05	-5.9566	.1315E-05	-5.8811	.1198E+01
28 HCL	.2468E-02	-2.6077	.2956E-02	-2.5292	.1198E+01
29 HSO4-	.1303E-02	-2.8851	.5104E-03	-3.2921	.3917E+00
30 CAOH+	.1932E-06	-6.7139	.7569E-07	-7.1210	.3917E+00
31 MGOH+	.2505E-05	-5.6011	.9813E-06	-6.0082	.3917E+00
32 FECL+	.8686E-04	-4.0612	.3402E-04	-4.4682	.3917E+00
33 FECL2	.8004E-05	-5.0967	.9589E-05	-5.0182	.1198E+01
34 FECL++	.6701E-07	-7.1738	.1577E-08	-8.8021	.2353E-01
35 FECL4-	.1327E-07	-7.8728	.3147E-09	-9.5021	.2353E-01
36 FECL2	.2626E-08	-8.4406	.4244E-08	-8.3621	.1198E+01
37 FECL2+	.5034E-07	-7.2981	.1972E-07	-7.7051	.3917E+00
38 FE2O4+	.2460E-10	-10.4609	.1355E-10	-10.8680	.3917E+00
39 ZNCL+	.3152E-07	-7.5012	.1235E-07	-7.9083	.3917E+00
40 ZNCL2	.1157E-07	-7.9368	.1386E-07	-7.8583	.1198E+01
41 ZNCL3-	.2392E-04	-4.6213	.9269E-05	-5.0283	.3917E+00
42 ZNCL4--	.2225E-03	-3.6500	.5269E-05	-5.2783	.2353E-01
43 AL2O4+	.1057E-17	-17.9759	.6141E-18	-18.3829	.3917E+00
44 CO3--	.5899E-17	-17.2292	.1741E-18	-18.7592	.2952E-01

SM2-300-F-2 HOURS = 79.0 PH(25) = 2.34
 300 DEGREES C AT 500 BARS AND V/P = 5
 91/02/18.
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 H2CO3	.7310E-02	-2.1361	.6757E-02	-2.0576	.1198E+01
46 AL(OH)4-	.4447E-05	-5.3520	.1742E-05	-5.7590	.3917E+00
47 FEOH++	.2376E-11	-11.6241	.5592E-12	-13.2524	.2353E-01
48 FEOH+	.3905E-07	-7.4084	.1529E-07	-7.8155	.3917E+00
49 AL(OH)++	.1091E-08	-8.9420	.5530E-10	-10.2573	.5067E-01
50 NaCl	.1355E+00	-.8662	.1623E+00	-.7897	.1198E+01
51 KCl	.4223E-02	-2.3744	.5059E-02	-2.2959	.1198E+01
52 KHSO4	.8581E-04	-4.0665	.1028E-03	-3.9880	.1198E+01
53 CaCO3	.2875E-14	-14.5413	.3444E-14	-14.4629	.1198E+01
54 MnSO4	.2583E-03	-3.5402	.3454E-03	-3.4617	.1198E+01
55 NaSO4-	.5240E-04	-4.2807	.2125E-04	-4.6726	.4055E+00
56 MgSO4	.1091E-03	-3.9622	.1307E-03	-3.8828	.1198E+01
57 CaSO4	.3672E-05	-5.4351	.4399E-05	-5.3566	.1198E+01
58 NaCO3-	.9034E-16	-16.0440	.3900E-16	-16.4089	.4317E+00
59 MgHCO3+	.4986E-07	-7.3022	.1953E-07	-7.7093	.3917E+00
60 CaHCO3+	.3935E-07	-7.4051	.1541E-07	-7.8121	.3917E+00
61 MgCO3	.5046E-20	-20.2970	.6045E-20	-20.2186	.1198E+01
62 BaCO3	.7259E-21	-21.1392	.8695E-21	-21.0607	.1198E+01
63 BaHCO3+	.5095E-09	-9.2929	.1991E-09	-9.7000	.3917E+00
64 BaOH+	.7619E-10	-10.1181	.3320E-10	-10.4788	.4358E+00
65 BaSO4	.7022E-10	-10.1529	.8425E-10	-10.0744	.1198E+01
66 SrOH+	.2209E-11	-11.4026	.1299E-11	-11.8543	.4358E+00
67 SrCO3	.1497E-19	-19.8247	.1794E-19	-19.7462	.1198E+01
68 SrHCO3+	.1051E-06	-6.9784	.4116E-07	-7.3855	.3917E+00
69 SrSO4	.3644E-07	-7.4384	.4365E-07	-7.3600	.1198E+01

SM3-30C-F-3 HOURS = 741.5 PH(25) = 2.73
 300 DEGREES C AT 500 PARS AND W/P = 5
 P1/02719.

WATER 1.0000(KG.LIQ.) 55.5082(MOLES LIQ.) 55.5082(MOLES TOTAL)
 STOICHIOMETRIC IONIC STRENGTH=.6012668E+00 OSMOTIC COEF.= .7479
 IONIC STRENGTH=.4492206E+00 ACTIVITY=.9850

FO2 INPUT AS REDOX CONTROL

LOG FO2=-15.00 LOG FH2=-10.31 LOG FH2O= 1.91 LOG FCO2= -.61
 LOG FH2S= N LOG FS2= N
 CALCULATED ACTIVITY HS- = .9021E-35M LOG FH2S=-29.03 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FO2
H2(AQ) CM	.1468E-12	.1762E-12 .1200E+01	.2960E-09	.3289E-11	-10.3141
O2(AQ) CM	.3243E-17	.3890E-17 .1200E+01	.1038E-12	.7263E-16	

CM - MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))2	LOG(A/(A(H+))2)
1 H+	.7728E-03	-3.3595	.1046E-01	.1000E+01	0
2 H2O		-.0066	.5551E+02		
3 FO2		-15.0000ATM			
4 Cl-	.4190E+00	-.6460	.5641E+00	.6221E-04	-4.2055
5 SO4--	.4525E-04	-5.8762	.1676E-02	.2540E-12	-12.5952
6 HCO3-	.3672E-07	-7.8184	.6000E-02	.6640E-11	-11.1778
7 STO2(AQ)	.2192E-01	-1.4168	.3192E-01	.3820E-01	-1.4168
8 Al+++	.2253E-18	-20.8801	.6301E-05	.1576E-10	-10.8017
9 Ca++	.4385E-02	-3.6554	.4391E-02	.1158E+04	3.0626
10 Mg++	.1032E-01	-3.0631	.1049E-01	.4527E+04	3.6558
11 Fe++	.1477E-04	-6.1281	.7520E-04	.3898E+01	.5909
12 K+	.2809E-01	-2.0196	.3276E-01	.2187E+02	1.3399
13 Na+	.3347E+00	-.6632	.4734E+00	.2994E+03	2.4763
14 NH4+	.1248E-01	-2.4056	.1414E-01	.1672E+04	3.2233
15 Zn++	.2754E-08	-10.1917	.2509E-03	.3367E-03	-3.4727
16 Ba++	.3560E-05	-6.8939	.3563E-05	.6684E+00	-.1750
17 Sr++	.2582E-04	-6.0234	.2625E-04	.4848E+01	.6856
18 Al+	.2500E-00	-10.0000	.8631E-05	.1857E-06	-6.7212

SM2-300-5-3 MOLALS = 261.5 PH(25) = 2.73
 300 DEGREES C AT 500 BARS AND W/P = 5
 81/02/15.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.7738E-03	-3.1114	.4370E-03	-3.3595	.5648E+00
2 H2O			.9850E+00	-0.0066	.9850E+00
3 F02			.1000E-14ATM	-15.0000	
4 Cl-	.4190E+00	-0.3778	.1426E+00	-0.8460	.3402E+00
5 SO4--	.4535E-04	-4.3435	.1330E-05	-5.8763	.2932E-01
6 HCO3-	.3672E-07	-7.4352	.1519E-07	-7.8184	.4138E+00
7 SiO2(AQ)	.3192E-01	-1.4959	.2830E-01	-1.4168	.1200E+01
8 Al+++	.2253E-18	-18.6472	.1318E-20	-20.8601	.5850E-02
9 Ca++	.4385E-02	-2.3560	.2211E-03	-3.6554	.5043E-01
10 Mg++	.1022E-01	-1.9862	.8648E-03	-3.0631	.8360E-01
11 Fe++	.1477E-04	-4.8307	.7446E-06	-6.1281	.5043E-01
12 K+	.2800E-01	-1.5514	.9558E-02	-2.0196	.3402E+00
13 Na+	.3247E+00	-0.4753	.1309E+00	-0.8832	.3909E+00
14 Mn++	.1268E-01	-1.8640	.3194E-03	-3.4956	.2336E-01
15 Zn++	.2754E-08	-8.5601	.6432E-10	-10.1917	.2336E-01
16 Ba++	.3560E-05	-5.4485	.1277E-06	-6.8939	.2566E-01
17 Sr++	.2582E-04	-4.5880	.9260E-06	-6.0334	.2566E-01
18 Au+	.2599E-09	-9.5952	.8114E-10	-10.0908	.2122E+00
19 Au+++	.2639E-32	-32.5785	.5629E-36	-36.2496	.2123E-02
20 AuCl2-	.8417E-05	-5.0740	.3290E-05	-5.4828	.2909E+00
21 AuCl4-	.2140E-06	-6.6697	.8364E-07	-7.0776	.3909E+00
22 Fe+++	.7770E-12	-12.1096	.4545E-14	-14.3425	.5850E-02
23 OH-	.5740E-07	-7.2411	.2103E-07	-7.6771	.2665E+00
24 H3SiO4-	.1414E-07	-7.8495	.5529E-02	-8.2574	.3909E+00
25 H2SiO4--	.5416E-15	-15.2662	.1265E-16	-16.8979	.2336E-01
26 KSO4-	.9334E-04	-4.0299	.3420E-04	-4.4659	.3665E+00
27 FFSO4	.1088E-05	-5.9622	.1305E-05	-5.8844	.1200E+01
28 HCL	.9025E-03	-3.0446	.1083E-02	-2.9655	.1200E+01
29 HSO4-	.7623E-03	-3.1179	.2980E-03	-3.5258	.3909E+00
30 CASH+	.5075E-06	-6.2946	.1984E-06	-6.7025	.2909E+00
31 MGDH+	.6422E-05	-5.1922	.2511E-05	-5.6002	.2909E+00
32 FECL+	.5418E-04	-4.2662	.2118E-04	-4.6740	.2909E+00
33 FECL2	.5022E-05	-5.2991	.6025E-05	-5.2200	.1200E+01
34 FECL++	.3838E-07	-7.4159	.8965E-09	-9.0475	.2336E-01
35 FECL4-	.2873E-08	-8.1029	.1839E-09	-9.7254	.2336E-01
36 FECL3	.2094E-08	-8.6786	.2515E-08	-8.5994	.1200E+01
37 FECL2+	.2894E-07	-7.5386	.1131E-07	-7.9465	.3909E+00
38 FES04+	.3141E-10	-10.5029	.1228E-10	-10.9108	.3909E+00
39 ZNCL+	.3092E-07	-7.5068	.1200E-07	-7.9177	.3909E+00
40 ZNCL2	.1141E-07	-7.9428	.1369E-07	-7.8637	.1200E+01
41 ZNCL3-	.2389E-04	-4.6218	.9340E-05	-5.0297	.3909E+00
42 ZNCL4--	.2269E-03	-3.6441	.5301E-05	-5.2757	.2336E-01
43 ALSO4+	.4182E-19	-19.3785	.1635E-19	-19.7864	.2909E+00
44 CO3--	.4943E-16	-16.3060	.1449E-17	-17.8389	.2932E-01

SM2-30C-E-3 HOURS = 261.5 PH(25) = 2.73
 200 DEGREES C AT 500 BARS AND W/P = 5
 01/02/76
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 H2CO3	.7999E-02	-2.0969	.9598E-02	-2.0178	.1200E+01
46 AL(OH)4-	.6301E-05	-5.2006	.2463E-05	-5.6085	.3909E+00
47 FFOH++	.3716E-11	-11.4300	.8678E-13	-13.0616	.2336E-01
48 FFOH+	.6649E-07	-7.1773	.2599E-07	-7.5851	.3909E+00
49 ALDH++	.7415E-10	-10.1299	.3739E-11	-11.4272	.5043E-01
50 NaCl	.1386E+00	-.8583	.1663E+00	-.7792	.1200E+01
51 KCl	.4522E-02	-2.3447	.5425E-02	-2.2656	.1200E+01
52 KHSO4	.5315E-04	-4.2745	.6377E-04	-4.1954	.1200E+01
53 CaCO3	.2273E-13	-13.6434	.2727E-13	-13.5643	.1200E+01
54 MnSO4	.4666E-02	-2.3310	.5599E-03	-3.2519	.1200E+01
55 NaSO4-	.8575E-04	-4.0668	.3472E-04	-4.4595	.4048E+00
56 MgSO4	.1627E-02	-3.7885	.1952E-03	-3.7094	.1200E+01
57 CaSO4	.5613E-05	-5.2508	.6735E-05	-5.1717	.1200E+01
58 NaCO3-	.7646E-15	-15.1166	.3296E-15	-15.4821	.4310E+00
59 MgHCO3+	.1401E-06	-6.8526	.5477E-07	-7.2615	.3909E+00
60 CaHCO3+	.1133E-06	-6.9458	.4429E-07	-7.3537	.3909E+00
61 MgCO3	.5128E-20	-20.2900	.6153E-20	-20.2109	.1200E+01
62 BaCO3	.7728E-20	-20.1119	.9272E-20	-20.0328	.1200E+01
63 BaHCO3+	.1075E-08	-8.7044	.7722E-09	-9.1123	.3909E+00
64 BaOH+	.2694E-09	-9.5697	.1172E-09	-9.9310	.4352E+00
65 BaSO4	.1448E-09	-9.8293	.1737E-09	-9.7602	.1200E+01
66 SrOH+	.1002E-10	-10.9991	.4360E-11	-11.3605	.4352E+00
67 SrCO3	.1406E-18	-18.8514	.1689E-18	-18.7723	.1200E+01
68 SrHCO3+	.3509E-06	-6.4438	.1407E-06	-6.8517	.3909E+00
69 SrSO4	.6626E-07	-7.1788	.7949E-07	-7.0997	.1200E+01

SM2-300-E-4 HOURS = 575.2 PH(25) = 3.02
 300 DEGREES C AT 500 BARS AND W/P = 5
 81/02/18.

WATER 1.0000(KG.LIQ.) 55.5082(MOLES LIQ.) 55.5083(MOLES TOTAL)
 STOICHIOMETRIC IONIC STRENGTH=.6021443E+00 OSMOTIC COEF.= .7489
 IONIC STRENGTH=.4481103E+00 ACTIVITY=.9840

FD2 INPUT AS PEDCX CONTROL

LOG FD2=-13.70 LOG FH2=-10.94 LOG FH2O= 1.91 LOG FCO2= -.83
 LOG FH2S= N LOG FS2= N
 CALCULATED ACTIVITY HS- = .1302E-37M LOG FH2S=-32.16 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FC2
H2(AQ) CM	.3224E-13	.3939E-13 .1189E+01	.6622E-10	.7357E-12	-10.9646
O2(AQ) CM	.6498E-14	.7781E-16 .1109E+01	.2076E-11	.1453E-14	

CM - MOLALITY CALCULATED FROM PEDCX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+)) ²	LOG(A/(A(H+)) ²)
1 H+	.3504E-03	-3.7034	.8913E-02	.1000E+01	0
2 H2O		-.0068	.5551E+02		
3 FCO2		-13.6900ATM			
4 Cl-	.4104E+00	-.8452	.5656E+00	.2827E-04	-4.5487
5 SO4--	.6487E-04	-5.7199	.1749E-02	.7468E-13	-13.1268
6 HCO3-	.7752E-07	-7.4935	.7660E-02	.6354E-11	-11.1969
7 SiO2(AQ)	.2297E-01	-1.4030	.3297E-01	.3954E-01	-1.4030
8 Al+++	.0475E-20	-22.2555	.6301E-05	.7158E-11	-11.1452
9 Ca++	.4506E-02	-2.6420	.4516E-02	.5807E+04	3.7639
10 Mg++	.8355E-02	-3.1544	.8555E-02	.1788E+05	4.2524
11 Fe++	.4527E-05	-6.6400	.2328E-04	.5834E+01	.7660
12 K+	.3023E-01	-1.9874	.3529E-01	.5200E+02	1.7160
13 Na+	.3265E+00	-.8907	.4763E+00	.6648E+03	2.8227
14 Mn++	.1400E-01	-3.4544	.1469E-01	.8365E+04	3.9224
15 Zn++	.3168E-08	-10.1298	.2907E-03	.1892E-02	-2.7230
16 Ba++	.3040E-05	-6.9604	.3054E-05	.2795E+01	.4464
17 SP++	.3093E-04	-5.0542	.3196E-04	.2835E+02	1.4526
18 Au+	.2747E-09	-10.0664	.9138E-05	.4336E-06	-6.3629

SMB-300-5-4 HCLHS = 575.2 PH(25) = 3.02
 200 DEGREES C AT 500 RAPS AND W/P = 5
 P1702/15.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.3504E-03	-3.4554	.1980E-03	-3.7034	.5649E+00
2 H2O			.9849E+00	-.0066	.9849E+00
3 F62			.2000E-13ATM	-13.6990	
4 CL-	.4194E+00	-.3774	.1425E+00	-.8452	.3405E+00
5 SO4--	.6487E-04	-4.1880	.1906E-05	-5.7199	.2938E-01
6 HCO3-	.7753E-07	-7.1105	.3210E-07	-7.4935	.4140E+00
7 SiO2(AQ)	.2297E-01	-1.4819	.3954E-01	-1.4030	.1199E+01
8 AL+++	.9475E-20	-20.0234	.5553E-22	-22.2555	.5861E-02
9 CA++	.4506E-02	-2.3462	.2276E-03	-3.6429	.5050E-01
10 MG++	.2355E-02	-2.0781	.7008E-03	-3.1544	.8388E-01
11 FE++	.4527E-05	-5.3442	.7286E-06	-6.6409	.5050E-01
12 V+	.2023E-01	-1.5195	.1029E-01	-1.9874	.3405E+00
13 NA+	.2365E+00	-.4731	.1216E+00	-.8807	.3912E+00
14 MN++	.1400E-01	-1.8538	.3278E-03	-3.4844	.2341E-01
15 NH4+	.2168E-05	-5.4602	.7416E-10	-10.1298	.2341E-01
16 PA++	.3049E-05	-5.5158	.1055E-06	-6.9604	.3592E-01
17 SP++	.3093E-04	-4.5096	.1111E-05	-5.9542	.3592E-01
18 AU+	.2747E-09	-9.5612	.8583E-10	-10.0664	.3125E+00
19 AU+++	.2848E-32	-32.5938	.5462E-36	-36.2626	.2144E-02
20 ANCL2-	.8920E-05	-5.0492	.3493E-05	-5.4568	.3912E+00
21 AUCL4-	.2090E-06	-6.6799	.8174E-07	-7.0876	.3912E+00
22 FF+++	.2281E-12	-12.6419	.1327E-14	-14.8740	.5861E-02
23 OH-	.1266E-06	-6.8975	.4643E-07	-7.3332	.3667E+00
24 H2SiO4-	.3222E-07	-7.4919	.1260E-07	-7.8996	.3912E+00
25 H2SiO4--	.2719E-14	-14.5656	.6366E-16	-16.1962	.2341E-01
26 KSO4-	.1440E-03	-3.8417	.5280E-04	-4.2774	.2667E+00
27 FF-04	.4780E-06	-6.3197	.5744E-06	-6.2408	.1199E+01
28 HCL	.4097E-02	-3.3876	.4913E-03	-3.3087	.1199E+01
29 HSO4-	.4946E-03	-3.3057	.1935E-03	-3.7134	.3912E+00
30 CADH+	.1152E-05	-5.9384	.4507E-06	-6.3461	.3912E+00
31 MCOH+	.1148E-04	-4.9399	.4492E-05	-5.3476	.3912E+00
32 FECL+	.1665E-04	-4.7785	.6515E-05	-5.1861	.3912E+00
33 FECL2	.1548E-05	-5.8105	.1856E-05	-5.7313	.1199E+01
34 FECL++	.1128E-07	-7.9476	.2641E-09	-9.5782	.2341E-01
35 FECL4-	.2326E-08	-8.6334	.5446E-10	-10.2640	.2341E-01
36 FECL2	.6200E-09	-9.2076	.7435E-09	-9.1287	.1199E+01
37 FECL2+	.8534E-08	-8.0688	.2338E-08	-8.4765	.3912E+00
38 FFSO4+	.1323E-10	-10.8782	.5177E-11	-11.2860	.3912E+00
39 ZNCL+	.3569E-07	-7.4474	.1396E-07	-7.8551	.3912E+00
40 ZNCL2	.1321E-07	-7.8792	.1584E-07	-7.8003	.1199E+01
41 ZNCL2-	.2765E-04	-4.5579	.1083E-04	-4.9655	.3912E+00
42 ZNCL4--	.2629E-03	-3.5802	.6155E-05	-5.2108	.2341E-01
43 ALSD4+	.2525E-20	-20.5978	.9875E-21	-21.0054	.3912E+00
44 CO3--	.2301E-15	-15.6281	.6759E-17	-17.1701	.2938E-01

SM3-300-5-4 HOURS = 575.3 PH(25) = 3.02
 300 DEGREES C AT FCC BARS AND W/P = 5
 P1/02/1P.
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 H2CO3	.7659E-02	-2.1159	.9184E-02	-2.0369	.1199E+01
46 AL(OH)4-	.4301E-05	-5.2087	.2465E-05	-5.6082	.3912E+00
47 FE(OH)3	.2407E-11	-11.6186	.5634E-13	-13.2492	.2341E-01
48 FFDH+	.4504E-07	-7.3464	.1762E-07	-7.7541	.3912E+00
49 AL(OH)3	.6897E-11	-11.1620	.3478E-12	-12.4587	.5050E-01
50 NaCl	.1397E+00	-.8549	.1675E+00	-.7759	.1199E+01
51 KCl	.4880E-02	-2.3114	.5852E-02	-2.2327	.1199E+01
52 KH2PO4	.3718E-04	-4.4297	.4450E-04	-4.3508	.1199E+01
53 CaCO3	.1092E-12	-12.9619	.1309E-12	-12.8820	.1199E+01
54 MnSO4	.6867E-03	-3.1633	.8235E-03	-3.0842	.1199E+01
55 Na2CO3	.1235E-03	-3.9082	.5004E-04	-4.3007	.4051E+00
56 MgSO4	.1891E-03	-3.7233	.2268E-03	-3.6443	.1199E+01
57 CaSO4	.9284E-05	-5.0818	.9935E-05	-5.0028	.1199E+01
58 Na2CO3	.2585E-14	-14.4455	.1546E-14	-14.8108	.4312E+00
59 MgHCO3+	.2397E-06	-6.6203	.9377E-07	-7.0279	.3912E+00
60 CaHCO3+	.2462E-06	-6.6088	.9629E-07	-7.0164	.3912E+00
61 MgCO3	.3979E-20	-20.4003	.4771E-20	-20.3214	.1199E+01
62 BaCO3	.3094E-19	-19.5004	.3711E-19	-19.4305	.1199E+01
63 BaHCO3+	.3570E-08	-8.4463	.1400E-08	-8.8539	.3912E+00
64 Fe(OH)3	.5100E-09	-9.2924	.2220E-09	-9.6536	.4354E+00
65 BaSO4	.1781E-09	-9.7493	.2136E-09	-9.6703	.1199E+01
66 Sr(OH)2	.2652E-10	-10.5763	.1155E-10	-10.9374	.4354E+00
67 SrCO3	.7894E-18	-18.1032	.9455E-18	-18.0243	.1199E+01
68 SrHCO3+	.9118E-06	-6.0401	.2567E-06	-6.4478	.3912E+00
69 SrSO4	.1140E-06	-6.9431	.1367E-06	-6.8642	.1199E+01

SM3-300-5-5 HOURS = 1347.0 PH(25) = 4.08
 300 DEGREES C AT 500 BARS AND W/P = 5
 8/10/27/19.

WATER 1.0000(KG.LIQ.) FF.FOR1(MOLES LIQ.) 55.5083(MOLES TOTAL)
 STOICHIOMETRIC IONIC STRENGTH=.5885092E+00 OSMOTIC COEFF.= .7513
 IONIC STRENGTH=.4315979E+00 ACTIVITY=.9851

FO2 INPUT AS REDOX CONTROL

LOG FO2= -9.49 LOG FH2=-13.07 LOG FH2O= 1.91 LOG FCO2= -.57
 LOG FH2S= N LOG FS2= N
 CALCULATED ACTIVITY HS- = .6525E-47M LOG FH2S=-42.48 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	POP	CC/C	LOG F CALC LOG FO2
H2(AO) CM	.2615E-15	.3115E-15 .1191E+01	.5271E-12	.5857E-14	-13.0666
O2(AO) CM	.1045E-11	.1245E-11 .1191E+01	.3344E-07	.2341E-10	

CM - MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))?	LOG(A/(AH)?)
1 H+	.3358E-04	-4.7205	.1406E-01	.1000E+01	C
2 H2O		-1.0065	.5551E+02		
3 FO2		-9.4940ATM			
4 CL-	.4000E+00	-.9513	.5544E+00	.2680E-05	-5.5719
5 SO4--	.8400E-04	-5.5944	.1520E-02	.9211E-15	-15.0357
6 HCO3-	.1458E-05	-6.2361	.1406E-01	.1157E-10	-10.9366
7 SiO2(AO)	.2074E-01	-1.6073	.2074E-01	.2470E-01	-1.6073
8 AL+++	.9780E-24	-26.2289	.7784E-05	.8565E-12	-12.0673
9 CA++	.2810E-02	-3.7054	.2842E-02	.5441E+06	5.7357
10 MG++	.5388E-02	-3.3384	.5635E-02	.1267E+07	6.1027
11 FE++	.6791E-06	-7.4554	.3581E-05	.9677E+02	1.9857
12 K+	.3366E-01	-1.9359	.3933E-01	.6090E+03	2.7846
13 NA+	.3240E+00	-.8502	.4730E+00	.6924E+04	3.8403
14 MN++	.1192E-01	-3.5392	.1274E-01	.7978E+06	5.9019
15 ZN++	.3091E-08	-10.1256	.2692E-03	.2068E+00	-.6845
16 BA++	.2910E-05	-6.9691	.2981E-05	.2965E+03	2.4720
17 SP++	.2102E-04	-6.1101	.3310E-04	.2143E+04	3.3310
18 AU+	.2585E-09	-10.0870	.8428E-05	.4301E-05	-5.3664

SMR-300-F-5 HOURS = 1347.0 PH(25) = 4.08
 300 DEGREES C AT 500 PARS AND W/P = 5
 81/02/18.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.3358E-04	-4.4739	.1903E-04	-4.7205	.5667E+00
2 H2O			.9851E+00	-.0065	.9851E+00
3 F02			.3200E-09ATM	-9.4949	
4 CL-	.4090E+00	-.3883	.1408E+00	-.8513	.3443E+00
5 SO4--	.8400E-04	-4.0757	.2543E-05	-5.5946	.3028E-01
6 HCO3-	.1458E-05	-5.8364	.6080E-06	-6.2161	.4171E+00
7 SiO2(AO)	.2074E-01	-1.6833	.2470E-01	-1.6073	.1191E+01
8 AL+++	.9780E-24	-24.0092	.5903E-26	-26.2289	.6030E-02
9 CA++	.3818E-02	-2.4181	.1970E-03	-3.7054	.5160E-01
10 MG++	.5388E-02	-2.2786	.4588E-03	-3.3384	.8515E-01
11 FE++	.6791E-06	-6.1680	.3505E-07	-7.4554	.5160E-01
12 K+	.3366E-01	-1.4729	.1159E-01	-1.9359	.3443E+00
13 NA+	.3340E+00	-.4763	.1318E+00	-.8802	.3945E+00
14 MN++	.1193E-01	-1.9234	.2859E-03	-3.5392	.2422E-01
15 ZN++	.3091E-08	-8.5099	.7489E-10	-10.1256	.2422E-01
16 BA++	.2910E-05	-5.5362	.1074E-06	-6.9691	.3690E-01
17 SR++	.2102E-04	-4.6772	.7761E-06	-6.1101	.3690E-01
18 AU+	.2585E-09	-9.5875	.8185E-10	-10.0870	.3166E+00
19 AU+++	.2621E-22	-32.5816	.6067E-36	-36.2170	.2315E-03
20 AUCL2-	.8210E-05	-5.0857	.3239E-05	-5.4696	.3945E+00
21 AUCL4-	.2176E-06	-6.6623	.8586E-07	-7.0662	.3945E+00
22 FE+++	.2667E-13	-13.4357	.2211E-15	-15.6554	.6030E-02
23 NH-	.1305E-05	-5.8845	.4831E-06	-6.3160	.3703E+00
24 H2SiO4-	.2076E-06	-6.6828	.8190E-07	-7.0867	.3945E+00
25 H2SiO4--	.1776E-12	-12.7504	.4303E-14	-14.3662	.2422E-01
26 KSO4-	.2143E-02	-3.6690	.7934E-04	-4.1005	.3703E+00
27 FES04	.9864E-07	-7.0059	.1175E-06	-6.9299	.1191E+01
28 HCL	.3910E-04	-4.4079	.4657E-04	-4.3319	.1191E+01
29 HSO4-	.6292E-04	-4.2012	.2482E-04	-4.6051	.3945E+00
30 CAOH+	.1029E-04	-4.9875	.4061E-05	-5.3914	.3945E+00
31 MGOH+	.7755E-04	-4.1104	.3059E-04	-4.5144	.3945E+00
32 FFCL+	.2496E-05	-5.6027	.9848E-06	-6.0067	.3945E+00
33 FFCL2-	.2323E-06	-6.6340	.2767E-06	-6.5580	.1191E+01
34 FFCL++	.1779E-06	-8.7499	.4309E-10	-10.3657	.2422E-01
35 FECL4-	.2517E-09	-9.4538	.8519E-11	-11.0696	.2422E-01
36 FECL2	.9902E-10	-10.0043	.1180E-09	-9.9283	.1191E+01
37 FFCL2+	.1361E-06	-8.8660	.5371E-09	-9.2700	.3945E+00
38 FES04+	.2897E-11	-11.5380	.1143E-11	-11.9419	.3945E+00
39 ZNCL+	.3524E-07	-7.4530	.1390E-07	-7.8569	.3945E+00
40 ZNCL2	.1306E-07	-7.8842	.1555E-07	-7.8082	.1191E+01
41 ZNCL2-	.2657E-04	-4.5756	.1048E-04	-4.9795	.3945E+00
42 ZNCL4--	.2426E-02	-3.6151	.5877E-05	-5.2308	.2422E-01
43 AL3F4+	.3882E-24	-24.4495	.1401E-24	-24.8535	.3443E+00
44 CO2--	.4399E-13	-13.3567	.1332E-14	-14.8756	.3028E-01

SM2-300-5-E HCLPS =1347.0 PH(25) = 4.09

300 DEGREES C AT 500 BARS AND W/P = 5

01/02/78.

(CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 H2CO3	.1404E-01	-1.8526	.1672E-01	-1.7766	.1191E+01
46 AL(OH)4-	.7784E-05	-5.1098	.3071E-05	-5.5128	.3945E+00
47 FEOH++	.4003E-11	-11.3974	.9698E-13	-13.0133	.2422E-01
48 FEOH+	.7122E-07	-7.1474	.2810E-07	-7.5513	.3945E+00
49 ALDH++	.7455E-14	-14.1276	.3547E-15	-15.4149	.5160E-01
50 NaCl	.1389E+00	-.8575	.1654E+00	-.7815	.1191E+01
51 KCl	.5455E-02	-2.2632	.6498E-02	-2.1872	.1191E+01
52 KHSO4	.5407E-05	-5.2670	.6441E-05	-5.1910	.1191E+01
53 CaCO3	.1875E-10	-10.7270	.2234E-10	-10.6510	.1191E+01
54 MnSO4	.8133E-03	-3.0898	.9688E-03	-3.0138	.1191E+01
55 NaSO4-	.1678E-05	-5.7757	.6687E-05	-4.1748	.4083E+00
56 MgSO4	.1664E-03	-3.7790	.1982E-03	-3.7030	.1191E+01
57 CaSO4	.9638E-05	-5.0160	.1148E-04	-4.9400	.1191E+01
58 NaCO3-	.7024E-12	-12.1524	.3050E-12	-12.5156	.4342E+00
59 MgHCO3+	.2947E-05	-5.5206	.1173E-05	-5.9245	.3945E+00
60 CaHCO3+	.4003E-05	-5.3976	.1579E-05	-5.8015	.3945E+00
61 MgCO3	.4775E-20	-20.3210	.5688E-20	-20.2450	.1191E+01
62 BaCO3	.6016E-17	-17.2207	.7167E-17	-17.1447	.1191E+01
63 BaHCO3+	.6588E-07	-7.1813	.2599E-07	-7.5852	.3945E+00
64 NaOH+	.5166E-05	-8.2868	.2264E-05	-8.6451	.4383E+00
65 BaSO4	.2346E-09	-9.6297	.2705E-09	-9.5537	.1191E+01
66 SrOH+	.1915E-09	-9.7178	.8392E-10	-10.0761	.4363E+00
67 SrCO3	.1092E-15	-15.9617	.1301E-15	-15.8857	.1191E+01
68 SrHCO3+	.1196E-04	-4.9223	.4718E-05	-5.3262	.3945E+00
69 SrSO4	.1070E-06	-6.9707	.1274E-06	-6.8947	.1191E+01

SM2-300-F-6 HOURS =2811.0 PH(25) = 4.17
 200 DEGREES C AT 500 BARS AND W/P = 5
 81/02/18.

WATER 1.0000(KG.LIO.) 55.5081(MOLES LIO.) 55.5083(MOLES TOTAL)
 STOICHIOMETRIC IONIC STRENGTH=.578760E+00 OSMOTIC COEFF.= .7521
 IONIC STRENGTH=.4216241E+00 ACTIVITY=.9852

FO2 INPUT AS REDOX CONTROL

LOG FO2= -9.10 LOG FH2=-13.26 LOG FP2O= 1.91 LOG FCC2= -.64
 LOG FH2S= N LOG FS2= N
 CALCULATED ACTIVITY HS= .1095E-47M LOG FH2S=-43.39 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FO2
H2(AQ) CM	.1671E-15	.1983E-15 .1186E+01	.3369E-12	.3743E-14	-13.262P
O2(AQ) CM	.2590E-11	.3073E-11 .1186E+01	.8289E-07	.5803E-10	

CM - MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))2	LOG(A/(A(H+))2)
1 H+	.2458E-04	-4.8552	.1212E-01	.1000E+01	0
2 H2O		-0.0064	.5551E+02		
3 FO2		-9.1024ATM			
4 CL-	.4013E+00	-0.8565	.5465E+00	.1942E-05	-5.7117
5 SO4--	.1150E-03	-5.4501	.1936E-02	.6911E-15	-15.1605
6 HCO3-	.1702E-05	-6.1467	.1215E-01	.9957E-11	-11.0019
7 SiO2(AQ)	.2062E-01	-1.6115	.2062E-01	.2446E-01	-1.6115
8 AL+++	.2396E-24	-26.8323	.6672E-05	.5410E-12	-12.2668
9 CA++	.3340E-02	-3.7577	.3368E-02	.8967E+06	5.9526
10 MG++	.4407E-02	-3.4216	.4689E-02	.1944E+07	6.2887
11 FE++	.7353E-06	-7.4149	.3939E-05	.1974E+03	2.2954
12 K+	.2970E-01	-2.0021	.3360E-01	.7130E+03	2.8531
13 NA+	.3364E+00	-0.8747	.4762E+00	.9560E+04	3.9805
14 MN++	.1000E-01	-3.5602	.1196E-01	.1384E+07	6.1411
15 ZN++	.3197E-08	-10.1018	.2662E-03	.4060E+00	-0.3914
16 BA++	.3108E-05	-6.9332	.3109E-05	.5986E+03	2.7771
17 SR++	.1628E-04	-6.2139	.2739E-04	.3136E+04	3.4964
18 AU+	.2557E-09	-10.0883	.8123E-05	.5846E-05	-5.2331

SM3-300-E-A HPLPS = 2811.0 PH(25) = 4.17
 200 DEGREES C AT 500 BARS AND V/P = 5
 PJ/02/18.

SPECTES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.2458E-04	-4.6094	.1396E-04	-4.8552	.5679E+00
2 H2O			.9853E+00	-.0064	.9853E+00
3 H2			.7900E-09 ATM	-9.1024	
4 Cl-	.4013E+00	-.3965	.1392E+00	-.8565	.3468E+00
5 SO4--	.1150E-03	-3.9394	.2547E-05	-5.4501	.3085E-01
6 HCO3-	.1702E-05	-5.7690	.7133E-06	-6.1467	.4191E+00
7 SiO2(AQ)	.2062E-01	-1.6857	.2446E-01	-1.6115	.1186E+01
8 AL+++	.2296E-24	-24.6205	.1471E-26	-26.8323	.6139E-02
9 CA++	.3340E-02	-2.4763	.1747E-03	-3.7577	.5231E-01
10 MG++	.4407E-02	-2.3559	.3788E-03	-3.4216	.8595E-01
11 FF++	.7353E-06	-6.1335	.2846E-07	-7.4149	.5231E-01
12 K+	.2870E-01	-1.5421	.9511E-02	-2.0021	.3468E+00
13 NA+	.3364E+00	-.4731	.1334E+00	-.8747	.3966E+00
14 MN++	.1090E-01	-1.9627	.2696E-03	-3.5692	.2475E-01
15 ZN++	.3197E-08	-8.4953	.7911E-10	-10.1018	.2475E-01
16 BA++	.3108E-05	-5.5076	.1166E-06	-6.9332	.3753E-01
17 SP++	.1628E-04	-4.7883	.6110E-06	-6.2139	.3753E-01
18 AU+	.2657E-09	-9.5823	.8160E-10	-10.0883	.3192E+00
19 AU+++	.2101E-32	-32.6777	.5102E-36	-36.2923	.2429E-03
20 AUCL2-	.7649E-05	-5.0997	.2153E-05	-5.5013	.3966E+00
21 AUCL4-	.1735E-06	-6.7606	.6882E-07	-7.1623	.3966E+00
22 FE+++	.2630E-13	-13.4401	.2229E-15	-15.6519	.6139E-02
23 OH-	.1768E-05	-5.7524	.6588E-06	-6.1813	.3725E+00
24 H3SiO4-	.2788E-06	-6.5547	.1106E-06	-6.9563	.3966E+00
25 H2SiO4--	.2202E-12	-12.4946	.7923E-14	-14.1011	.2475E-01
26 KSO4-	.2550E-03	-3.5934	.9501E-04	-4.0222	.3725E+00
27 FFSO4	.1811E-06	-6.8193	.1799E-06	-6.7450	.1186E+01
28 HCL	.2945E-04	-4.5459	.3275E-04	-4.4717	.1186E+01
29 HSO4-	.6402E-04	-4.1937	.2529E-04	-4.5952	.3966E+00
30 CAOH+	.1238E-04	-4.9073	.4909E-05	-5.3090	.3966E+00
31 MGOH+	.8684E-04	-4.0613	.3444E-04	-4.4629	.3966E+00
32 FECL+	.2692E-05	-5.5698	.1068E-05	-5.9714	.3966E+00
33 FECL2	.2490E-06	-6.6022	.2965E-06	-6.5279	.1186E+01
34 FECL++	.1734E-08	-8.7609	.4291E-10	-10.3674	.2475E-01
35 FECL4-	.3308E-09	-9.4804	.8187E-11	-11.0869	.2475E-01
36 FFCL3	.9668E-10	-10.0146	.1147E-09	-9.9404	.1186E+01
37 FFCL2+	.1332E-08	-8.8753	.5285E-09	-9.2769	.3966E+00
38 FFSO4+	.4051E-11	-11.3924	.1607E-11	-11.7940	.3966E+00
39 ZNCL+	.2459E-07	-7.4267	.1451E-07	-7.8383	.3966E+00
40 ZNCL2	.1352E-07	-7.8690	.1604E-07	-7.7948	.1186E+01
41 ZNCL3-	.2694E-04	-4.5696	.1068E-04	-4.9713	.3966E+00
42 ZNCL4--	.2392E-07	-3.6213	.5919E-05	-5.2278	.2475E-01
43 AL5O4+	.1228E-24	-24.9108	.4870E-25	-25.3124	.3966E+00
44 CO3--	.6905E-13	-13.1608	.2130E-14	-14.6715	.3085E-01

SM3-200-E-6 PCUFFS = 2811.0 PH(25) = 4.17
 300 DEGREES C AT 500 BARS AND W/P = 5
 81/02/18.
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 H2CO3	.1213E-01	-1.9161	.1439E-01	-1.8419	.1186E+01
46 AL(OH)4-	.6672E-05	-5.1758	.2646E-05	-5.5774	.3966E+00
47 FE(OH)++	.5386E-11	-11.2687	.1333E-12	-12.8752	.2475E-01
48 FE(OH)+	.1060E-06	-6.9746	.4205E-07	-7.3762	.3966E+00
49 AL(OH)++	.2499E-14	-14.6022	.1307E-15	-15.8836	.5231E-01
50 NaCl	.1395E+00	-.8555	.1655E+00	-.7812	.1186E+01
51 KCl	.4647E-02	-2.3328	.5513E-02	-2.2586	.1186E+01
52 KHSO4	.4768E-05	-5.3216	.5657E-05	-5.2474	.1186E+01
53 CaCO3	.2670E-10	-10.5735	.3168E-10	-10.4992	.1186E+01
54 MnSO4	.1063E-02	-2.9736	.1261E-02	-2.8993	.1186E+01
55 NaSO4-	.2302E-03	-3.6379	.9445E-04	-4.0248	.4103E+00
56 MgSO4	.1923E-03	-3.7160	.2282E-03	-3.6417	.1186E+01
57 CaSO4	.1197E-04	-4.9221	.1420E-04	-4.8478	.1186E+01
58 NaCO3-	.1132E-11	-11.9458	.4940E-12	-12.3062	.4360E+00
59 MgHCO3+	.2840E-05	-5.5467	.1126E-05	-5.9483	.3966E+00
60 CaHCO3+	.4142E-05	-5.3828	.1643E-05	-5.7844	.3966E+00
61 MgCO3	.3406E-20	-20.4678	.4041E-20	-20.3935	.1186E+01
62 BaCO3	.1049E-16	-16.9790	.1245E-16	-16.9048	.1186E+01
63 BaHCO3+	.9350E-07	-7.0783	.3312E-07	-7.4800	.3966E+00
64 Fe(OH)3	.7610E-08	-8.1181	.3353E-08	-8.4745	.4401E+00
65 BaSO4	.3568E-09	-9.4476	.4233E-09	-9.3733	.1186E+01
66 Fe(OH)2	.2048E-09	-9.6888	.9012E-10	-10.0452	.4401E+00
67 SPCO3	.1381E-15	-15.8597	.1639E-15	-15.7855	.1186E+01
68 SPHCO3+	.1089E-04	-4.9590	.4359E-05	-5.3606	.3966E+00
69 SPSO4	.1160E-06	-6.9283	.1399E-06	-6.8540	.1186E+01

+++++

GPC-200-E-1 HOURS = 1.0 PH(25) = 5.07
 200 DEGREES C AT 500 PARS AND W/F = F
 91/02/18.

+++++

WATER 1.0000(KG.LIO.) 55.5081(MOLES LIO.) 55.5083(MOLES TOTAL)
 STOICHIOMETRIC IONIC STRENGTH=.6771105E+00 OSMOTIC COEF.= .6406
 IONIC STRENGTH=.5746043E+00 ACTIVITY=.9827

FO2 INPUT AS PEOX CONTROL

LOG FO2=-10.49 LOG FH2=-17.94 LOG FP2O= 1.25 LOG FCO2= .03
 LOG FH2S= N LOG FS2= N
 CALCULATED ACTIVITY FS- = .1399E-61M LOG FH2S=-58.51 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FO2
H2(AQ) CM	.1161E-20	.1307E-20 .1126E+01	.2240E-17	.2600E-19	-17.9416
O2(AQ) CM	.3463E-13	.2901E-12 .1126E+01	.1108E-08	.7758E-12	

CM - MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))Z	LOG(A/(A(H+))Z)
1 H+	.4931E-05	-5.3079	.4960E-02	.1000E+01	0
2 H2O		-0.0076	.5551E+02		
3 FO2		-10.4949ATM			
4 CL-	.5268E+00	-5.866	.5670E+00	.1275E-05	-5.8946
5 SO4--	.3090E-02	-3.5760	.1945E-01	.6429E-14	-14.1919
6 HCO3-	.1872E-02	-2.9739	.5440E-02	.5226E-09	-9.2818
7 SiO2(AQ)	.6928E-02	-2.1071	.6940E-02	.7815E-02	-2.1071
8 AL+++	.4964E-15	-16.8559	.9216E-05	.1161E+00	-9.9350
9 CA++	.5085E-02	-3.1891	.5464E-02	.2672E+08	7.4268
10 MG++	.2968E-01	-2.2640	.4278E-01	.2248E+09	8.3519
11 FE++	.2345E-05	-5.5253	.6953E-05	.1232E+05	4.0905
12 K+	.1802E-01	-2.0524	.1895E-01	.1801E+04	3.2555
13 NA+	.4475E+00	-5.6134	.4898E+00	.4940E+05	4.6946
14 MN++	.4098E-03	-4.3925	.4696E-03	.1232E+07	6.0906
15 ZN++	.2037E-07	-8.8288	.1224E-04	.6124E+02	1.7870
16 BA++	.1137E-05	-6.9466	.1236E-05	.4669E+04	3.6697
17 SP++	.3311E-04	-5.4826	.4565E-04	.1359E+06	5.1333
18 AU+	.2223E-11	-11.9889	.2536E-06	.2085E-06	-6.6809

GPC3C-200-F-1 HCLPS = 1.0 PH(25) = 5.07
 200 DEGREES C AT 500 PAPS AND W/P = 5
 91/02/19.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.4931E-05	-5.1592	.4921E-05	-5.3079	.7100E+00
2 H2O			.9827E+00	-.0076	.9827E+00
3 F02			.3200E-10	-10.4949	
4 CL-	.5268E+00	-.2794	.2590E+00	-.5666	.4917E+00
5 SO4--	.3090E-02	-2.5100	.2655E-03	-3.5760	.8590E-01
6 HCO3-	.1872E-03	-3.7276	.1062E-03	-3.9739	.5672E+00
7 SiO2(AQ)	.4928E-02	-2.1587	.7815E-02	-2.1071	.1126E+01
8 AL+++	.4964E-15	-15.3042	.1384E-16	-16.8588	.2789E-01
9 CA++	.5085E-02	-2.2937	.6470E-03	-3.1891	.1272E+00
10 MG++	.2968E-01	-1.5275	.5445E-02	-2.2640	.1835E+00
11 FE++	.2345E-05	-5.6299	.2983E-05	-6.5253	.1272E+00
12 K+	.1802E-01	-1.7442	.8862E-02	-2.0524	.4917E+00
13 NA+	.4475E+00	-.3492	.2436E+00	-.6134	.5443E+00
14 MN++	.4098E-03	-3.3875	.2983E-04	-4.5253	.7281E-01
15 ZN++	.2037E-07	-7.6510	.1483E-08	-8.8288	.7281E-01
16 BA++	.1137E-05	-5.9441	.1131E-05	-6.9466	.9942E-01
17 SR++	.3211E-04	-4.4800	.3202E-05	-5.4826	.9942E-01
18 AU+	.2223E-11	-11.6521	.1026E-11	-11.9888	.4616E+00
19 NH4++	.2891E-35	-35.5389	.7367E-38	-38.1327	.2548E-02
20 AUCL2-	.2536E-06	-6.5959	.1380E-06	-6.8601	.5443E+00
21 AUCL4-	.2588E-09	-9.5870	.1409E-09	-9.8512	.5443E+00
22 FE+++	.1725E-11	-11.7607	.4820E-13	-13.3152	.2789E-01
23 PH-	.2162E-05	-5.6650	.1122E-05	-5.9496	.5192E+00
24 H2SiO4-	.1274E-05	-5.8950	.6932E-06	-6.1591	.5443E+00
25 H2SiO4--	.1935E-10	-10.7124	.1409E-11	-11.8512	.7281E-01
26 KSO4-	.4132E-03	-3.3828	.2146E-03	-3.6684	.5192E+00
27 FES04	.5085E-06	-6.2230	.6741E-06	-6.1713	.1126E+01
28 HCL	.9855E-06	-6.0062	.1110E-05	-5.0546	.1126E+01
29 HSO4-	.4171E-04	-4.3797	.2270E-04	-4.6439	.5443E+00
30 CACH+	.6244E-06	-6.2045	.3299E-06	-6.4687	.5443E+00
31 MG0H+	.1382E-03	-3.8594	.7523E-04	-4.1236	.5443E+00
32 FECL+	.5452E-05	-5.2477	.2077E-05	-5.5119	.5443E+00
33 FECL2+	.1084E-08	-8.9641	.7909E-10	-10.1019	.7281E-01
34 FECL4-	.2092E-09	-9.5230	.2179E-10	-10.6618	.7281E-01
35 FECL2	.4712E-09	-9.3266	.5307E-09	-9.2751	.1126E+01
36 FECL2+	.5441E-09	-9.2642	.2961E-09	-9.5285	.5443E+00
37 FES04+	.8569E-10	-10.0671	.4664E-10	-10.3312	.5443E+00
38 ZNCL+	.2970E-07	-7.4012	.2161E-07	-7.6654	.5443E+00
39 ZNCL2	.1645E-07	-7.7827	.1853E-07	-7.7321	.1126E+01
40 ZNCL2-	.2989E-05	-5.5245	.1627E-05	-5.7867	.5443E+00
41 ZNCL4--	.9172E-05	-5.0375	.6679E-06	-6.1753	.7281E-01
42 ALSO4+	.3016E-15	-15.5206	.1641E-15	-15.7848	.5443E+00
43 CO3--	.5248E-08	-8.2800	.4509E-09	-9.3460	.8590E-01
44 H2CO3	.5085E-02	-2.2935	.5730E-02	-2.2418	.1126E+01

GOCPC-200-5-1 HOPS = 1.0 PH(25) = 5.07
 200 DFGPFFS C AT 500 BARS AND W/P = F
 81/02/18.
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 AL(OH)4-	.9266E-05	-5.0331	.5043E-05	-5.2973	.5443E+00
46 FE(OH)3	.4446E-14	-14.3521	.2227E-15	-15.4899	.7261E-01
47 F(OH)2	.3542E-06	-6.4507	.1928E-06	-6.7149	.5443E+00
48 AL(OH)3	.1528E-09	-9.8130	.1957E-10	-10.7084	.1272E+00
49 NaCl	.2966E-01	-1.4017	.4467E-01	-1.3500	.1126E+01
50 KCl	.5120E-03	-3.2907	.5767E-03	-3.2391	.1126E+01
51 KHSO4	.2704E-05	-5.5680	.3045E-05	-5.5164	.1126E+01
52 CaCO3	.2974E-07	-7.5267	.3349E-07	-7.4750	.1126E+01
53 MnSO4	.5985E-04	-4.2229	.6741E-04	-4.1713	.1126E+01
54 NaCO3-	.2652E-02	-2.5762	.1461E-02	-2.6294	.5583E+00
55 MgSO4	.1283E-01	-1.8917	.1445E-01	-1.8400	.1126E+01
56 CaSO4	.3494E-02	-3.4567	.3935E-03	-3.4051	.1126E+01
57 NaCO3-	.1331E-07	-7.8750	.7774E-08	-8.1093	.5843E+00
58 MgHCO3+	.1248E-02	-2.9037	.6794E-04	-4.1679	.5443E+00
59 CaHCO3+	.2992E-04	-4.5288	.1574E-04	-4.8030	.5443E+00
60 MgCO3	.2644E-17	-17.5773	.2980E-17	-17.5258	.1126E+01
61 BaCO3	.1902E-12	-12.7442	.2030E-12	-12.6928	.1126E+01
62 BaHCO3+	.9198E-07	-7.0362	.5006E-07	-7.3005	.5443E+00
63 BaOH+	.3267E-09	-9.4850	.1922E-09	-9.7162	.5883E+00
64 BaCO3	.6293E-08	-8.1942	.7201E-08	-8.1426	.1126E+01
65 SP(OH)2	.1987E-09	-9.7018	.1149E-09	-9.9322	.5883E+00
66 SP(OH)3	.1216E-10	-10.8802	.1484E-10	-10.8285	.1126E+01
67 SP(OH)3	.1116E-04	-4.9522	.6075E-05	-5.2164	.5443E+00
68 SO4	.1380E-05	-5.8602	.1554E-05	-5.8086	.1126E+01

GPC3C-200-5-2 HOURS = 122.25 PH(25) = 4.0
 200 DEGREES C AT 500 BARS AND W/P = 5
 8/102/18.

WATER 1.0000(KG.LIT.) 55.5082(MOLES LIT.) 55.5083(MOLES TOTAL)
 STICHTOMETRIC IONIC STRENGTH=.6533130E+00 OSMOTIC COEF.= .8439
 IONIC STRENGTH=.5640569E+00 ACTIVITY=.9830

FD2 INPUT AS PEROX CONTROL

LOG FD2=-11.60 LOG FH2=-17.39 LOG FH2O= 1.25 LOG FC02= .23
 LOG FH2S= N LOG FS2= N
 CALCULATED ACTIVITY HS- = .1011E-58M LOG FH2S=-54.90 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FD2
H2(AO) CM	.4163E-20	.4678E-20 .1124E+01	.8392E-17	.9325E-19	-17.3879
O2(AO) CM	.2712E-14	.3047E-14 .1124E+01	.8677E-10	.6074E-13	

CM - MOLALITY CALCULATED FROM PEROX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+)) ^{1/2}	LOG(A/(A(H+)) ^{1/2})
1 H+	.3996E-04	-4.5581	.6382E-02	.1000E+01	0
2 H2O		-.0074	.5551E+02		
3 FD2		-11.6021ATM			
4 CL-	.5204E+00	-.5907	.5600E+00	.7099E-05	-5.1488
5 SO4--	.2402E-02	-3.6813	.1508E-01	.1594E-12	-12.7975
6 HCO3-	.5343E-04	-4.5178	.8290E-02	.8396E-09	-9.0759
7 SiO2(AO)	.1060E-01	-1.9240	.1060E-01	.1191E-01	-1.9240
8 AL+++	.3335E-12	-14.0278	.4301E-05	.4430E+00	-3.3536
9 CA++	.4276E-02	-3.2616	.4516E-02	.7155E+06	5.8546
10 MG++	.2862E-01	-2.2780	.3846E-01	.6889E+07	6.6382
11 FF++	.3945E-05	-6.2966	.1432E-04	.6600E+03	2.8195
12 K+	.1920E-01	-2.0470	.1905E-01	.3244E+03	2.5111
13 NA+	.4420E+00	-.6179	.4831E+00	.8712E+04	3.9401
14 MN++	.6154E-03	-4.2218	.6101E-03	.7841E+05	4.8944
15 ZN++	.2947E-07	-8.5269	.2295E-04	.3796E+01	.5793
16 BA++	.1061E-05	-6.9732	.1091E-05	.1390E+03	2.1429
17 SP++	.3434E-04	-5.4632	.3880E-04	.4497E+04	3.6530
18 AM+	.6282E-11	-11.5361	.7108E-06	.1052E-06	-6.9760

CPC3C-200-5-2 HCLFS = 123.25 PH(25) = 4.0
 200 DECEPES C AT 500 BAPS AND W/P = 5
 01/02/78.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.3806E-04	-4.4092	.2766E-04	-4.5581	.7100E+00
2 H2O			.9830E+00	-.0074	.9830E+00
3 F02			.2500E-11ATM	-11.6021	
4 CL-	.5204E+00	-.2637	.2566E+00	-.5907	.4931E+00
5 SO4--	.2402E-02	-2.6193	.2083E-03	-3.6813	.8670E-01
6 HCO3-	.5343E-04	-4.2722	.3035E-04	-4.5178	.5681E+00
7 SiO2(AQ)	.1060E-01	-1.9747	.1191E-01	-1.9240	.1124E+01
8 AL+++	.3335E-12	-12.4770	.9379E-14	-14.0278	.2813E-01
9 CA++	.4276E-02	-2.3689	.5475E-03	-3.2616	.1260E+00
10 MG++	.2863E-01	-1.5432	.5273E-02	-2.2780	.1842E+00
11 FE++	.3945E-05	-5.4040	.1051E-06	-6.2966	.1280E+00
12 K+	.1820E-01	-1.7400	.8974E-02	-2.0470	.4931E+00
13 NA+	.4420E+00	-.3545	.2410E+00	-.6179	.5452E+00
14 MN++	.8154E-02	-3.0886	.6001E-04	-4.2218	.7359E-01
15 ZN++	.2947E-07	-7.4037	.2905E-08	-8.5369	.7359E-01
16 BA++	.1061E-05	-5.9747	.1064E-06	-6.9732	.1002E+00
17 SP++	.2434E-04	-4.4642	.3442E-05	-5.4632	.1002E+00
18 AU+	.6282E-11	-11.2019	.2910E-11	-11.5361	.4632E+00
19 AU+++	.7057E-24	-34.1517	.1843E-26	-36.7345	.2613E-02
20 AUCL2-	.7045E-06	-6.1521	.3841E-06	-6.4155	.5452E+00
21 AUCL4-	.6224E-08	-8.2059	.3394E-08	-8.4693	.5452E+00
22 FE+++	.8651E-11	-11.0629	.2433E-12	-12.6138	.2813E-01
23 OH-	.2840E-06	-6.4157	.1958E-06	-6.6994	.5203E+00
24 H2SiO4-	.3448E-06	-6.4625	.1880E-06	-6.7259	.5452E+00
25 H2SiO4--	.9234E-12	-12.0346	.4795E-13	-13.1678	.7359E-01
26 KSO4-	.3276E-03	-3.4846	.1705E-03	-3.7683	.5203E+00
27 FES04	.7988E-06	-6.0987	.8955E-06	-6.0479	.1124E+01
28 HCl	.5502E-05	-5.2595	.6183E-05	-5.2068	.1124E+01
29 HSO4-	.1827E-03	-3.7360	.1001E-03	-3.9994	.5452E+00
30 CADH+	.9386E-07	-7.0275	.5118E-07	-7.2909	.5452E+00
31 MG0H+	.2377E-04	-4.6229	.1296E-04	-4.8873	.5452E+00
32 FFCL+	.9464E-05	-5.0239	.5160E-05	-5.2873	.5452E+00
33 FFCL++	.5354E-08	-8.2714	.3970E-09	-9.4045	.7359E-01
34 FFCL4-	.1424E-08	-8.8435	.1055E-09	-9.9767	.7359E-01
35 FFCL3	.2308E-08	-8.6367	.2594E-06	-8.5860	.1124E+01
36 FFCL2+	.2680E-08	-9.5718	.1461E-08	-8.8353	.5452E+00
37 FES04+	.3375E-09	-9.4717	.1840E-09	-9.7351	.5452E+00
38 ZNCL+	.7688E-07	-7.1142	.4192E-07	-7.3776	.5452E+00
39 ZNCL2	.3169E-07	-7.4990	.3562E-07	-7.4482	.1124E+01
40 ZNCL3-	.5681E-05	-5.2456	.3097E-05	-5.5090	.5452E+00
41 ZNCL4--	.1712E-04	-4.7666	.1260E-05	-5.8997	.7359E-01
42 ALS04+	.1600E-12	-12.7957	.8726E-13	-13.0592	.5452E+00
43 CO3--	.2644E-09	-9.5778	.2292E-10	-10.6397	.8670E-01
44 H2CO3	.8192E-02	-2.0866	.9206E-02	-2.0359	.1124E+01

GPC30-200-5-2. HOURS = 123.25 PH(25) = 4.0

200 DEGREES C AT 500 BARS AND W/P = 5

91/02/1P.

(CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 AL(OH)4-	.6283E-05	-5.2010	.3425E-05	-5.4653	.5452E+00
46 FFCH++	.3935E-14	-14.4050	.2896E-15	-15.5382	.7359E-01
47 FFCH+	.1065E-06	-6.9726	.5808E-07	-7.2360	.5452E+00
48 ALOH++	.1843E-07	-7.7345	.2359E-08	-8.6272	.1260E+00
49 NaCl	.7896E-01	-1.4094	.4379E-01	-1.3587	.1124E+01
50 KCl	.5147E-02	-3.2885	.5784E-02	-3.2377	.1124E+01
51 KHSO4	.1210E-04	-4.9171	.1360E-04	-4.8664	.1124E+01
52 CaCO3	.1282E-08	-8.8920	.1441E-08	-8.8413	.1124E+01
53 MnSO4	.9466E-04	-4.0238	.1064E-05	-3.9731	.1124E+01
54 NaSO4-	.2057E-02	-2.6968	.1150E-02	-2.9393	.5592E+00
55 MgSO4	.9772E-02	-2.0100	.1068E-01	-1.9593	.1124E+01
56 CaSO4	.2725E-03	-3.6326	.2612E-03	-3.5829	.1124E+01
57 NaCO3-	.6686E-09	-9.1748	.3911E-09	-9.4077	.5850E+00
58 MgHCO3+	.3449E-04	-4.4624	.1580E-04	-4.7258	.5452E+00
59 CaHCO3+	.6982E-05	-5.1560	.3807E-05	-5.4194	.5452E+00
60 MgCO3	.4125E-17	-17.3846	.4636E-17	-17.3329	.1124E+01
61 BaCO3	.8636E-14	-14.0637	.9705E-14	-14.0130	.1124E+01
62 BaHCO3+	.2468E-07	-7.6077	.1346E-07	-7.8711	.5452E+00
63 BaOH+	.5461E-10	-10.2627	.3217E-10	-10.4926	.5890E+00
64 BaSO4	.4720E-08	-8.3253	.5314E-08	-8.2746	.1124E+01
65 SrOH+	.2692E-10	-10.4327	.2175E-10	-10.6626	.5890E+00
66 SrCO3	.7020E-12	-12.1537	.7889E-12	-12.1030	.1124E+01
67 SrHCO3+	.2320E-05	-5.4776	.1815E-05	-5.7410	.5452E+00
68 SrSO4	.1134E-05	-5.9452	.1275E-05	-5.8945	.1124E+01

GPC2C-200-5-3 HCLPS = 292.0 PH(25) = 3.01
 200 DEGREES C AT 500 BARS AND W/P = F
 01/02/18.

WATER 1.0000(KG.LIQ.) 55.5082(MOLES LIQ.) 55.5083(MOLES TOTAL)
 STOICHIOMETRIC IONIC STRENGTH=.653992PF+00 OSMOTIC COEF.= .8442
 IONIC STRENGTH=.565257E+00 ACTIVITY=.9830

EQ2 INPUT AS REDOX CONTROL

LOG EQ2=-12.00 LOG FH2=-17.19 LOG FH2O= 1.25 LOG FCO2= .19
 LOG FH2S= N LOG FS2= N
 CALCULATED ACTIVITY HS- = .7015E-5PM LOG FH2S=-54.02 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FC?
H2(AQ) CM	.6580E-20	.7397E-20 .1124E+01	.1327E-16	.1474E-16	-17.1890
O2(AQ) CM	.1084E-14	.1219E-14 .1124E+01	.3470E-10	.2429E-13	

CM - MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))17	LOG(A/(AH)2)
1 H+	.4301E-04	-4.5152	.7710E-02	.1000E+01	0
2 H2O		-.0075	.5557E+02		
3 EQ2		-12.0000ATM			
4 CL-	.5216E+00	-.5898	.5612E+00	.7851E-05	-5.1051
5 SO4--	.2419E-02	-3.6788	.1510E-01	.1953E-12	-12.7092
6 HCO3-	.4427E-04	-4.5996	.7570E-02	.7677E-09	-9.1148
7 SiO2(AQ)	.1040E-01	-1.9321	.1040E-01	.1169E-01	-1.9321
8 Al+++	.7949E-12	-13.8569	.6301E-05	.4685E+00	-.2112
9 Ca++	.4499E-02	-3.2408	.4741E-02	.6161E+06	5.7896
10 Mg++	.2917E-01	-2.2852	.3788E-01	.5562E+07	6.7452
11 Fe++	.2957E-05	-6.4221	.1074E-04	.4058E+03	2.6083
12 K+	.2125E-01	-1.9799	.2225E-01	.3430E+03	2.5353
13 Na+	.4406E+00	-.6194	.4616E+00	.7866E+04	3.8958
14 Mn++	.9161E-03	-4.1718	.1023E-02	.7222E+05	4.8587
15 Zn++	.3788E-07	-8.5552	.2218E-04	.2986E+01	.4751
16 Ba++	.7102E-06	-7.1480	.7271E-06	.7628E+02	1.8824
17 Sr++	.3793E-04	-5.4205	.4223E-04	.4073E+04	3.6099
18 Au+	.5823E-11	-11.5693	.6600E-06	.8630E-07	-7.0540

CPC20-200-E-7 HDUPS = 202.0 PH(25) = 3.91

200 DEGREES C AT 500 BARS AND W/P = 5

5/102/18.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.4301E-04	-4.3665	.3053E-04	-4.5152	.7100E+00
2 H2O			.9830E+00	-1.0075	.9830E+00
3 F02			.1000E-11ATM	-12.0000	
4 CL-	.5214E+00	-.2826	.2571E+00	-.5898	.4930E+00
5 SO4--	.2410E-02	-2.6163	.2095E-02	-3.6788	.8661E-01
6 HCO3-	.4427E-04	-4.3529	.2514E-04	-4.5996	.5680E+00
7 SiO2(AO)	.1040E-01	-1.9829	.1169E-01	-1.9321	.1124E+01
8 AL+++	.4949E-12	-12.3055	.1391E-13	-13.8568	.2810E-01
9 CA++	.4486E-02	-2.3478	.5744E-03	-3.2408	.1279E+00
10 MG++	.2917E-01	-1.5502	.5186E-02	-2.2852	.1841E+00
11 FE++	.2057E-05	-5.5291	.3764E-06	-6.4221	.1279E+00
12 K+	.2125E-01	-1.6727	.1047E-01	-1.9799	.4930E+00
13 NA+	.4466E+00	-.3559	.2402E+00	-.6194	.5451E+00
14 MN++	.9161E-03	-3.0380	.6733E-04	-4.1718	.7350E-01
15 ZN++	.3788E-07	-7.4216	.2784E-08	-8.5553	.7350E-01
16 BA++	.7102E-06	-6.1486	.7111E-07	-7.1480	.1001E+00
17 SR++	.3792E-04	-4.4211	.3798E-05	-5.4205	.1001E+00
18 AU+	.5822E-11	-11.2349	.2696E-11	-11.5693	.4630E+00
19 AU+++	.5050E-24	-34.2967	.1316E-24	-24.8808	.2606E-02
20 AUCL2-	.6555E-06	-6.1834	.3573E-06	-6.4469	.5451E+00
21 AUCL4-	.4481E-08	-8.3486	.2443E-08	-8.6122	.5451E+00
22 FE+++	.5694E-11	-11.2446	.1600E-12	-12.7959	.2810E-01
23 OH-	.3420E-06	-6.4584	.1810E-06	-6.7422	.5202E+00
24 H3SiO4-	.2066E-06	-6.5124	.1472E-06	-6.7769	.5451E+00
25 H2SiO4--	.7448E-12	-12.1280	.5474E-13	-13.2617	.7350E-01
26 KSO4-	.3847E-03	-3.4149	.2001E-03	-3.6987	.5202E+00
27 FES04	.6002E-06	-6.2217	.6748E-06	-6.1709	.1124E+01
28 HCL	.6083E-05	-5.2159	.6836E-05	-5.1651	.1124E+01
29 HSO4-	.2039E-03	-3.6905	.1112E-03	-3.9540	.5451E+00
30 CADH+	.8922E-07	-7.0496	.4863E-07	-7.3131	.5451E+00
31 MGDH+	.2119E-04	-4.6739	.1155E-04	-4.9375	.5451E+00
32 FECL+	.7105E-05	-5.1494	.3873E-05	-5.4119	.5451E+00
33 FECL++	.2532E-08	-8.4520	.2596E-09	-9.5857	.7350E-01
34 FECL4-	.9517E-09	-9.0215	.6905E-10	-10.1552	.7350E-01
35 FECL3	.1527E-08	-8.8162	.1716E-08	-8.7654	.1124E+01
36 FECL2+	.1770E-08	-8.7520	.9649E-09	-9.0155	.5451E+00
37 FES04+	.2233E-09	-9.6511	.1217E-09	-9.9146	.5451E+00
38 ZNCL+	.7385E-07	-7.1316	.4026E-07	-7.3951	.5451E+00
39 ZNCL2	.3049E-07	-7.5158	.3428E-07	-7.4650	.1124E+01
40 ZNCL2-	.5470E-05	-5.2613	.2987E-05	-5.5248	.5451E+00
41 ZNCL4--	.1656E-04	-4.7809	.1217E-05	-5.9146	.7350E-01
42 ALS04+	.2387E-12	-12.6221	.1301E-12	-12.8856	.5451E+00
43 CO3--	.1986E-09	-9.7019	.1720E-10	-10.7644	.8661E-01
44 H2CO3	.7489E-02	-2.1256	.8418E-02	-2.0748	.1124E+01

GPC3C-200-F-2 HOURS = 292.0 PH(25) = 3.91
 200 DEGREES C AT 500 BARS AND W/S = F
 51/02/1P.
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 AL(OH)4-	.6276E-05	-5.2023	.3421E-05	-5.4658	.5451E+00
46 FFCH++	.2347E-14	-14.6294	.1725E-15	-15.7631	.7350E-01
47 FECH+	.7221E-07	-7.1408	.3942E-07	-7.4043	.5451E+00
48 ALQH++	.2477E-07	-7.6061	.3169E-08	-8.4991	.1279E+00
49 NaCl	.3890E-01	-1.4101	.4372E-01	-1.3593	.1124E+01
50 KCl	.6018E-02	-3.2205	.6765E-03	-3.1697	.1124E+01
51 KHSO4	.1568E-04	-4.8047	.1762E-04	-4.7539	.1124E+01
52 CaCO3	.1005E-08	-8.9960	.1135E-09	-8.9452	.1124E+01
53 MnSO4	.1068E-03	-3.9714	.1201E-03	-3.9205	.1124E+01
54 NaSO4-	.2062E-02	-2.6857	.1153E-02	-2.5382	.5591E+00
55 MgSO4	.2661E-02	-2.0148	.1086E-01	-1.9640	.1124E+01
56 CaSO4	.2452E-03	-3.6104	.2757E-02	-3.5596	.1124E+01
57 NaCO3-	.5002E-09	-9.3009	.2926E-09	-9.5339	.5849E+00
58 MgHCO3+	.2510E-04	-4.5513	.1532E-04	-4.8148	.5451E+00
59 CaHCO3+	.6069E-05	-5.2169	.3308E-05	-5.4804	.5451E+00
60 MgCO3	.2708E-17	-17.4308	.4169E-17	-17.2800	.1124E+01
61 BaCO3	.4322E-14	-14.3622	.4871E-14	-14.3124	.1124E+01
62 BaHCO3+	.1367E-07	-7.8541	.7454E-08	-8.1276	.5451E+00
63 RACH+	.2205E-10	-10.4804	.1949E-10	-10.7103	.5889E+00
64 BaSO4	.2180E-08	-8.4976	.3574E-08	-8.4468	.1124E+01
65 SOCH+	.3691E-10	-10.4326	.2174E-10	-10.6627	.5889E+00
66 SROCO3	.5212E-12	-12.2257	.6524E-12	-12.1848	.1124E+01
67 SPOHCO3+	.2044E-05	-5.5165	.1659E-05	-5.7801	.5451E+00
68 SPSO4	.1255E-05	-5.9001	.1415E-05	-5.8492	.1124E+01

CPC20-200-F-4 MOLES = 674.0 PH(25) = 4.74
 200 DEGREES C AT 500 PARS AND W/P = F
 P1702/1P.

WATER 1.0000(MG/LIC.) 55.5081(MOLES LIC.) 55.5081(MOLES TOTAL)
 STOICHIOMETRIC IONIC STRENGTH=.6479028E+00 OSMOTIC COEF.= .8445
 IONIC STRENGTH=.5608031E+00 ACTIVITY=.9831

FO2 INPUT AS REDOX CONTROL

LOG FO2= -9.20 LOG FH2=-1P.59 LOG FH2O= 1.25 LOG FCO2= .18
 LOG FH2S= N LOG FS2= N
 CALCULATED ACTIVITY HS- = .5537E-64M LOG FH2S=-60.62 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FO2
H2(AQ) CM	.2624E-21	.2947E-21 .1127E+01	.5291E-1P	.5878E-20	-1P.5886
O2(AQ) CM	.6P38E-12	.7630E-12 .1123E+01	.2188E-07	.1532E-10	

CM - MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))Z	LOG(A/(AH)Z)
1 H+	.1263E-04	-5.0143	.7157E-02	.1000E+01	0
2 H2O		-.0074	.5551E+02		
3 FO2		-9.2007ATM			
4 CL-	.5175E+00	-.592P	.5557E+00	.2471E-05	-5.6071
5 SO4--	.22P3E-02	-3.6837	.1459E-01	.1939E-13	-13.7124
6 HCO3-	.1244E-02	-4.1170	.7460E-02	.7390E-09	-9.1314
7 SiO2(AQ)	.1007E-01	-1.9467	.1007E-01	.1131E-01	-1.9467
8 AL++	.1439E-13	-15.3918	.1814E-04	.4479E+00	-.3488
9 CA++	.4762E-02	-3.2140	.5040E-02	.6526E+07	6.8146
10 MG++	.2763E-01	-2.2928	.3718E-01	.5444E+08	7.7359
11 FF++	.82P5E-06	-6.9725	.3044E-05	.1135E+04	3.0551
12 K+	.1782E-01	-2.0558	.1P64E-01	.9089E+03	2.9585
13 NA+	.4397E+00	-.6200	.4804E+00	.2479E+05	4.3944
14 MN++	.1130E-02	-4.0785	.1261E-02	.8915E+06	5.9501
15 PA++	.8890E-06	-7.0490	.9452E-06	.9542E+02	2.9796
16 SP++	.3127E-04	-5.5028	.3505E-04	.3357E+05	4.5259
17 AU+	.4940E-11	-11.6400	.5585E-06	.2368E-06	-6.6257

GPC20-200-5-4 HCLPS = 674.0 PH(25) = 4.74
 200 DEGREES C AT 500 BARS AND W/P = 5
 81/02/18.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.1362E-04	-4.8656	.9675E-05	-5.0143	.7100E+00
2 H2O			.9831E+00	-.0074	.9831E+00
3 F02			.6300E-09 ATM	-9.2007	
4 CL-	.5175E+00	-.2861	.2554E+00	-.5928	.4935E+00
5 SO4--	.2383E-02	-2.6220	.2072E-03	-3.6837	.8695E-01
6 HCO3-	.1344E-02	-3.8716	.7638E-04	-4.1170	.5683E+00
7 SiO2(AQ)	.1007E-01	-1.9971	.1131E-01	-1.9467	.1123E+01
8 AL+++	.1439E-13	-13.8421	.4057E-15	-15.3918	.2620E-01
9 CA++	.4762E-02	-2.3222	.6109E-03	-3.2140	.1783E+00
10 MG++	.2763E-01	-1.5586	.5096E-02	-2.2928	.1844E+00
11 FE++	.8285E-06	-6.0817	.1063E-06	-6.9735	.1283E+00
12 K+	.1782E-01	-1.7491	.8794E-02	-2.0558	.4925E+00
13 NA+	.4397E+00	-.3569	.2399E+00	-.6200	.5455E+00
14 MN++	.1130E-02	-2.9468	.8346E-04	-4.0785	.7383E-01
15 PA++	.8890E-06	-6.0511	.8933E-07	-7.0490	.1005E+00
16 SR++	.3127E-04	-4.5049	.3142E-05	-5.5028	.1005E+00
17 AU+	.4940E-11	-11.3062	.2291E-11	-11.6400	.4637E+00
18 AU+++	.1069E-33	-33.9710	.2616E-36	-36.5504	.2634E-07
19 AUCL2-	.5491E-06	-6.2602	.2496E-06	-6.5235	.5455E+00
20 AUCL4-	.9229E-08	-8.0302	.5089E-08	-8.2934	.5455E+00
21 FE+++	.2529E-11	-11.5970	.7133E-13	-13.1467	.2820E-01
22 OH-	.1097E-05	-5.9597	.5714E-06	-6.2431	.5207E+00
23 H2SiO4-	.9351E-06	-6.0292	.5101E-06	-6.2923	.5455E+00
24 H2SiO4--	.7141E-11	-11.1462	.5272E-12	-12.2780	.7383E-01
25 KSO4-	.3191E-03	-3.4961	.1661E-03	-3.7795	.5207E+00
26 FESO4	.1669E-06	-6.7776	.1874E-06	-6.7272	.1123E+01
27 UO2	.1916E-05	-5.7175	.2152E-05	-5.6671	.1123E+01
28 HSO4-	.6385E-04	-4.1949	.3483E-04	-4.4580	.5455E+00
29 CAOH+	.2992E-06	-6.5239	.1623E-06	-6.7871	.5455E+00
30 MGOH+	.6566E-04	-4.1827	.3582E-04	-4.4458	.5455E+00
31 FECL+	.1981E-05	-5.7021	.1061E-05	-5.9663	.5455E+00
32 FECL++	.1557E-08	-8.8077	.1150E-09	-9.9395	.7383E-01
33 FECL4-	.4112E-09	-9.3860	.3036E-10	-10.5177	.7383E-01
34 FECL3	.6677E-09	-9.1754	.7499E-09	-9.1250	.1123E+01
35 FECL2+	.7779E-09	-9.1091	.4244E-09	-9.3722	.5455E+00
36 FESO4+	.9835E-10	-10.0072	.5365E-10	-10.2704	.5455E+00
37 ALSO4+	.6881E-14	-14.1623	.3754E-14	-14.4255	.5455E+00
38 CO3--	.1897E-08	-8.7220	.1649E-09	-9.7827	.8695E-01
39 H2CO3	.7215E-02	-2.1418	.9103E-02	-2.0914	.1123E+01
40 AL(OH)4-	.1816E-04	-4.7409	.6907E-05	-5.0041	.5455E+00
41 FECH++	.2288E-14	-14.4821	.2428E-15	-15.6148	.7383E-01
42 FECH+	.6406E-07	-7.1934	.3495E-07	-7.4566	.5455E+00
43 ALOH++	.2275E-09	-8.6431	.2918E-09	-9.5349	.1283E+00
44 NAOL	.2862E-01	-1.4131	.4328E-01	-1.3627	.1123E+01

GPC2C-200-5-4 HOURS = 674.0 PH(25) = 4.74
 200 DEGREES C AT 500 BARS AND W/P = 5
 81/02/18.
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 KCL	.5024E-03	-3.2090	.5642E-03	-3.2484	.1123E+01
46 KHSO4	.4128E-05	-5.3843	.4636E-05	-5.3338	.1123E+01
47 CaCO3	.1030E-07	-7.9872	.1157E-07	-7.9367	.1123E+01
48 HNSO4	.1310E-02	-3.8828	.1472E-03	-3.8322	.1123E+01
49 NASO4-	.2035E-02	-2.6914	.1139E-02	-2.9437	.5594E+00
50 HSO4-	.9400E-02	-2.0269	.1056E-01	-1.9765	.1123E+01
51 CASO4	.2582E-03	-3.5881	.2899E-03	-3.5377	.1123E+01
52 NACD3-	.4787E-08	-8.3200	.2801E-08	-8.5527	.5852E+00
53 HPHCO3+	.8382E-04	-4.0767	.4573E-04	-4.3398	.5455E+00
54 CAHCO3+	.1859E-04	-4.7079	.1069E-04	-4.9711	.5455E+00
55 HCO3-	.3511E-17	-17.4546	.3943E-17	-17.4042	.1123E+01
56 BACD3	.5222E-13	-12.2821	.5865E-13	-13.2317	.1123E+01
57 PAHCO3+	.5213E-07	-7.2829	.2844E-07	-7.5461	.5455E+00
58 PAOH+	.1311E-09	-9.8824	.7725E-10	-10.1121	.5892E+00
59 BASO4	.3952E-08	-8.4031	.4439E-08	-8.3527	.1123E+01
60 SROH+	.9635E-10	-10.0161	.5477E-10	-10.2458	.5892E+00
61 SPOD2	.4614E-11	-11.3359	.5182E-11	-11.2855	.1123E+01
62 SRHCO3+	.7644E-05	-5.1167	.4170E-05	-5.3798	.5455E+00
63 SPPO4	.1031E-05	-5.9869	.1158E-05	-5.9265	.1123E+01

GPC3C-200-5-5 MCHRS = 1399.0 PH(25) = 4.05
200 DEGREES C AT 500 BARS AND W/P = 5
01/02/19.

WATER 1.0000(KG.LIQ.) 55.5082(MOLES LIQ.) 55.5083(MOLES TOTAL)
STOICHIOMETRIC IONIC STRENGTH=.6540478E+00 OSMOTIC COEF.= .8453
IONIC STRENGTH=.5659642E+00 ACTIVITY= .9828

FO2 INPUT AS REDOX CONTROL

LOG FO2=-12.10 LOG FH2=-17.14 LOG FH2O= 1.25 LOG FCO2= .22
LOG FH2S= N LOG FS2= N
CALCULATED ACTIVITY HS- = .9095E-58M LOG FH2S=-54.00 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FO2
H2(AQ) CM	.7401E-20	.9321E-20 .1124E+01	.1492E-16	.1658E-18	-17.1378
O2(AQ) CM	.8565E-15	.9630E-15 .1124E+01	.2741E-10	.1919E-13	

CM - MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))?	LOG(A/(A(H+))?)
1 H+	.3447E-04	-4.4613	.8157E-02	.1000E+01	0
2 H2O		-0.0075	.5551E+02		
3 FO2		-12.1024ATM			
4 CL-	.5237E+00	-5.882	.5640E+00	.6317E-05	-5.1995
5 SO4--	.2444E-02	-2.6746	.1469E-01	.1267E-12	-12.8972
6 HCO3-	.5897E-04	-4.4751	.8100E-02	.8197E-09	-9.0864
7 SiO2(AQ)	.2785E-02	-1.9585	.8786E-02	.1100E-01	-1.9585
8 AL+++	.2169E-12	-14.2153	.6672E-05	.4155E+00	-2.814
9 CA++	.4391E-02	-3.2506	.4641E-02	.9375E+06	5.9720
10 MG++	.2669E-01	-2.3087	.3599E-01	.8200E+07	6.9138
11 FE++	.4008E-06	-7.2022	.1791E-05	.1040E+02	2.0202
12 K+	.1844E-01	-2.0416	.1931E-01	.3713E+03	2.5697
13 NA+	.4482E+00	-6.120	.4902E+00	.9984E+04	3.9993
14 MN++	.1004E-02	-4.0048	.1222E-02	.1342E+06	5.1277
15 ZN++	.4996E-07	-8.4442	.2907E-04	.6003E+01	.7784
16 BA++	.1764E-05	-6.7521	.1018E-05	.2948E+03	2.4695
17 SP++	.3403E-04	-5.4678	.2880E-04	.5685E+04	3.7548
18 AU+	.4013E-11	-11.7310	.4569E-06	.7591E-07	-7.1197

GPCPC-200-F-5 MOLES = 1369.0 PH(25) = 4.05
 200 DEGREES C AT 500 PARS AND W/P = F
 91/02/18.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.3447E-04	-4.4625	.2447E-04	-4.6113	.7100E+00
2 H2O			.9828E+00	-.0075	.9828E+00
3 F02			.7900E-12ATM	-12.1024	
4 CL-	.5237E+00	-.2009	.2591E+00	-.5882	.4929E+00
5 SO4--	.2444E-02	-2.6119	.2115E-03	-3.6746	.8655E-01
6 HCO3-	.5897E-04	-4.2293	.3349E-04	-4.4751	.5679E+00
7 SiO2(AQ)	.9755E-02	-2.0094	.1100E-01	-1.9585	.1124E+01
8 AL+++	.2169E-12	-12.6628	.6091E-14	-14.2153	.2808E-01
9 CA++	.4391E-02	-2.3575	.5615E-03	-3.2506	.1279E+00
10 MG++	.2669E-01	-1.5737	.4912E-02	-2.3087	.1840E+00
11 FE++	.4908E-06	-6.2091	.6277E-07	-7.2023	.1279E+00
12 K+	.1844E-01	-1.7342	.9087E-02	-2.0416	.4929E+00
13 NA+	.4482E+00	-.3484	.2444E+00	-.6120	.5451E+00
14 MN++	.1094E-02	-2.0608	.8038E-04	-4.0948	.7345E-01
15 ZN++	.4896E-07	-7.3102	.3506E-08	-8.4442	.7345E-01
16 PA++	.1764E-05	-5.7524	.1766E-06	-6.7531	.1001E+00
17 SR++	.3403E-04	-4.4682	.3406E-05	-5.4679	.1001E+00
18 AU+	.4013E-11	-11.3965	.1858E-11	-11.7310	.4629E+00
19 AU+++	.1991E-34	-34.7010	.5179E-37	-37.2856	.2601E-02
20 AMCL2-	.4551E-06	-6.3419	.2481E-06	-6.6054	.5451E+00
21 AMCL4-	.1790E-08	-8.7471	.9757E-09	-9.0107	.5451E+00
22 FE+++	.7143E-12	-12.1461	.2806E-13	-13.6977	.2808E-01
23 OH-	.4342E-06	-6.3623	.2258E-06	-6.6462	.5201E+00
24 H2SiO4-	.3600E-06	-6.4427	.1962E-06	-6.7073	.5451E+00
25 H2SiO4--	.1092E-11	-11.9619	.8017E-13	-13.0960	.7345E-01
26 KSO4-	.3370E-02	-3.4723	.1753E-03	-3.7562	.5201E+00
27 FES04	.1005E-06	-6.9978	.1130E-06	-6.9469	.1124E+01
28 HCL	.4893E-05	-5.2104	.5502E-05	-5.2595	.1124E+01
29 HSO4-	.1651E-02	-3.7824	.8997E-04	-4.0459	.5451E+00
30 CAGH+	.1088E-06	-6.9623	.5931E-07	-7.2268	.5451E+00
31 MG0H+	.2504E-04	-4.6014	.1365E-04	-4.8650	.5451E+00
32 FECL+	.1183E-05	-5.9269	.6449E-06	-6.1905	.5451E+00
33 FECL++	.4448E-09	-9.3519	.3267E-10	-10.4859	.7345E-01
34 FECL4-	.1212E-09	-9.9165	.8901E-11	-11.0506	.7345E-01
35 FECL3	.1935E-09	-9.7132	.2176E-09	-9.6623	.1124E+01
36 FECL2+	.2236E-09	-9.6506	.1219E-09	-9.9141	.5451E+00
37 FES04+	.2827E-10	-10.5487	.1541E-10	-10.8123	.5451E+00
38 ZNCL+	.9575E-07	-7.0188	.5219E-07	-7.2824	.5451E+00
39 ZNCL2	.3967E-07	-7.4015	.4460E-07	-7.3506	.1124E+01
40 ZNCL3-	.7157E-05	-5.1453	.3901E-05	-5.4089	.5451E+00
41 ZNCL4--	.2172E-04	-4.6621	.1596E-05	-5.7971	.7345E-01
42 AL2O4+	.1056E-12	-12.9764	.5755E-13	-13.2399	.5451E+00
43 CO3--	.2303E-09	-9.4811	.2859E-10	-10.5438	.8655E-01
44 H2CO3	.7994E-02	-2.0972	.8988E-02	-2.0464	.1124E+01

GPC3C-200-5-F HOURS = 1389.0 PH(25) = 4.05
 200 DEGREES C AT 500 RAPS AND W/P = F
 21/02/19.
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 AL(OH)4-	.6459E-05	-5.1767	.3629E-05	-5.4402	.5451E+00
46 FFCH++	.3674E-15	-15.4349	.2698E-16	-16.5689	.7345E-01
47 FFCH+	.1496E-07	-7.8249	.8157E-08	-8.0885	.5451E+00
48 ALCH++	.1354E-07	-7.8684	.1732E-08	-8.7615	.1279E+00
49 NaCl	.3971E-01	-1.4011	.4465E-01	-1.3502	.1124E+01
50 KCl	.5240E-03	-2.2807	.5891E-03	-3.2298	.1124E+01
51 KHSO4	.1101E-04	-4.9584	.1237E-04	-4.9075	.1124E+01
52 CaCO3	.1764E-08	-8.7853	.1843E-08	-8.7344	.1124E+01
53 MnSO4	.1287E-03	-3.8904	.1447E-03	-3.8295	.1124E+01
54 NaSO4-	.2119E-02	-2.6740	.1184E-02	-2.9266	.5590E+00
55 MgSO4	.0241E-02	-2.0343	.1034E-01	-1.9834	.1124E+01
56 CaSO4	.2420E-02	-3.6161	.2721E-03	-3.5653	.1124E+01
57 NaCO3-	.8457E-09	-9.0728	.4946E-09	-9.3057	.5848E+00
58 MgHCO3+	.2546E-04	-4.4503	.1633E-04	-4.7138	.5451E+00
59 CaHCO3+	.7904E-05	-5.1021	.4308E-05	-5.3657	.5451E+00
60 MgCO3	.3750E-17	-17.4260	.4216E-17	-17.2751	.1124E+01
61 BaCO3	.1788E-13	-13.7477	.7010E-13	-13.6260	.1124E+01
62 BaHCO3+	.4523E-07	-7.3446	.2465E-07	-7.6081	.5451E+00
63 BaOH+	.1025E-09	-9.9892	.6036E-10	-10.2193	.5889E+00
64 BaSO4	.7969E-08	-8.0986	.8960E-08	-8.0477	.1124E+01
65 SrOH+	.4130E-10	-10.3841	.7432E-10	-10.6140	.5889E+00
66 SrCO3	.8660E-12	-12.0625	.9737E-12	-12.0116	.1124E+01
67 SrHCO3+	.3636E-05	-5.4393	.1982E-05	-5.7029	.5451E+00
68 SrSO4	.1139E-05	-5.9433	.1281E-05	-5.8924	.1124E+01

GPCRB-200-5-1 HOURS = 3.00 PH(25) = 4.8
200 DEGREES C AT 500 BARS AND W/P = 5
91/02/18.

WATER 1.0000(KG.LIQ.) 55.5081(MOLES LIQ.) 55.5083(MOLES TOTAL)
STOICHIOMETRIC IONIC STRENGTH=.6210155E+00 OSMOTIC COEF.= .8389
IONIC STRENGTH=.5385089E+00 ACTIVITY=.9844

FO2 INPUT AS REDOX CONTROL

LOG FO2=-13.00 LOG FH2=-16.69 LOG FH2O= 1.25 LOG FCO2= -.04
LOG FH2S= N LOG FS2= N
CALCULATED ACTIVITY HS- = .1975E-56M LOG FH2S=-53.04 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FO2
H2(AQ) CM	.2095E-19	.2343E-19 .1116E+01	.4224E-16	.4694E-18	-16.6893
O2(AQ) CM	.1090E-15	.1219E-15 .1118E+01	.3489E-11	.2442E-14	

CM - MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))Z	LOG(A/(A(H+))Z)
1 H+	.1449E-04	-4.9876	.4330E-02	.1000E+01	0
2 H2O		-.0068	.5551E+02		
3 FO2		-13.9000ATM			
4 CL-	.4870E+00	-.6165	.5202E+00	.2488E-05	-5.6041
5 SO4--	.1973E-02	-3.7569	.1459E-01	.1853E-13	-13.7321
6 HCO3-	.7607E-04	-4.3628	.4540E-02	.4463E-09	-9.3504
7 SiO2(AQ)	.5907E-02	-2.1802	.5908E-02	.5604E-02	-2.1802
8 AL+++	.1030E-13	-15.5286	.1038E-04	.2718E+00	-.5657
9 CA++	.7706E-02	-2.0990	.8084E-02	.9468E+07	6.9763
10 MG++	.3592E-01	-2.1763	.4640E-01	.6295E+08	7.7990
11 FE++	.1520E-05	-6.7039	.5372E-05	.1868E+04	3.2713
12 K+	.1587E-01	-2.1033	.1655E-01	.7661E+03	7.8843
13 NA+	.3897E+00	-.6707	.4239E+00	.2075E+05	4.3169
14 MN++	.1902E-04	-5.8424	.2093E-04	.1358E+05	4.1326
15 ZN++	.4894E-07	-8.4319	.2295E-04	.3494E+02	1.5434
16 BA++	.7707E-06	-7.1033	.7998E-06	.7447E+03	2.8720
17 SR++	.4685E-04	-5.3194	.5478E-04	.4527E+05	4.6558
18 AU+	.1015E-11	-12.3239	.1015E-06	.4610E-07	-7.3362

GPO3R-200-F-1 H2O2S = 3.00 PH(25) = 4.8
200 DEGREES C AT 500 BARS AND W/P = F
81/02/1E.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.1449E-04	-4.8388	.1029E-04	-4.9876	.7099E+00
2 H2O			.9844E+00	-.0068	.9844E+00
3 F02			.1000E-12ATM	-13.0000	
4 CL-	.4870E+00	-.3124	.2418E+00	-.6165	.4966E+00
5 SO4--	.1973E-02	-2.7050	.1750E-03	-3.7569	.8874E-01
6 HCO3-	.7607E-04	-4.1188	.4337E-04	-4.3628	.5702E+00
7 ST02(AO)	.5907E-02	-2.2286	.6604E-02	-2.1802	.1118E+01
8 AL+++	.1030E-13	-13.9871	.2961E-15	-15.5286	.2874E-01
9 CA++	.7706E-02	-2.1132	.1002E-02	-2.9990	.1301E+00
10 MG++	.3582E-01	-1.4459	.6664E-02	-2.1763	.1860E+00
11 FE++	.1520E-05	-5.8181	.1977E-06	-6.7039	.1301E+00
12 K+	.1597E-01	-1.7993	.7883E-02	-2.1033	.4966E+00
13 NA+	.3897E+00	-.4093	.2134E+00	-.6707	.5478E+00
14 MN++	.1902E-04	-4.7209	.1437E-05	-5.8424	.7558E-01
15 7N++	.4894E-07	-7.3103	.3699E-08	-8.4319	.7558E-01
16 BA++	.7707E-06	-6.1131	.7883E-07	-7.1033	.1023E+00
17 SR++	.4685E-04	-4.3293	.4793E-05	-5.3194	.1023E+00
18 AU+	.1015E-11	-11.9935	.4743E-12	-12.3239	.4672E+00
19 AU+++	.2972E-36	-36.5270	.8276E-39	-39.0822	.2785E-02
20 AUCL2-	.1015E-06	-6.9935	.5561E-07	-7.2549	.5478E+00
21 AUCL4-	.2195E-10	-10.6586	.1202E-10	-10.9200	.5478E+00
22 FE+++	.5501E-12	-12.2595	.1581E-13	-13.8010	.2874E-01
23 OH-	.1028E-05	-5.9879	.5380E-06	-6.2692	.5233E+00
24 H3ST04-	.5115E-06	-6.2911	.2902E-06	-6.5526	.5478E+00
25 H2ST04--	.3603E-11	-11.4434	.2723E-12	-12.5649	.7558E-01
26 KSO4-	.2405E-03	-3.6189	.1258E-03	-3.9002	.5233E+00
27 FES04	.2635E-06	-6.5792	.2946E-06	-6.5308	.1118E+01
28 HCL	.1939E-05	-5.7125	.2167E-05	-5.6641	.1118E+01
29 HSO4-	.5714E-04	-4.2431	.3130E-04	-4.5045	.5478E+00
30 CAOH+	.4605E-06	-6.3368	.2523E-06	-6.5982	.5478E+00
31 MGOH+	.8053E-04	-4.0941	.4411E-04	-4.3555	.5478E+00
32 FECL+	.2476E-05	-5.4590	.1904E-05	-5.7204	.5478E+00
33 FECL++	.2192E-09	-9.4959	.2413E-10	-10.6175	.7558E-01
34 FECL4-	.7156E-10	-10.1453	.5409E-11	-11.2669	.7558E-01
35 FECL3	.1262E-09	-9.8985	.1411E-09	-9.8504	.1118E+01
36 FECL2+	.1540E-09	-9.8126	.8434E-10	-10.0740	.5478E+00
37 FFS04+	.1834E-10	-10.7365	.1005E-10	-10.9979	.5478E+00
38 7NCL+	.9185E-07	-7.0369	.5031E-07	-7.2984	.5478E+00
39 7NCL2	.3604E-07	-7.4432	.4029E-07	-7.3948	.1118E+01
40 7NCL3-	.6027E-05	-5.2199	.3302E-05	-5.4813	.5478E+00
41 7NCL4--	.1674E-04	-4.7762	.1265E-05	-5.8978	.7558E-01
42 ALS04+	.4226E-14	-14.3741	.2315E-14	-14.6355	.5478E+00
43 CO3--	.9925E-09	-9.0032	.8808E-10	-10.0551	.8874E-01
44 H2CO3	.4377E-02	-2.3588	.4893E-02	-2.3104	.1118E+01

GPC3R-200-F-1 HOURS = 3.00 PH(25) = 4.8
 200 DEGREES C AT 500 BARS AND W/P = 5
 81/02/18.
 (CONTINUED)

SPECIES	MOLALITY	LOG (M)	ACTIVITY	LOG(A)	GAMMA
45 AL(OH)4-	.1038E-04	-4.9839	.5684E-05	-5.2454	.5478E+00
46 FEOH++	.6704E-15	-15.1737	.5067E-16	-16.2952	.7558E-01
47 FEOH+	.1118E-06	-6.9517	.6122E-07	-7.2131	.5478E+00
48 AL(OH)++	.1542E-08	-8.8120	.2005E-09	-9.6976	.1301E+00
49 NaCl	.3269E-01	-1.4656	.3654E-01	-1.4372	.1118E+01
50 KCl	.4283E-03	-3.3662	.4789E-03	-3.3198	.1118E+01
51 KHSO4	.3340E-05	-5.4762	.3734E-05	-5.4278	.1118E+01
52 CaCO3	.9067E-08	-8.0425	.1014E-07	-7.9941	.1118E+01
53 MnSO4	.1916E-05	-5.7177	.2141E-05	-5.6693	.1118E+01
54 NaSO4-	.1525E-02	-2.8169	.8559E-03	-3.0676	.5614E+00
55 MgSO4	.1042E-01	-1.9816	.1166E-01	-1.9331	.1118E+01
56 CaSO4	.3595E-03	-3.4442	.4019E-03	-3.3958	.1118E+01
57 NaCO3-	.2268E-08	-8.6443	.1331E-08	-8.8758	.5868E+00
58 MgHCO3+	.6199E-04	-4.2076	.3396E-04	-4.4691	.5478E+00
59 CaHCO3+	.1818E-04	-4.7402	.9960E-05	-5.0017	.5478E+00
60 MgCO3	.2785E-17	-17.5551	.3114E-17	-17.5067	.1118E+01
61 BaCO3	.2473E-13	-13.6069	.2764E-13	-13.5584	.1118E+01
62 BaHCO3+	.2602E-07	-7.5847	.1425E-07	-7.8461	.5478E+00
63 BaOH+	.1087E-09	-9.9639	.6420E-10	-10.1925	.5908E+00
64 BaSO4	.2061E-08	-8.5284	.3310E-08	-8.4802	.1118E+01
65 SrOH+	.1380E-09	-9.8601	.8154E-10	-10.0686	.5908E+00
66 SrCO3	.3776E-11	-11.4230	.4221E-11	-11.3746	.1118E+01
67 SrHCO3+	.6505E-05	-5.1908	.3612E-05	-5.4422	.5478E+00
68 SrSO4	.1334E-05	-5.8747	.1492E-05	-5.8263	.1118E+01

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60038-200-5-2 HOURS = 74.50 PH(25) = 5.1
200 DEGREES C AT 500 BARS AND W/P = 5
91/02/19.

+++++

WATER 1.0000(KG.LIQ.) 55.5081(MOLES LIQ.) 55.5083(MOLES TOTAL)
STOICHIOMETRIC IONIC STRENGTH=.5821849E+00 OSMOTIC COEF.= .8437
IONIC STRENGTH=.5186245E+00 ACTIVITY=.9850

FO2 INPUT AS PEOX CONTROL

LOG FO2=-10.30 LOG FH2=-18.04 LOG FH2O= 1.25 LOG FCO2= .11
LOG FH2S= N LOG FS2= N
CALCULATED ACTIVITY HS- = .2382E-62M LOG FH2S=-59.28 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FO2
H2(AQ) CM	.9415E-21	.1048E-20 .1113E+01	.1898E-17	.2109E-19	-18.0376
O2(AQ) CM	.5474E-13	.6095E-13 .1113E+01	.1752E-08	.1226E-11	

CM - MOLALITY CALCULATED FROM PEOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))Z	LOG(A/(AH)Z)
1 H+	.6975E-05	-5.3052	.6041E-02	.1000E+01	0
2 H2O		-.0066	.5551E+02		
3 FO2		-10.3010ATM			
4 CL-	.4730E+00	-.6267	.5047E+00	.1170E-05	-5.9319
5 SO4--	.1213E-02	-3.9599	.8765E-02	.2690E-14	-14.5703
6 HCO3-	.2229E-03	-3.8946	.6670E-02	.6312E-09	-9.1998
7 SiO2(AQ)	.9368E-02	-1.9817	.9369E-02	.1043E-01	-1.9817
8 AL+++	.5052E-15	-16.8303	.9637E-05	.1217E+00	-.9147
9 CA++	.6762E-02	-3.0501	.7011E-02	.3633E+08	7.5603
10 MG++	.2378E-01	-2.1982	.4035E-01	.2583E+09	8.4122
11 FE++	.1526E-05	-6.6965	.5372E-05	.8201E+04	3.9139
12 K+	.1671E-01	-2.0786	.1731E-01	.1665E+04	3.2266
13 NA+	.3784E+00	-.6818	.4106E+00	.4201E+05	4.6234
14 MN++	.6838E-04	-5.2772	.7281E-04	.2154E+06	5.3332
15 ZN++	.2090E-07	-8.7919	.9026E-05	.6584E+02	1.8185
16 BA++	.1977E-06	-7.6869	.2181E-06	.8384E+03	2.9235
17 SR++	.2462E-04	-5.5917	.2538E-04	.1044E+06	5.0187
18 AU+	.2649E-11	-11.9043	.2538E-06	.2517E-06	-6.5991

GPC3P-200-5-2 HCLPS = 74.50 PH(25) = 5.1
 200 DEGREE C AT 500 BARS AND W/P = F
 R1/02/10

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.6975E-05	-5.1564	.4952E-05	-5.3052	.7100E+00
2 H2O			.9850E+00	-.0066	.9850E+00
3 F02			.5000E-10 ATM	-10.2010	
4 CL-	.4730E+00	-.3251	.2362E+00	-.6267	.4994E+00
5 SO4--	.1213E-02	-2.9163	.1097E-03	-3.9599	.9044E-01
6 HCO3-	.2229E-03	-3.6520	.1275E-03	-3.8946	.5720E+00
7 SIO2(AQ)	.9368E-02	-2.0284	.1043E-01	-1.9817	.1113E+01
8 AL+++	.5052E-15	-15.2066	.1478E-16	-16.8303	.2926E-01
9 CA++	.6762E-02	-2.1699	.8911E-03	-3.0501	.1318E+00
10 MG++	.3378E-01	-1.4714	.6326E-02	-2.1982	.1876E+00
11 FE++	.1526E-05	-5.8164	.2011E-06	-6.6965	.1318E+00
12 K+	.1671E-01	-1.7770	.8345E-02	-2.0786	.4994E+00
13 NA+	.3784E+00	-.4221	.2081E+00	-.6818	.5499E+00
14 MN++	.6838E-04	-4.1651	.5282E-05	-5.2772	.7725E-01
15 ZN++	.2090E-07	-7.6798	.1615E-08	-8.7919	.7725E-01
16 BA++	.1977E-06	-6.7040	.2056E-07	-7.6869	.1040E+00
17 SP++	.2462E-04	-4.6088	.2560E-05	-5.5917	.1040E+00
18 AU+	.2649E-11	-11.5769	.1247E-11	-11.9043	.4705E+00
19 AU+++	.3831E-35	-35.4166	.1124E-37	-37.9493	.2933E-02
20 AUCL2-	.2536E-06	-6.5959	.1304E-06	-6.8556	.5499E+00
21 AUCL4-	.2702E-09	-9.5683	.1486E-09	-9.8280	.5499E+00
22 FE+++	.1249E-11	-11.9033	.3656E-13	-13.4370	.2926E-01
23 OH-	.2127E-05	-5.6727	.1118E-05	-5.9514	.5258E+00
24 H2SIO4-	.1672E-05	-5.7768	.9193E-06	-6.0365	.5499E+00
25 H2SIO4--	.2403E-10	-10.6192	.1856E-11	-11.7313	.7725E-01
26 KSO4-	.1588E-03	-3.7993	.8347E-04	-4.0785	.5258E+00
27 FESO4	.1686E-06	-6.7731	.1877E-06	-6.7264	.1113E+01
28 HCL	.9152E-06	-6.0385	.1019E-05	-5.9919	.1113E+01
29 HSO4-	.1717E-04	-4.7654	.9439E-05	-5.0251	.5499E+00
30 CADH+	.8478E-06	-6.0717	.4662E-06	-6.3315	.5499E+00
31 MGDH+	.1586E-03	-3.7998	.8718E-04	-4.0596	.5499E+00
32 FECL+	.3440E-05	-5.4635	.1891E-05	-5.7232	.5499E+00
33 FECL++	.7053E-09	-9.1516	.5449E-10	-10.2637	.7725E-01
34 FECL4-	.1473E-09	-9.8317	.1138E-10	-10.9437	.7725E-01
35 FECL3	.2731E-09	-9.5637	.3040E-09	-9.5171	.1113E+01
36 FECL2+	.3383E-09	-9.4707	.1860E-09	-9.7304	.5499E+00
37 FESO4+	.2647E-10	-10.5772	.1456E-10	-10.8369	.5499E+00
38 ZNCL+	.3901E-07	-7.4089	.2145E-07	-7.6686	.5499E+00
39 ZNCL2-	.1507E-07	-7.8219	.1678E-07	-7.7753	.1113E+01
40 ZNCL3-	.2442E-05	-5.6122	.1343E-05	-5.8719	.5499E+00
41 ZNCL4--	.6508E-05	-5.1865	.5028E-06	-6.2986	.7725E-01
42 AISO4+	.1217E-15	-15.8805	.7241E-16	-16.1402	.5499E+00
43 CO3--	.5946E-08	-8.2258	.5378E-09	-9.2694	.9044E-01
44 H2CO3	.6217E-02	-2.2064	.6921E-02	-2.1598	.1113E+01

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GPC3R-200-5-2 HOURS = 74.50 PH(25) = 5.1
 200 DEGREES C AT 500 BAPS AND W/P = F
 91/02/18.
 (CONTINUED)

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SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 AL(OH) ₃ -	.0437E-05	-5.0161	.5299E-05	-5.2758	.5499E+00
46 FEOH ⁺⁺	.3153E-14	-14.5013	.2435E-15	-15.6134	.7725E-01
47 FEOH ⁺	.2354E-06	-6.6282	.1294E-06	-6.8879	.5499E+00
48 AL(OH) ⁺⁺	.1579E-09	-9.8016	.2081E-10	-10.6817	.1318E+00
49 NaCl	.3125E-01	-1.5051	.3480E-01	-1.4585	.1113E+01
50 KCl	.4448E-03	-3.2519	.4952E-03	-3.3053	.1113E+01
51 KHSO ₄	.1071E-05	-5.9703	.1192E-05	-5.9237	.1113E+01
52 CaCO ₃	.4942E-07	-7.3061	.5502E-07	-7.2595	.1113E+01
53 MnSO ₄	.4429E-05	-5.3527	.4921E-05	-5.3071	.1113E+01
54 NaSO ₄ -	.9279E-03	-3.0325	.5228E-03	-3.2817	.5634E+00
55 MgSO ₄	.6242E-02	-2.2047	.6849E-02	-2.1581	.1113E+01
56 CaSO ₄	.2011E-03	-3.6966	.2239E-03	-3.6500	.1113E+01
57 NaCO ₃ -	.1346E-07	-7.8709	.7921E-08	-8.1012	.5884E+00
58 MgHCO ₃ ⁺	.1726E-03	-2.7630	.5489E-04	-4.0228	.5499E+00
59 CaHCO ₃ ⁺	.4732E-04	-4.3249	.2602E-04	-4.5847	.5499E+00
60 MgCO ₃	.3762E-17	-17.4246	.4188E-17	-17.3780	.1113E+01
61 BaCO ₃	.3954E-13	-13.4030	.4402E-13	-13.3563	.1113E+01
62 BaHCO ₃ ⁺	.1987E-07	-7.7018	.1093E-07	-7.9615	.5499E+00
63 BaOH ⁺	.5877E-10	-10.2308	.3481E-10	-10.4583	.5923E+00
64 BaSO ₄	.4859E-09	-9.3134	.5410E-09	-9.2668	.1113E+01
65 SrOH ⁺	.1529E-09	-9.8156	.6056E-10	-10.0431	.5923E+00
66 SrCO ₃	.1237E-10	-10.9077	.1377E-10	-10.8611	.1113E+01
67 SrHCO ₃ ⁺	.1031E-04	-4.9866	.5672E-05	-5.2463	.5499E+00
68 SrSO ₄	.4485E-06	-6.3482	.4994E-06	-6.3016	.1113E+01

GPC3B-200-5-3 HOURS = 267.50 PH(25) = 4.6
200 DEGREES C AT 500 BARS AND W/P = 5
R1/02/18.

WATER 1.0000(KG.LIQ.) 55.5082(MOLES LIQ.) 55.5083(MOLES TOTAL)
STOICHIOMETRIC IONIC STRENGTH=.5886072E+00 OSMOTIC COEF.= .8452
TONIC STRENGTH=.5256796E+00 ACTIVITY=.9846

FO2 INPUT AS PFD0X CONTROL

LOG FO2=-12.00 LOG FH2=-17.19 LOG FH2O= 1.25 LOG FCO2= .13
LOG FH2S= N LOG FS2= N
CALCULATED ACTIVITY HS- = .1759E-58 LOG FH2S=-54.93 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FO2
H2(AQ) CM	.6645E-20	.7409E-20 .1115E+01	.1340E-16	.1489E-18	-17.1682
O2(AQ) CM	.1093E-14	.1210E-14 .1115E+01	.3498E-10	.2449E-13	

CM - MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))Z	LOG(A/(AH)Z)
1 H+	.2126E-04	-4.8211	.6604E-02	.1000E+01	- .0000
2 H2O		-.0067	.5551E+02		
3 FO2		-12.0000ATM			
4 CL-	.4819E+00	-.6195	.5151E+00	.3626E-05	-5.4406
5 SO4--	.1183E-02	-3.9736	.8297E-02	.2422E-13	-13.6158
6 HCO3-	.7796E-04	-4.3512	.6770E-02	.6724E-09	-9.1723
7 SiO2(AQ)	.1008E-01	-1.9491	.1009E-01	.1124E-01	-1.9491
8 AL+++	.4051E-13	-14.9290	.8895E-05	.3423E+00	-4.6656
9 CA++	.6412E-02	-3.0752	.6612E-02	.3690E+07	6.5671
10 MG++	.3244E-01	-2.2170	.3833E-01	.2662E+08	7.4252
11 FE++	.5983E-05	-6.1053	.2059E-04	.3443E+04	3.5369
12 K+	.1742E-01	-2.0613	.1806E-01	.5752E+03	2.7598
13 NA+	.3900E+00	-.6693	.4235E+00	.1418E+05	4.1518
14 MN++	.7197E-04	-5.2583	.7645E-04	.2420E+05	4.3839
15 ZN++	.6009E-07	-8.3367	.2754E-04	.2021E+02	1.3055
16 BA++	.9111E-06	-7.0260	.9452E-06	.4133E+03	2.6163
17 SP++	.3876E-04	-5.4028	.4451E-04	.1736E+05	4.2395
18 AU+	.2565E-11	-11.9194	.2538E-06	.7975E-07	-7.0963

GPC3B-200-5-3 HOURS = 267.50 PH(2F) = 4.6
 200 DEGPFFS C AT 500 BARS AND W/P = 5
 81/02/18.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.2126E-04	-4.6724	.1510E-04	-4.8211	.7100E+00
2 H2O			.9846E+00	-1.0067	.9846E+00
3 F02			.1000E-11ATM	-12.0000	
4 CL-	.4819E+00	-3.3171	.2402E+00	-3.6195	.4984E+00
5 SO4--	.1183E-02	-2.9270	.1063E-03	-3.9736	.8983E-01
6 HCO3-	.7796E-04	-4.1081	.4454E-04	-4.3512	.5713E+00
7 SiO2(AQ)	.1008E-01	-1.9963	.1124E-01	-1.9491	.1115E+01
8 AL+++	.4051E-12	-13.3924	.1178E-14	-14.9290	.2907E-01
9 CA++	.6412E-02	-2.1930	.8411E-03	-3.0752	.1312E+00
10 MG++	.3244E-01	-1.4889	.6068E-02	-2.2170	.1870E+00
11 FE++	.5983E-05	-5.2231	.7847E-06	-6.1053	.1312E+00
12 K+	.1742E-01	-1.7589	.8683E-02	-2.0613	.4984E+00
13 NA+	.3900E+00	-4.4090	.2141E+00	-3.6693	.5491E+00
14 MN++	.7197E-04	-4.1428	.5516E-05	-5.2583	.7665E-01
15 ZN++	.6009E-07	-7.2212	.4606E-08	-8.3367	.7665E-01
16 BA++	.9111E-06	-6.0404	.9419E-07	-7.0260	.1034E+00
17 SP++	.3826E-04	-4.4172	.3956E-05	-5.4028	.1034E+00
18 AU+	.2565E-11	-11.5909	.1204E-11	-11.9194	.4694E+00
19 AU+++	.4960E-35	-35.3045	.1428E-37	-37.8453	.2879E-02
20 AUCL2-	.2535E-06	-6.5961	.1392E-06	-6.8564	.5491E+00
21 AUCL4-	.7673E-09	-9.4350	.2017E-09	-9.6953	.5491E+00
22 FE+++	.5628E-11	-11.2497	.1636E-12	-12.7862	.2907E-01
23 OH-	.6988E-06	-6.1557	.3668E-06	-6.4356	.5249E+00
24 H2SiO4-	.5921E-06	-6.2276	.3251E-06	-6.4880	.5491E+00
25 H2SiO4--	.2810E-11	-11.5512	.2154E-12	-12.6668	.7665E-01
26 KSO4-	.1603E-03	-3.7950	.8416E-04	-4.0749	.5249E+00
27 FES04	.6366E-06	-6.1961	.7098E-06	-6.1489	.1115E+01
28 HCL	.2932E-05	-5.5479	.3158E-05	-5.5006	.1115E+01
29 HSO4-	.5078E-04	-4.2943	.2788E-04	-4.5547	.5491E+00
30 CADH+	.2628E-06	-6.5804	.1443E-06	-6.8408	.5491E+00
31 MGDH+	.4986E-04	-4.2022	.2738E-04	-4.5626	.5491E+00
32 FECL+	.1366E-04	-4.8644	.7503E-05	-5.1248	.5491E+00
33 FECL++	.2234E-09	-8.4902	.2479E-09	-9.6057	.7665E-01
34 FECL4-	.7100E-09	-9.1487	.5442E-10	-10.2642	.7665E-01
35 FECL3	.1282E-08	-8.8920	.1430E-08	-8.8447	.1115E+01
36 FECL2+	.1567E-08	-8.8049	.8605E-09	-9.0652	.5491E+00
37 FES04+	.1150E-09	-9.9395	.6312E-10	-10.1998	.5491E+00
38 ZNCL+	.1133E-06	-6.9459	.6220E-07	-7.2062	.5491E+00
39 ZNCL2	.4436E-07	-7.3530	.4946E-07	-7.3057	.1115E+01
40 ZNCL3-	.7330E-05	-5.1349	.4025E-05	-5.3952	.5491E+00
41 ZNCL4--	.1999E-04	-4.6992	.1532E-05	-5.8147	.7665E-01
42 ALS04+	.1018E-12	-13.9922	.5561E-14	-14.2525	.5491E+00
43 CO2--	.6863E-09	-9.1635	.6164E-10	-10.2101	.6983E-01
44 H2CO3	.6613E-02	-2.1796	.7373E-02	-2.1323	.1115E+01

GPC3B-200-5-3. HOURS = 267.50 PH(25) = 4.6
 200 DEGREES C AT 500 BARS AND W/P = 5
 P1/02/18.
 (CONTINUED)

SPECTRS	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 AL(OH)4-	.8891E-05	-5.0510	.4882E-05	-5.3114	.5491E+00
46 FEOH+	.4663E-14	-14.3313	.3574E-15	-15.4468	.7665E-01
47 FEOH+	.3016E-06	-6.5206	.1656E-06	-6.7800	.5491E+00
48 AL(OH)4-	.4146E-08	-8.3824	.5438E-09	-9.2646	.1312E+00
49 NaCl	.3265E-01	-1.4861	.3641E-01	-1.4388	.1115E+01
50 KCl	.4698E-03	-3.3281	.5238E-03	-3.2808	.1115E+01
51 KHSO4	.3286E-05	-5.4833	.3664E-05	-5.4360	.1115E+01
52 CaCO3	.5339E-08	-8.2725	.5953E-08	-8.2253	.1115E+01
53 MnSO4	.4475E-05	-5.3492	.4990E-05	-5.3019	.1115E+01
54 NaSO4-	.9265E-03	-3.0331	.5213E-03	-3.2829	.5627E+00
55 MgSO4	.5783E-02	-2.2378	.6448E-02	-2.1906	.1115E+01
56 CaSO4	.1837E-03	-3.7360	.2048E-03	-3.6887	.1115E+01
57 NaCO3-	.1590E-09	-8.7987	.9345E-09	-9.0294	.5878E+00
58 MgHCO3+	.5783E-04	-4.2379	.3175E-04	-4.4982	.5491E+00
59 CaHCO3+	.1563E-04	-4.8060	.6582E-05	-5.0664	.5491E+00
60 MgCO3	.3932E-17	-17.4166	.4272E-17	-17.3693	.1115E+01
61 NaCO3	.2072E-13	-13.6823	.2312E-13	-13.6361	.1115E+01
62 BaHCO3+	.3185E-07	-7.4969	.1749E-07	-7.7572	.5491E+00
63 PAOH+	.8836E-10	-10.0537	.5229E-10	-10.2816	.5918E+00
64 RASO4	.2154E-08	-8.6668	.2401E-08	-8.6156	.1115E+01
65 SPOH+	.7752E-10	-10.1105	.4588E-10	-10.3384	.5918E+00
66 SPOH+	.2187E-11	-11.6601	.2439E-11	-11.6129	.1115E+01
67 SPOHCO3+	.5577E-05	-5.2526	.3062E-05	-5.5140	.5491E+00
68 SRSO4	.6705E-06	-6.1736	.7476E-06	-6.1263	.1115E+01

GPC3E-200-5-4 HOURS = 602.50 PH(25) = 4.2
200 DEGREES C AT 500 PARS AND W/P = 5
P1/02/1F.

WATER 1.0000(KG.LIQ.) 55.5082(MOLES LIQ.) 55.5082(MOLES TOTAL)
STOICHIOMETRIC IONIC STRENGTH=.5668483E+00 OSMOTIC COEF.= .8467
IONIC STRENGTH=.5322779E+00 ACTIVITY=.9843

FO2 INPUT AS REDOX CONTROL

LOG FO2=-12.30 LOG FH2=-17.04 LOG FH2C= 1.25 LOG FCO2= .18
LOG FH2S= N LOG FS2= N
CALCULATED ACTIVITY HS- = .1347E-57M LOG FH2S=-53.78 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FO2
H2(AO) CM	.9382E-20	.1047E-19 .1114E+01	.1891E-16	.2101E-18	-17.0379
O2(AO) CM	.5450E-15	.6095E-15 .1116E+01	.1747E-10	.1223E-13	

CM -- MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))Z	LOG(A/(AH)Z)
1 H+	.3844E-04	-4.5640	.7437E-02	.1000E+01	0
2 H2O		-.0069	.5551E+02		
3 FO2		-12.3010ATM			
4 CL-	.4902E+00	-.6129	.5250E+00	.6654E-05	-5.1769
5 SO4--	.1261E-02	-3.9487	.8401E-02	.8379E-13	-13.0768
6 HCO3-	.4802E-04	-4.5621	.7440E-02	.7479E-09	-9.1261
7 SiO2(AO)	.8870E-02	-2.0042	.9870E-02	.9903E-02	-2.0042
8 Al+++	.3437E-12	-14.0030	.7042E-05	.4888E+00	-.3109
9 Ca++	.6699E-02	-3.0580	.6911E-02	.1175E+07	6.0700
10 Mg++	.3004E-01	-2.2516	.3574E-01	.7524E+07	6.8764
11 Fe++	.1504E-04	-5.7069	.5192E-04	.2637E+04	3.4211
12 K+	.1694E-01	-2.0744	.1757E-01	.3087E+03	2.4896
13 Na+	.4032E+00	-.6554	.4384E+00	.8104E+04	3.9087
14 MN++	.0910E-04	-5.1226	.1056E-03	.1013E+05	4.0055
15 Zn++	.7584E-07	-8.2387	.2671E-04	.7751E+01	.8893
16 Ba++	.1917E-05	-6.7053	.1963E-05	.2647E+03	2.4228
17 Sr++	.4224E-04	-5.3622	.4670E-04	.5833E+04	3.7659
18 AU+	.3480E-11	-11.7870	.3554E-06	.5972E-07	-7.2239

GPC3B-200-5-4 HOURS = 602.50 PH(25) = 4.3
200 DEGREES C AT 500 BARS AND W/R = 5
81/02/18.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.3844E-04	-4.4153	.2729E-04	-4.5640	.7099E+00
2 H2O			.9843E+00	-.0069	.9843E+00
3 F02			.5000E-12 ATM	-12.3010	
4 CL-	.4902E+00	-.3096	.2438E+00	-.6129	.4974E+00
5 SO4--	.1261E-02	-2.8994	.1125E-03	-3.9487	.8926E-01
6 HCO3-	.4802E-04	-4.3185	.2741E-04	-4.5621	.5707E+00
7 SiO2(AQ)	.8870E-02	-2.0521	.9903E-02	-2.0042	.1116E+01
8 AL+++	.3437E-12	-12.4639	.9932E-14	-14.0030	.2890E-01
9 CA++	.6699E-02	-2.1740	.8749E-03	-3.0580	.1306E+00
10 MG++	.3004E-01	-1.5223	.5602E-02	-2.2516	.1865E+00
11 FF++	.1504E-04	-4.8229	.1964E-05	-5.7069	.1306E+00
12 K+	.1694E-01	-1.7712	.8425E-02	-2.0744	.4974E+00
13 NA+	.4032E+00	-.2945	.2211E+00	-.6554	.5484E+00
14 MN++	.0910E-04	-4.0039	.7541E-05	-5.1226	.7610E-01
15 ZN++	.7584E-07	-7.1201	.5771E-08	-8.2287	.7610E-01
16 PA++	.1917E-05	-5.7173	.1971E-06	-6.7053	.1028E+00
17 SR++	.4224E-04	-4.3743	.4343E-05	-5.3622	.1028E+00
18 AU+	.3480E-11	-11.4584	.1620E-11	-11.7879	.4683E+00
19 AU+++	.1580E-34	-34.8014	.4470E-37	-37.3497	.2830E-02
20 AUCL2-	.3542E-06	-6.4508	.1947E-06	-6.7117	.5484E+00
21 AUCL4-	.1224E-08	-8.9124	.6710E-09	-9.1733	.5484E+00
22 FE+++	.2154E-10	-10.6667	.6226E-12	-12.2058	.2890E-01
23 OH-	.3870E-06	-6.4122	.2028E-06	-6.6929	.5241E+00
24 H2SiO4-	.2880E-06	-6.5393	.1584E-06	-6.8002	.5484E+00
25 H2SiO4--	.7620E-12	-12.1175	.5805E-13	-13.2362	.7610E-01
26 KSO4-	.1650E-03	-3.7826	.8646E-04	-4.0632	.5241E+00
27 FES04	.1685E-05	-5.7725	.1881E-05	-5.7257	.1116E+01
28 HCL	.5191E-05	-5.2848	.5795E-05	-5.2369	.1116E+01
29 HSO4-	.0731E-04	-4.0110	.5336E-04	-4.2728	.5484E+00
30 CAOH+	.1514E-06	-6.8200	.8301E-07	-7.0809	.5484E+00
31 MGDH+	.2540E-04	-4.5936	.1308E-04	-4.8545	.5484E+00
32 FECL+	.3476E-04	-4.4589	.1906E-04	-4.7198	.5484E+00
33 FECL++	.1250E-07	-7.9001	.9578E-09	-9.0187	.7610E-01
34 FECL4-	.2892E-08	-8.5388	.2201E-09	-9.6574	.7610E-01
35 FECL3	.5101E-08	-8.2924	.5605E-08	-8.2445	.1116E+01
36 FECL2+	.6156E-08	-9.2107	.3376E-08	-8.4716	.5484E+00
37 FES04+	.4638E-09	-9.3326	.2544E-09	-9.5945	.5484E+00
38 ZNCL+	.1443E-06	-6.8407	.7913E-07	-7.1016	.5484E+00
39 ZNCL2	.5723E-07	-7.2424	.6389E-07	-7.1945	.1116E+01
40 ZNCL2-	.9626E-05	-5.0165	.5279E-05	-5.2774	.5484E+00
41 ZNCL4--	.2681E-04	-4.5717	.2040E-05	-5.6903	.7610E-01
42 ALS04+	.9103E-13	-13.0408	.4992E-13	-13.3017	.5484E+00
43 CO3--	.2351E-09	-9.6287	.2099E-10	-10.6781	.8526E-01
44 H2CO3	.7345E-02	-2.1340	.8201E-02	-2.0661	.1116E+01

GPC38-200-5-4 HOURS = 602.50 PH(25) = 4.3
 200 DEGREES C AT 500 BARS AND W/P = 5
 51/02/15.
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 AL(OH)4-	.7023E-05	-5.1535	.3851E-05	-5.4144	.5484E+00
46 FE(OH)++	.9885E-14	-14.0050	.7522E-15	-15.1237	.7610E-01
47 FE(OH)+	.4179E-06	-6.3789	.2292E-06	-6.6398	.5484E+00
48 AL(OH)++	.1942E-07	-7.7116	.2536E-08	-8.5958	.1306E+00
49 NaCl	.3419E-01	-1.4661	.3817E-01	-1.4183	.1116E+01
50 KCl	.4622E-03	-3.3352	.5160E-03	-3.2873	.1116E+01
51 KHSO4	.6095E-05	-5.2151	.6905E-05	-5.1672	.1116E+01
52 CaCO3	.1986E-08	-8.7240	.2108E-08	-8.6761	.1116E+01
53 MnSO4	.6469E-05	-5.1891	.7223E-05	-5.1413	.1116E+01
54 NaSO4-	.1014E-02	-2.9938	.5701E-03	-3.2441	.5620E+00
55 MgSO4	.5647E-02	-2.2482	.6304E-02	-2.2004	.1116E+01
56 CaSO4	.2020E-03	-3.6946	.2255E-03	-3.6468	.1116E+01
57 NaCO3-	.5594E-09	-9.2573	.3285E-09	-9.4834	.5873E+00
58 MgHCO3+	.3290E-04	-4.4828	.1804E-04	-4.7437	.5484E+00
59 CaHCO3+	.1002E-04	-4.9992	.5494E-05	-5.2601	.5484E+00
60 MgCO3	.3930E-17	-17.4056	.4388E-17	-17.3578	.1116E+01
61 BaCO3	.1475E-13	-13.8312	.1647E-13	-13.7824	.1116E+01
62 BaHCO3+	.4107E-07	-7.3865	.2252E-07	-7.6474	.5484E+00
63 BaOH+	.1023E-09	-9.9899	.6051E-10	-10.2181	.5913E+00
64 BaSO4	.4766E-08	-8.3219	.5321E-08	-8.2740	.1116E+01
65 SrOH+	.4712E-10	-10.3268	.2766E-10	-10.5550	.5913E+00
66 SrCO3	.8154E-12	-12.0881	.9114E-12	-12.0403	.1116E+01
67 SrHCO3+	.3772E-05	-5.4234	.2069E-05	-5.6843	.5484E+00
68 SrSO4	.7794E-06	-6.1088	.8691E-06	-6.0609	.1116E+01

GPCBP-200-5-F HQUPS = 64P.00 PH(25) = 2.94
 300 DEGREES C AT 500 BARS AND W/P = F
 R1/02/1P.

WATER 1.0000(KG.LIO.) 55.5081(MOLES LIO.) 55.5083(MOLES TOTAL)
 STOTCHIMETRIC IONIC STRENGTH=.5622948E+00 OSMOTIC COEF.= .7400
 IONIC STRENGTH=.4207439E+00 ACTIVITY=.9865

FC2 INPUT AS REDOX CONTROL

LOG F02= -9.90 LOG FH2=-12.92 LOG FH2G= 1.91 LOG FCO2= -.86
 LOG FH2S= N LOG FS2= N
 CALCULATED ACTIVITY HS- = .4408E-45M LOG FH2S=-39.65 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG F02
H2(AQ) CM	.3719E-15	.4411E-15 .1186E+01	.7498E-12	.8331E-14	-12.9155
O2(AQ) CM	.5248E-12	.6225E-12 .1186E+01	.1679E-07	.1176E-10	

CM - MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))Z	LOG(A/(AH)Z)
1 H+	.3317E-03	-3.7250	.8591E-02	.1000E+01	0
2 H2O		-.0059	.5551E+02		
3 F02		-9.7959ATM			
4 CL-	.2887E+00	-.8701	.5192E+00	.2541E-04	-4.5951
5 SC4--	.1404E-03	-3.8526	.3011E-02	.1540E-12	-12.8125
6 HCO3-	.7124E-07	-7.5248	.6860E-02	.5627E-11	-11.2497
7 SiO2(AQ)	.1939E-01	-1.6384	.1939E-01	.2299E-01	-1.6384
8 AL+++	.4291E-19	-21.5686	.3706E-04	.4039E-10	-10.3937
9 CA++	.5314E-02	-3.5555	.5339E-02	.7843E+04	3.8945
10 MG++	.2324E-01	-2.6302	.2451E-01	.5633E+05	4.7507
11 FE++	.1384E-04	-6.1398	.7162E-04	.2042E+02	1.3101
12 K+	.1636E-01	-2.2459	.1916E-01	.3014E+02	1.4791
13 NA+	.3149E+00	-.9033	.4417E+00	.6632E+03	2.8217
14 MN++	.9917E-03	-4.6093	.1110E-02	.6929E+03	2.8406
15 ZN++	.2055E-08	-10.2929	.1514E-03	.1436E-02	-2.8429
16 SP++	.4952E-04	-5.7303	.5136E-04	.5244E+02	1.7197
17 AU+	.1136E-08	-9.4404	.8885E-04	.1926E-05	-5.7155

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CO₂P-200-E-F PDPS = 648.00 PH(25) = 2.94
 300 DEGREES C AT 500 BARS AND W/P = 5
 81/02/1P.

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SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.3317E-03	-3.4793	.1884E-03	-3.7250	.5680E+00
2 H2O			.9865E+00	-.0059	.9865E+00
3 F02			.1600E-09ATM	-9.7959	
4 CL-	.3887E+00	-.4104	.1249E+00	-.8701	.3470E+00
5 SO4--	.1404E-03	-3.8526	.4339E-05	-5.3626	.3091E-01
6 HCO3-	.7124E-07	-7.1473	.2967E-07	-7.5248	.4193E+00
7 SiO2(AQ)	.1939E-01	-1.7125	.2299E-01	-1.6384	.1186E+01
8 AL+++	.4391E-19	-19.3574	.2700E-21	-21.5686	.6149E-02
9 CA++	.5314E-02	-2.2746	.2783E-03	-3.5555	.5237E-01
10 MG++	.2324E-01	-1.6338	.1999E-02	-2.6992	.8602E-01
11 FF++	.1384E-04	-4.8589	.7248E-06	-6.1398	.5237E-01
12 K+	.1626E-01	-1.7862	.5677E-02	-2.2459	.3470E+00
13 NA+	.3140E+00	-.5019	.1249E+00	-.9033	.3968E+00
14 MN++	.9917E-03	-3.0036	.2459E-04	-4.6093	.2479E-01
15 ZN++	.2055E-08	-8.6872	.5095E-10	-10.2929	.2479E-01
16 SP++	.4952E-04	-4.3052	.1861E-05	-5.7303	.3758E-01
17 AU+	.1136E-08	-8.9447	.3627E-09	-9.4404	.3194E+00
18 AU+++	.7611E-30	-30.1186	.1856E-32	-33.7313	.2439E-03
19 AUCL2-	.3317E-04	-4.4792	.1316E-04	-4.8806	.3968E+00
20 AUCL4-	.5567E-04	-4.2544	.2209E-04	-4.6558	.3968E+00
21 FF+++	.6179E-11	-11.2091	.3600E-13	-13.4202	.6149E-02
22 OH-	.1311E-06	-6.8824	.4887E-07	-7.2110	.3727E+00
23 H2SiO4-	.1941E-07	-7.7120	.7702E-08	-8.1134	.3968E+00
24 H2SiO4--	.1649E-14	-14.7828	.4088E-16	-16.3865	.2479E-01
25 KSO4-	.1779E-02	-3.7490	.6630E-04	-4.1785	.3727E+00
26 FES04	.3496E-05	-5.4565	.4146E-05	-5.3824	.1186E+01
27 HCL	.3722E-03	-3.4292	.4415E-03	-3.3551	.1186E+01
28 HSO4-	.1056E-02	-2.9761	.4192E-03	-3.3776	.3968E+00
29 CADH+	.1462E-05	-5.8350	.5802E-06	-6.2364	.3968E+00
30 MGDH+	.3298E-04	-4.4898	.1348E-04	-4.8702	.3968E+00
31 FECL+	.4915E-04	-4.3085	.1950E-04	-4.7099	.3968E+00
32 FECL2	.4425E-05	-5.3541	.5248E-05	-5.2800	.1186E+01
33 FECL++	.2860E-06	-6.5427	.7090E-08	-8.1494	.2479E-01
34 FECL4-	.4966E-07	-7.3040	.1231E-06	-8.9097	.2479E-01
35 FECL3	.1501E-07	-7.8237	.1780E-07	-7.7496	.1186E+01
36 FECL2+	.2123E-06	-6.6711	.8463E-07	-7.0725	.3968E+00
37 FES04+	.8444E-09	-9.0734	.2351E-09	-9.4748	.3968E+00
38 ZNCL+	.2283E-07	-7.6416	.9058E-08	-8.0430	.3968E+00
39 ZNCL2	.8181E-08	-8.0872	.9703E-08	-8.0121	.1186E+01
40 ZNCL3-	.1526E-04	-4.8018	.6263E-05	-5.2032	.3968E+00
41 ZNCL4--	.1356E-02	-3.8676	.3363E-05	-5.4733	.2479E-01
42 ALS04+	.2755E-19	-19.5598	.1093E-19	-19.9612	.3968E+00
43 CO3--	.2139E-15	-15.6699	.6610E-17	-17.1798	.3091E-01
44 H2CO3	.6858E-02	-2.1638	.6133E-02	-2.0897	.1186E+01

GFC3P-200-F-5 HCUPS = 648.00 PH(25) = 2.94
 200 DEGREES C AT 500 BARS AND W/P = 5
 P1/02/18.
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 AL(OH)4-	.3706E-04	-4.4310	.1471E-04	-4.8325	.3968E+00
46 FEOH++	.6799E-10	-10.1675	.1666E-11	-11.7732	.2479E-01
47 FEOH+	.1481E-06	-6.8293	.5878E-07	-7.2308	.3968E+00
48 ALOH++	.3399E-10	-10.4687	.1780E-11	-11.7496	.5237E-01
49 NaCl	.1266E+00	-.8975	.1502E+00	-.8234	.1186E+01
50 KCl	.2570E-02	-2.5901	.3048E-02	-2.5160	.1186E+01
51 KHSO4	.4493E-04	-4.3475	.5328E-04	-4.2734	.1186E+01
52 CaCO3	.1320E-12	-12.8794	.1566E-12	-12.8053	.1186E+01
53 MnSO4	.1186E-02	-3.9260	.1406E-03	-3.8519	.1186E+01
54 NaSO4-	.2635E-03	-3.5792	.1082E-03	-3.9659	.4105E+00
55 MgSO4	.1242E-02	-2.9059	.1473E-02	-2.8318	.1186E+01
56 CaSO4	.2333E-04	-4.6322	.2767E-04	-4.5581	.1186E+01
57 NaCO3-	.3290E-14	-14.4828	.1435E-14	-14.8431	.4362E+00
58 MgHCO3+	.6272E-06	-6.2026	.2489E-06	-6.6040	.3968E+00
59 CaHCO3+	.2762E-06	-6.5588	.1096E-06	-6.9602	.3968E+00
60 MgCO3	.1016E-19	-19.9930	.1205E-19	-19.9189	.1166E+01
61 SrOH+	.4624E-10	-10.3250	.2026E-10	-10.6912	.4403E+00
62 SrCO3	.1306E-17	-17.8842	.1549E-17	-17.8101	.1186E+01
63 SrHCO3+	.1401E-05	-5.8536	.5559E-06	-6.2550	.3968E+00
64 SrSO4	.4396E-06	-6.3569	.5214E-06	-6.2829	.1186E+01

CPC3B-200-5-6 HOURS = 743.50 PH(25) = 2.59
300 DEGREES C AT 500 BARS AND W/P = 5
81/02/18.

WATER 1.0000(KG.LIO.) 55.5085(MOLFS LIO.) 55.5083(MOLES TOTAL)
STOICHIOMETRIC IONIC STRENGTH=.5644691E+00 OSMOTIC COEF.= .7455
IONIC STRENGTH=.4179912E+00 ACTIVITY=.9860

FO2 INPUT AS REDOX CONTROL

LOG FO2= -9.40 LOG FH2=-13.11 LOG FH2O= 1.91 LOG FCO2= -.81
LOG FH2S= N LOG FS2= N
CALCULATED ACTIVITY HS- = .1066E-45M LOG FH2S=-39.67 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FC2
H2(AO) CM	.2354E-15	.2788E-15 .1185E+01	.4745E-12	.5272E-14	-13.1147
O2(AO) CM	.1314E-11	.1556E-11 .1185E+01	.4203E-07	.2942E-10	

CM - MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))Z	LOG(A/(A(H+))Z)
1 H+	.1212E-02	-3.1274	.1314E-01	.1000E+01	0
2 H2O		-0.0061	.5551E+02		
3 FO2		-9.3979ATM			
4 CL-	.3916E+00	-0.9660	.5312E+00	.1015E-03	-3.9934
5 SO4--	.5335E-04	-5.7805	.2294E-02	.9219E-12	-12.0353
6 HCO3-	.2123E-07	-8.0500	.8110E-02	.6646E-11	-11.1774
7 SiO2(AQ)	.2498E-01	-1.5288	.2498E-01	.2959E-01	-1.5288
8 AL+++	.3445E-17	-19.6718	.1186E-04	.5134E-10	-10.2895
9 CA++	.5280E-02	-3.5485	.5389E-02	.5086E+03	2.7063
10 MG++	.1628E-01	-2.8527	.1662E-01	.2524E+04	3.4021
11 FE++	.2295E-03	-4.9184	.1200E-02	.2170E+02	1.3364
12 K+	.2942E-01	-1.9902	.3435E-01	.1372E+02	1.1372
13 NA+	.3177E+00	-0.8987	.4471E+00	.1693E+03	2.2287
14 MN++	.7413E-03	-4.7331	.7754E-03	.3325E+02	1.5217
15 ZN++	.6509E-02	-9.7836	.5048E-03	.2960E-03	-3.5287
16 BA++	.4240E-05	-6.7834	.4362E-05	.2961E+00	-0.5286
17 SP++	.6880E-04	-5.5854	.6962E-04	.4671E+01	.6695
18 AU+	.2063E-09	-10.1802	.2665E-03	.9855E-07	-7.0528

GPC3R-200-5-A HOURS = 743.50 PH(25) = 2.59
 300 DEGREES C AT 500 BARS AND W/P = F
 81/02/18.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.1312E-02	-2.8820	.7457E-03	-3.1274	.5663E+00
2 H2O			.9860E+00	-.0061	.9860E+00
3 F02			.4000F-09ATM	-9.3979	
4 CL-	.3916E+00	-.4072	.1361E+00	-.8660	.3477E+00
5 SO4--	.5335E-04	-4.2728	.1658E-05	-5.7805	.3107E-01
6 HCO3-	.2123E-07	-7.6731	.8912E-08	-8.0500	.4198E+00
7 ST02(AQ)	.2498E-01	-1.6024	.2959E-01	-1.5288	.1185E+01
8 AL+++	.3445E-17	-17.4628	.2129E-19	-19.6718	.6180E-02
9 CA++	.5380E-02	-2.2692	.2828E-03	-3.5485	.5257E-01
10 MG++	.1628E-01	-1.7884	.1404E-02	-2.8527	.8624E-01
11 FE++	.2295E-03	-3.6392	.1207E-04	-4.9184	.5257E-01
12 K+	.2042E-01	-1.5212	.1023E-01	-1.9902	.3477E+00
13 NA+	.3177E+00	-.4980	.1263E+00	-.8987	.3974E+00
14 MN++	.7413E-03	-3.1300	.1849E-04	-4.7331	.2494E-01
15 NH4+	.6599E-09	-8.1805	.1646E-09	-9.7836	.2494E-01
16 BA++	.4360E-05	-5.3605	.1646E-06	-6.7834	.3776E-01
17 SR++	.6880E-04	-4.1624	.2598E-05	-5.5854	.3776E-01
18 AU+	.2063E-09	-9.6856	.6603E-10	-10.1802	.3201E+00
19 AU+++	.3387E-29	-29.4702	.8373E-33	-33.0771	.2472E-03
20 AUCL2-	.6145E-05	-5.2115	.2442E-05	-5.6123	.3974E+00
21 AUCL4-	.2604E-03	-3.5844	.1035E-03	-3.9851	.3974E+00
22 FF+++	.5095E-09	-9.2929	.3149E-11	-11.5019	.6180E-02
23 OH-	.3305E-07	-7.4809	.1234E-07	-7.9087	.3734E+00
24 H3SIO4-	.6300E-08	-8.2006	.2504E-08	-8.6014	.3974E+00
25 H2SIO4--	.1346E-15	-15.8709	.3358E-17	-17.4740	.2494E-01
26 KSO4-	.1222E-03	-3.9128	.4564E-04	-4.3407	.3734E+00
27 FFSO4	.2226E-04	-4.6525	.2637E-04	-4.5789	.1185E+01
28 HCL	.1489E-02	-2.8270	.1764E-02	-2.7534	.1185E+01
29 HSO4-	.1595E-02	-2.7972	.6340E-03	-3.1979	.3974E+00
30 CAOH+	.3746E-06	-6.4265	.1489E-06	-6.8272	.3974E+00
31 MGOH+	.6017E-05	-5.2206	.2391E-05	-5.6214	.3974E+00
32 FECL+	.9248E-03	-3.0837	.3278E-03	-3.4844	.3974E+00
33 FECL2	.7515E-04	-4.1241	.8903E-04	-4.0505	.1185E+01
34 FECL++	.2378E-04	-4.6238	.5931E-06	-6.2269	.2494E-01
35 FECL4-	.4248E-05	-5.3718	.1059E-06	-6.9749	.2494E-01
36 FECL3	.1281E-05	-5.8925	.1517E-05	-5.8189	.1185E+01
37 FECL2+	.1798E-04	-4.7451	.7147E-05	-5.1459	.3974E+00
38 FFSO4+	.2669E-07	-7.5736	.1061E-07	-7.9744	.3974E+00
39 NHCL+	.7433E-07	-7.1288	.2954E-07	-7.5298	.3974E+00
40 ZNCL2	.2697E-07	-7.5692	.3195E-07	-7.4956	.1185E+01
41 NHCL3-	.5238E-04	-4.2808	.2082E-04	-4.6816	.3974E+00
42 ZNCL4--	.4522E-03	-3.3445	.1128E-04	-4.9476	.2494E-01
43 ALSO4+	.8289E-18	-18.0815	.3294E-18	-18.4823	.3974E+00
44 CO3--	.1604E-16	-16.7949	.4982E-18	-18.3026	.3107E-01

GPC3B-700-5-A HOURS = 743.50 PH(25) = 2.59
 300 DEGREES C AT 500 BARS AND W/P = 5
 81/02/18.
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 H2CO3	.8109E-02	-2.0910	.9607E-02	-2.0174	.1185E+01
46 AL(OH)4-	.1186E-04	-4.9259	.4713E-05	-5.3267	.3974E+00
47 FE(OH)3	.1414E-06	-8.8495	.3527E-10	-10.4526	.2494E-01
48 FE(OH)2	.6217E-06	-6.2064	.2471E-06	-6.6072	.3974E+00
49 AL(OH)3	.6741E-09	-9.1713	.3544E-10	-10.4505	.5257E-01
50 NaCl	.1293E+00	-.8883	.1532E+00	-.8147	.1185E+01
51 KCl	.4680E-02	-2.3298	.5544E-02	-2.2562	.1185E+01
52 KHSO4	.1225E-03	-3.9117	.1452E-03	-3.8381	.1185E+01
53 CaCO3	.1012E-13	-13.9947	.1199E-13	-13.9211	.1185E+01
54 MnSO4	.3410E-04	-4.4672	.4040E-04	-4.3936	.1185E+01
55 NaSO4-	.1016E-03	-3.9931	.4176E-04	-4.3792	.4110E+00
56 MgSO4	.3336E-03	-3.4768	.3952E-03	-3.4032	.1185E+01
57 CaSO4	.9065E-05	-5.0426	.1074E-04	-4.9690	.1185E+01
58 NaCO3-	.2503E-15	-15.6015	.1093E-15	-15.9613	.4367E+00
59 MgHCO3+	.1312E-06	-6.8819	.5216E-07	-7.2827	.3974E+00
60 CaHCO3+	.8361E-07	-7.0777	.3323E-07	-7.4785	.3974E+00
61 MgCO3	.8439E-20	-20.0737	.9998E-20	-20.0001	.1185E+01
62 BaCO3	.3470E-20	-20.4596	.4111E-20	-20.3860	.1185E+01
63 BaHCO3+	.1470E-08	-8.8327	.5842E-09	-9.2334	.3974E+00
64 PAOH+	.2012E-09	-9.6964	.8868E-10	-10.0522	.4408E+00
65 BASO4	.2357E-09	-9.6276	.2793E-09	-9.5540	.1185E+01
66 SPOH+	.1628E-10	-10.7884	.7176E-11	-11.1441	.4408E+00
67 SPOCO3	.1375E-18	-18.8616	.1629E-18	-18.7880	.1185E+01
68 SPOHCO3+	.5826E-06	-6.2346	.2315E-06	-6.6354	.3974E+00
69 SPSO4	.2247E-06	-6.6295	.2780E-06	-6.5559	.1185E+01

GPC3R-200-5-7 HOURS = 1017.5 PH(25) = 2.50
300 DEGREES C AT 500 BARS AND W/P = 5
81/02/18.

WATER 1.0000(KG/LIO.) 55.5082(MOLES LIO.) 55.5083(MOLES TOTAL)
STOICHIOMETRIC IONIC STRENGTH=.5470317E+00 OSMOTIC COEF.= .7474
IONIC STRENGTH=.4062312E+00 ACTIVITY=.9863

FO2 INPUT AS PEDGX CONTRDL

LOG FO2=-19.70 LOG FH2= -7.96 LOG FH2O= 1.01 LOG FCO2= -.94
LOG FH2S= N LOG FS2= N
CALCULATED ACTIVITY HS- = .4088E-25M LOG FH2S=-18.87 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FO2
H2(AQ) CM	.3345E-10	.3944E-10 .1179E+01	.6744E-07	.7494E-09	-7.9640
O2(AQ) CM	.6599E-22	.7781E-22 .1179E+01	.2112E-17	.1478E-20	

CM - MOLALITY CALCULATED FROM PEDGX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+)) ^{1/2}	LOG(A/(AH) ^{1/2})
1 H+	.2141E-02	-2.9137	.1225E-01	.1000E+01	0
2 H2O		-.0060	.5551E+02		
3 FO2		-19.6990ATM			
4 CL-	.3815E+00	-.8737	.5170E+00	.1631E-03	-3.7874
5 SO4--	.3055E-04	-6.0127	.2040E-02	.1445E-11	-11.8401
6 HCO3-	.9661E-08	-8.3894	.6100E-02	.4976E-11	-11.3032
7 SI02(AQ)	.2609E-01	-1.5119	.2609E-01	.3077E-01	-1.5119
8 AL+++	.2045E-16	-18.8887	.1001E-04	.7120E-10	-10.1475
9 CA++	.5284E-02	-3.5491	.5289E-02	.1898E+03	2.2784
10 MG++	.1483E-01	-2.8282	.1501E-01	.8696E+03	2.9393
11 FE++	.4341E-03	-4.6345	.2149E-02	.1560E+02	1.1930
12 K+	.3091E-01	-1.9650	.3601E-01	.8887E+01	.9487
13 NA+	.3070E+00	-.9109	.4312E+00	.1007E+03	2.0029
14 MN++	.7668E-03	-4.7071	.7881E-03	.1319E+02	1.1204
15 ZN++	.9122E-08	-8.6821	.5813E-03	.1398E-03	-3.8546
16 BA++	.7996E-06	-7.5112	.7998E-06	.2072E-01	-1.6837
17 SP++	.5899E-04	-5.6433	.5935E-04	.1528E+01	.1842
18 AU+	.3516E-10	-10.9443	.1015E-05	.9320E-08	-8.0306

GPC38-200-5-7 HOURS = 1017.5 PH(25) = 2.50
300 DEGREES C AT 500 PAPS AND W/R = 5
81/02/1P.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.2141E-02	-2.6694	.1220E-02	-2.9137	.5697E+00
2 H2O			.9863E+00	-.0060	.9863E+00
3 F02			.2000E-19ATM	-19.6990	
4 CL-	.3815E+00	-.4185	.1338E+00	-.8737	.3506E+00
5 SO4--	.3055E-04	-4.5150	.9713E-06	-6.0127	.3179E-01
6 HCO3-	.9661E-08	-8.0150	.4079E-08	-8.3894	.4223E+00
7 SiO2(AQ)	.2609E-01	-1.5834	.3077E-01	-1.5119	.1179E+01
8 AL+++	.2045E-16	-16.6893	.1292E-18	-18.8887	.6318E-02
9 CA++	.5284E-02	-2.2771	.2824E-03	-3.5491	.5345E-01
10 MG++	.1483E-01	-1.8269	.1294E-02	-2.8882	.8724E-01
11 FE++	.4341E-03	-3.3624	.2320E-04	-4.6345	.5345E-01
12 K+	.3091E-01	-1.5099	.1064E-01	-1.9650	.3506E+00
13 NA+	.3070E+00	-.5129	.1228E+00	-.9109	.4000E+00
14 MN++	.7668E-03	-3.1153	.1963E-04	-4.7071	.2560E-01
15 ZN++	.8122E-08	-8.0903	.2079E-09	-9.6821	.2560E-01
16 BA++	.7996E-06	-6.0971	.3082E-07	-7.5112	.3854E-01
17 SP++	.5890E-04	-4.2292	.2274E-05	-5.6433	.3854E-01
18 AU+	.3516E-10	-10.4539	.1137E-10	-10.9443	.3233E+00
19 AU+++	.1037E-34	-34.9840	.2719E-36	-38.5655	.2621E-02
20 AUCL2-	.1015E-05	-5.9927	.4058E-06	-6.3917	.4000E+00
21 AUCL4-	.7829E-09	-9.1063	.3132E-09	-9.5042	.4000E+00
22 FE+++	.4162E-11	-11.3907	.2620E-13	-13.5801	.6318E-02
23 OH-	.2006E-07	-7.6976	.7547E-08	-8.1222	.3762E+00
24 H3SiO4-	.2979E-08	-8.4002	.1592E-08	-8.7982	.4000E+00
25 H2SiO4--	.5097E-16	-16.2926	.1305E-17	-17.8844	.2560E-01
26 KSO4-	.7523E-04	-4.1230	.2834E-04	-4.5477	.3762E+00
27 FES04	.2520E-04	-4.5987	.2971E-04	-4.5271	.1179E+01
28 HCL	.2405E-02	-2.6189	.2835E-02	-2.5474	.1179E+01
29 HSF4-	.1519E-02	-2.8185	.6076E-03	-3.2164	.4000E+00
30 CADH+	.2273E-06	-6.6434	.9092E-07	-7.0413	.4000E+00
31 MGDH+	.3369E-05	-5.4725	.1348E-05	-5.8704	.4000E+00
32 FFCL+	.1548E-02	-2.8102	.6192E-03	-3.2087	.4000E+00
33 FECL2	.1402E-03	-3.8534	.1653E-03	-3.7818	.1179E+01
34 FECL++	.1901E-06	-6.7210	.4867E-08	-8.3128	.2560E-01
35 FECL4-	.3221E-07	-7.4920	.8246E-09	-9.0838	.2560E-01
36 FFCL?	.1019E-07	-7.9916	.1202E-07	-7.9201	.1179E+01
37 FFCL2+	.1441E-06	-6.8415	.5762E-07	-7.2394	.4000E+00
38 FFES04+	.1298E-09	-9.8868	.5191E-10	-10.2847	.4000E+00
39 ZNCL+	.9166E-07	-7.0378	.3666E-07	-7.4358	.4000E+00
40 ZNCL?	.3304E-07	-7.4810	.3856E-07	-7.4094	.1179E+01
41 ZNCL3-	.6235E-04	-4.2051	.2494E-04	-4.6031	.4000E+00
42 ZNCL4--	.5188E-03	-3.2850	.1328E-04	-4.8768	.2560E-01
43 AIS04+	.2928E-17	-17.5334	.1171E-17	-17.9314	.4000E+00
44 CO3--	.4385E-17	-17.3580	.1394E-18	-18.8557	.3179E-01

GPG38-200-5-7 HOURS = 1017.5 PH(25) = 2.50
 300 DEGREES C AT 500 BARS AND W/P = 5
 81/02/1P.
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 H2CO3	.6100E-02	-2.2147	.7192E-02	-2.1432	.1179E+01
46 AL(OH)4-	.1000E-04	-4.9998	.4002E-05	-5.3977	.4000E+00
47 FEOH++	.7038E-11	-11.1526	.1802E-12	-12.7443	.2560E-01
48 FEOH+	.7265E-06	-6.1388	.2906E-06	-6.5367	.4000E+00
49 ALDH++	.2461E-08	-8.6089	.1315E-09	-9.8810	.5345E-01
50 NaCl	.1241E+00	-.9061	.1464E+00	-.8345	.1179E+01
51 KCl	.4895E-02	-2.3102	.5772E-02	-2.2387	.1179E+01
52 KHSO4	.1250E-03	-3.9029	.1474E-03	-3.8314	.1179E+01
53 CaCO3	.2843E-14	-14.5463	.3351E-14	-14.4748	.1179E+01
54 MnSO4	.2132E-04	-4.6713	.2513E-04	-4.5997	.1179E+01
55 NaSO4-	.5754E-04	-4.2400	.2379E-04	-4.6235	.4135E+00
56 MgSO4	.1810E-03	-3.7424	.2134E-03	-3.6708	.1179E+01
57 CaSO4	.5330E-05	-5.2733	.6284E-05	-5.2018	.1179E+01
58 NaCO3-	.6776E-16	-16.1690	.2975E-16	-16.5265	.4390E+00
59 MgHCO3+	.5500E-07	-7.2596	.2200E-07	-7.6576	.4000E+00
60 CaHCO3+	.3797E-07	-7.4206	.1519E-07	-7.8185	.4000E+00
61 MgCO3	.5850E-20	-20.2325	.6897E-20	-20.1613	.1179E+01
62 BaCO3	.1826E-21	-21.7384	.2153E-21	-21.6669	.1179E+01
63 BaHCO3+	.1251E-09	-9.9027	.5005E-10	-10.3006	.4000E+00
64 BaOH+	.2291E-10	-10.6399	.1015E-10	-10.9934	.4431E+00
65 BaSO4	.2598E-10	-10.5854	.3063E-10	-10.5138	.1179E+01
66 SrOH+	.8670E-11	-11.0620	.3841E-11	-11.4155	.4431E+00
67 SrCO3	.3385E-19	-19.4705	.3991E-19	-19.3989	.1179E+01
68 SrHCO3+	.2319E-06	-6.6347	.9275E-07	-7.0327	.4000E+00
69 SrSO4	.1209E-06	-6.9174	.1426E-06	-6.8459	.1179E+01

+++++

GPC3-300-5-1 HOURS =3.0 PH(25) = 3.35
 300 DEGREES C AT 500 BARS AND W/R = F
 81/0271E.

+++++

WATER 1.0003(KG.LIO.) 55.5229(MOLES LIO.) 55.5083(MOLES TOTAL)
 STOICHIOMETRIC IONIC STRENGTH= 1 OSMOTIC COFF.= I
 IONIC STRENGTH= 0 ACTIVITY=1.0000

PEDOX OPTION = 5

4 GOLD + O2(GAS,AQ) + 4 H+ == 4 AU+ + 2 H2O

LOG FO2 = -8.53 LOG FH2 = -13.54 LOG FH2O = 1.92 LOG FCC2 = -.72
 LOG FH2S = N LOG FS2 = N
 CALCULATED ACTIVITY HS- = .2801E-50M LOG FH2S = -46.32 LOG FS2 = I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FO2
H2(AQ) CM	.1039E-15	.1039E-15	.2095E-12	.2227E-14	-13.5434
O2(AQ) CM	.1153E-10	.1153E-10	.3689E-06	.2583E-09	
		.1000E+01			

CM = MOLALITY CALCULATED FROM PEDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))Z	LOG(A/(AH)Z)
1 H+	.6391E-05	-5.1951	-C	.1000E+01	0
2 H2O		0	.5551E+02		
3 FO2		-8.5282ATM			
4 CL-	.2348E+00	-1.6293	.5632E+00	.1496E-05	-5.8244
5 SO4--	.2793E-06	-6.5539	.4830E-02	.1137E-16	-16.9441
6 HCO3-	.1298E-05	-5.8867	.1217E-01	.8282E-11	-11.0818
7 SiO2(AQ)	.1203E-01	-1.9198	.1203E-01	.1203E-01	-1.9198
8 AL+++	.9669E-12	-9.6805	.1075E-04	.8032E+06	5.9048
9 CA++	.2812E-02	-2.4187	.4142E-02	.9345E+08	7.9715
10 MG++	.1757E-01	-1.7553	.2205E-01	.4314E+09	8.6349
11 FE++	.1306E-05	-5.8571	.9490E-04	.3413E+05	4.5331
12 K+	.1144E-01	-1.9416	.2215E-01	.1793E+04	3.2525
13 NA+	.1512E+00	-1.8200	.4682E+00	.2372E+05	4.3751
14 MN++	.1073E-01	-1.9693	.1469E-01	.2636E+09	8.4209
15 ZN++	.1593E-09	-9.6616	.1989E-02	.5353E+01	.7286
16 BA++	.1058E-05	-5.9757	.1672E-05	.2597E+05	4.4145
17 SR++	.2527E-05	-5.5975	.3538E-04	.6205E+05	4.7927
18 AU+	.8572E-10	-10.1072	.9646E-05	.1224E-04	-4.9121

GPC3-300-5-1 HOURS = 3.0 PH(25) = 3.35
 300 DEGREES C AT 500 BARS AND W/P = 5
 P1/0271P.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.6381E-05	-5.1951	.6381E-05	-5.1951	.1000E+01
2 H2O			.1000E+01	0	.1000E+01
3 F02			.2964E-0P4TM	-8.5282	
4 CL-	.2348E+00	-6.6293	.2348E+00	-6.6293	.1000E+01
5 SO4--	.2793E-06	-6.5539	.2793E-06	-6.5539	.1000E+01
6 HCO3-	.1298E-05	-5.8867	.1298E-05	-5.8867	.1000E+01
7 SiO2(AO)	.1203E-01	-1.9198	.1203E-01	-1.9198	.1000E+01
8 AL+++	.9669E-13	-13.0146	.2087E-09	-9.6805	.1000E+01
9 CA++	.3813E-02	-2.4187	.3813E-02	-2.4187	.1000E+01
10 MG++	.1757E-01	-1.7553	.1757E-01	-1.7553	.1000E+01
11 FE++	.1306E-05	-5.8840	.1306E-05	-5.8840	.1000E+01
12 K+	.1144E-01	-1.9416	.1144E-01	-1.9416	.1000E+01
13 NA+	.1513E+00	-8.2001	.1513E+00	-8.2001	.1000E+01
14 MN++	.1073E-01	-1.9693	.1073E-01	-1.9693	.1000E+01
15 ZN++	.1582E-09	-9.8006	.2180E-09	-9.6616	.1000E+01
16 BA++	.1058E-05	-5.9757	.1058E-05	-5.9757	.1000E+01
17 SP++	.2527E-05	-5.5974	.2527E-05	-5.5974	.1000E+01
18 AU+	.8572E-10	-10.0660	.7813E-10	-10.1072	.1000E+01
19 AM+++	.1962E-26	-36.7073	.1264E-35	-35.8982	.1000E+01
20 AUCL2-	.9429E-05	-5.0255	.5595E-05	-5.0658	.1000E+01
21 AUCL4-	.2147E-06	-6.6685	.1382E-05	-5.8594	.1000E+01
22 FE+++	.4580E-14	-14.3391	.1295E-13	-13.8877	.1000E+01
23 NH-	.1463E-05	-5.8349	.1463E-05	-5.8348	.1000E+01
24 H3SiO4-	.1199E-06	-6.9247	.1190E-06	-6.9246	.1000E+01
25 H2SiO4--	.1864E-13	-13.7295	.1864E-13	-13.7294	.1000E+01
26 KSO4-	.8601E-05	-5.0655	.8601E-05	-5.0655	.1000E+01
27 FES04	.4810E-06	-6.3178	.5117E-06	-6.2910	.1000E+01
28 HCL	.2604E-04	-4.5844	.2603E-04	-4.5844	.1000E+01
29 HSO4-	.0142E-06	-6.0390	.9141E-06	-6.0390	.1000E+01
30 CADH+	.2379E-02	-3.6236	.2379E-03	-3.6236	.1000E+01
31 MGDH+	.3546E-02	-2.4502	.3547E-02	-2.4502	.1000E+01
32 FECL+	.6120E-04	-4.2133	.6511E-04	-4.1864	.1000E+01
33 FECL2	.2867E-04	-4.5426	.3050E-04	-4.5157	.1000E+01
34 FECL++	.1498E-08	-8.8274	.4208E-08	-8.3759	.1000E+01
35 FECL4-	.1764E-09	-8.8653	.3857E-08	-8.4138	.1000E+01
36 FECL3	.1132E-07	-7.9460	.3203E-07	-7.4945	.1000E+01
37 FECL2+	.3092E-07	-7.5097	.8745E-07	-7.0582	.1000E+01
38 FFS04+	.2600E-11	-11.5850	.7353E-11	-11.1335	.1000E+01
39 7NCL+	.4800E-07	-7.3099	.6747E-07	-7.1709	.1000E+01
40 7NCL2	.9138E-07	-7.0392	.1258E-06	-6.9002	.1000E+01
41 7NCL3-	.1027E-03	-3.9885	.1414E-03	-3.8495	.1000E+01
42 7NCL4--	.9599E-06	-4.0178	.1322E-02	-3.8767	.1000E+01
43 ALSD4+	.2521E-12	-12.5985	.5440E-09	-9.2644	.1000E+01
44 CO3--	.8490E-14	-14.0716	.8482E-14	-14.0715	.1000E+01

GPC2-300-5-1 HOURS = 3.0 PH(25) = 3.25

300 DEGREES C AT FOC BARS AND V/P = 5

81702718.

(CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 H2CO3	.1197E-01	-1.9218	.1197E-01	-1.9218	.1000E+01
46 AL(OH)4-	.4225E+10	9.6258	.9123E+13	12.9602	.1000E+01
47 FEOH++	.6081E-11	-11.2160	.1720E-10	-10.7645	.1000E+01
48 FEOH+	.3171E-05	-5.4988	.3373E-05	-5.4719	.1000E+01
49 AL(OH)++	.1908E-01	-1.7105	.4118E+02	1.6147	.1000E+01
50 NaCl	.3167E+00	-.4994	.3167E+00	-.4993	.1000E+01
51 KCl	.1069E-01	-1.9709	.1069E-01	-1.9709	.1000E+01
52 KHSO4	.2341E-06	-6.6306	.2341E-06	-6.6306	.1000E+01
53 CaCO3	.2752E-08	-8.5603	.2753E-08	-8.5602	.1000E+01
54 MnSO4	.3952E-02	-2.4032	.3952E-02	-2.4032	.1000E+01
55 NaSO4-	.8435E-05	-5.0739	.8435E-05	-5.0739	.1000E+01
56 MgSO4	.8333E-03	-3.0792	.8333E-03	-3.0792	.1000E+01
57 CaSO4	.2440E-04	-4.6126	.2440E-04	-4.6126	.1000E+01
58 NaCO3-	.2230E-11	-11.6517	.2231E-11	-11.6516	.1000E+01
59 MgHCO3+	.9505E-04	-4.0220	.9506E-04	-4.0220	.1000E+01
60 CaHCO3+	.6525E-04	-4.1854	.6525E-04	-4.1854	.1000E+01
61 MgCO3	.1559E-18	-18.8072	.1559E-18	-18.8072	.1000E+01
62 BaCO3	.4494E-15	-15.3472	.4495E-15	-15.3472	.1000E+01
63 BaHCO3+	.5465E-06	-6.2624	.5465E-06	-6.2624	.1000E+01
64 BaOH+	.6752E-07	-7.1706	.6752E-07	-7.1706	.1000E+01
65 BaSO4	.3023E-09	-9.5196	.3023E-09	-9.5196	.1000E+01
66 SrOH+	.8273E-09	-9.0823	.8273E-09	-9.0823	.1000E+01
67 SrCO3	.2697E-14	-14.5690	.2698E-14	-14.5690	.1000E+01
68 SrHCO3+	.3280E-04	-4.4842	.3280E-04	-4.4842	.1000E+01
69 SrSO4	.4557E-07	-7.3412	.4557E-07	-7.3414	.1000E+01

GPC3-300-F-2 HOURS =93.0 PH(25) = 2.38
 300 DEGREES C AT 500 BARS AND W/P = F
 9170271P.

WATER 1.0000(KG.LIO.) FF.5082(MOLES LIO.) 55.5083(MOLES TOTAL)
 STOICHIOMETRIC IONIC STRENGTH=.5884493E+00 OSMOTIC COEF.= .7531
 IONIC STRENGTH=.4438338E+00 ACTIVITY=.9852

FO2 INPUT AS REDOX CONTROL

LOG FO2=-15.80 LOG FH2=-9.92 LOG FH2O= 1.91 LOG FCO2= -.63
 LOG FH2S= N LOG FS2= N
 CALCULATED ACTIVITY HS= .1607E-33M LOG FH2S=-27.22 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FO2
H2(AQ) CM	.3680E-12	.4405E-12 .1197E+01	.7418E-09	.8242E-11	-9.9160
O2(AQ) CM	.5200E-18	.6225E-18 .1197E+01	.1664E-12	.1165E-16	

CM = MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+)) ^{1/2}	LOG(A/(AH) ^{1/2})
1 H+	.2478E-02	-2.8536	.1800E-01	.1000E+01	0
2 H2O		-1.0065	.5551E+02		
3 FO2		-15.7959ATM			
4 CL-	.4104E+00	-.8534	.5504E+00	.1963E-03	-3.7070
5 SO4--	.7188E-05	-6.6720	.5621E-03	.4176E-12	-12.3793
6 HCO3-	.1755E-07	-8.1380	.1231E-01	.1020E-10	-10.9916
7 SiC2(AQ)	.1866E-01	-1.6510	.1866E-01	.2233E-01	-1.6510
8 AL+++	.4719E-16	-18.5551	.1260E-04	.1014E-09	-9.9942
9 CA++	.8531E-02	-2.3623	.8533E-02	.2208E+03	2.3439
10 MG++	.3528E-02	-3.5272	.3537E-02	.1514E+03	2.1801
11 FE++	.8633E-04	-5.3581	.4297E-03	.2234E+01	.3491
12 K+	.1800E-01	-2.1926	.2181E-01	.4582E+01	.6610
13 NA+	.3249E+00	-.8949	.4578E+00	.9093E+02	1.9587
14 MN++	.2015E-01	-2.3226	.2026E-01	.2425E+03	2.3847
15 ZN++	.2430E-08	-10.2396	.2080E-02	.2935E-04	-4.5323
16 BA++	.6178E-05	-6.6508	.6180E-05	.1139E+00	-.9435
17 SR++	.7706E-04	-5.5548	.7761E-04	.1420E+01	.1524
18 AU+	.3973E-09	-9.9046	.1371E-04	.8802E-07	-7.0510

GPC-300-5-2 HOURS = 93.0 PH(25) = 2.38
 300 DEGREES C AT 500 BARS AND W/P = F
 F1702718.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.2478E-02	-2.6060	.1401E-02	-2.8536	.5654E+00
2 H2O			.9852E+00	-1.0065	.9852E+00
3 HCO3-			.1600E-15 ATM	-15.7959	
4 Cl-	.4104E+00	-1.3868	.1401E+00	-1.6534	.3415E+00
5 FCO4--	.7188E-05	-5.1434	.2128E-06	-6.6720	.2960E-01
6 HCO3-	.1755E-07	-7.7558	.7278E-08	-8.1380	.4148E+00
7 SiO2(AQ)	.1846E-01	-1.7292	.2233E-01	-1.6510	.1197E+01
8 AL+++	.4719E-16	-16.3261	.2786E-16	-18.5551	.5903E-02
9 CA++	.8531E-02	-2.0740	.4332E-03	-3.3633	.5078E-01
10 MG++	.3528E-02	-2.4525	.2970E-03	-3.5272	.8420E-01
11 FE++	.8623E-04	-4.0638	.4384E-05	-5.3581	.5078E-01
12 K+	.1880E-01	-1.7260	.6419E-02	-2.1926	.3415E+00
13 NA+	.3240E+00	-1.4882	.1274E+00	-1.8949	.3920E+00
14 MN++	.2015E-01	-1.6958	.4758E-02	-3.3224	.2362E-01
15 ZN++	.2430E-09	-8.6128	.5740E-10	-10.2396	.2362E-01
16 BA++	.6178E-05	-5.2091	.2235E-06	-6.6508	.3617E-01
17 SP++	.7706E-04	-4.1132	.2787E-05	-5.5548	.3617E-01
18 AU+	.2973E-09	-9.4008	.1246E-09	-9.9046	.3135E+00
19 AU+++	.1622E-31	-31.7900	.2546E-35	-25.4503	.2186E-03
20 AUCL2-	.1245E-04	-4.9048	.4881E-05	-5.3115	.3920E+00
21 AUCL4-	.1255E-05	-5.9012	.4921E-06	-6.3079	.3920E+00
22 FE+++	.9182E-11	-11.0371	.5421E-13	-13.2660	.5903E-02
23 NH-	.1786E-07	-7.7482	.6564E-08	-8.1828	.3676E+00
24 H3SiO4-	.2566E-08	-8.5907	.1006E-08	-8.9974	.3920E+00
25 H2SiO4--	.2041E-16	-16.5170	.7182E-18	-18.1438	.2362E-01
26 KSO4-	.1000E-04	-5.0000	.3676E-05	-5.4346	.3676E+00
27 FESO4	.1027E-05	-5.9883	.1230E-05	-5.9101	.1197E+01
28 HCL	.2850E-02	-2.5452	.3412E-02	-2.4670	.1197E+01
29 HSO4-	.3900E-03	-3.4089	.1529E-03	-3.8156	.3920E+00
30 CADH+	.3094E-06	-6.5095	.1212E-06	-6.9162	.3920E+00
31 MGCH+	.6865E-06	-6.1633	.2691E-06	-6.5700	.3920E+00
32 FECL+	.2127E-03	-3.5048	.1226E-03	-3.9115	.3920E+00
33 FECL2	.2863E-04	-4.5421	.3428E-04	-4.4650	.1197E+01
34 FECL++	.4451E-06	-6.3516	.1051E-07	-7.9784	.2362E-01
35 FECL4-	.8673E-07	-7.0618	.2046E-08	-8.6886	.2362E-01
36 FECL3	.2280E-07	-7.6234	.2850E-07	-7.5452	.1197E+01
37 FECL2+	.3226E-06	-6.4781	.1304E-06	-6.8848	.3920E+00
38 FESO4+	.5980E-10	-10.2223	.2344E-10	-10.6300	.3920E+00
39 ZNCL+	.2715E-07	-7.5663	.1064E-07	-7.9730	.3920E+00
40 ZNCL2	.9895E-08	-8.0046	.1185E-07	-7.9264	.1197E+01
41 ZNCL3-	.2027E-04	-4.6931	.7946E-05	-5.0998	.3920E+00
42 ZNCL4--	.1877E-03	-3.7265	.4433E-05	-5.3533	.2362E-01
43 ALSO4+	.1411E-17	-17.8504	.5532E-18	-18.2571	.3920E+00
44 CO3--	.7316E-17	-17.1257	.2166E-18	-18.6644	.2960E-01

GPC3-200-F-2 HOURS = 93.0 PH(25) = 2.38
 300 DEGREES C AT 500 BARS AND W/P = 5
 81/02/18.
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 H2CO3	.1231E-01	-1.9098	.1474E-01	-1.8316	.1197E+01
46 AL(OH)4-	.1280E-04	-4.8997	.4938E-05	-5.3064	.3920E+00
47 FFCH++	.1368E-10	-10.8640	.3230E-12	-12.4908	.2362E-01
48 FFCH+	.1218E-06	-6.9143	.4776E-07	-7.3210	.3920E+00
49 ALCH++	.4858E-08	-8.3136	.2467E-09	-9.6079	.5078E-01
50 NaCl	.1329E+00	-.8765	.1591E+00	-.7983	.1197E+01
51 KCl	.2991E-02	-2.5242	.3581E-02	-2.4460	.1197E+01
52 KH2PO4	.1835E-04	-4.7364	.2197E-04	-4.6582	.1197E+01
53 CaCO3	.6671E-14	-14.1758	.7986E-14	-14.0977	.1197E+01
54 MnSO4	.1115E-03	-3.9528	.1335E-03	-3.8746	.1197E+01
55 Na2SO4	.1222E-04	-4.8753	.5408E-05	-5.2669	.4059E+00
56 MgSO4	.8967E-05	-5.0474	.1073E-04	-4.9692	.1197E+01
57 CaSO4	.1744E-05	-5.7535	.2112E-05	-5.6753	.1197E+01
58 NaCO3-	.1110E-15	-15.9547	.4794E-16	-16.3193	.4320E+00
59 MgHCO3+	.2299E-07	-7.6385	.9012E-08	-8.0452	.3920E+00
60 CaHCO3+	.1060E-06	-6.9746	.4156E-07	-7.3813	.3920E+00
61 MgCO3	.2710E-20	-20.5670	.3245E-20	-20.4888	.1197E+01
62 BaCO3	.2026E-20	-20.6933	.2426E-20	-20.6151	.1197E+01
63 BaHCO3+	.1652E-08	-8.7821	.6475E-09	-9.1888	.3920E+00
64 BaOH+	.1468E-09	-9.8332	.6403E-10	-10.1936	.4361E+00
65 BaSO4	.4065E-10	-10.3909	.4866E-10	-10.3128	.1197E+01
66 SPDH+	.9392E-11	-11.0273	.4096E-11	-11.3877	.4361E+00
67 SPCO3-	.6349E-19	-19.1973	.7600E-19	-19.1192	.1197E+01
68 SRHCO3+	.5175E-06	-6.2861	.2029E-06	-6.6928	.3920E+00
69 SRSO4	.3199E-07	-7.4950	.3830E-07	-7.4168	.1197E+01

GPC3-300-E-1 HOURS = 310.5 PH(25) = 2.65
 200 DEGREES C AT FCC BAPS AND W/P = F
 81/02/78.

WATER 1.0000(KG.LIT0.) 55.5082(MOLES LIT0.) 55.5083(MOLES TOTAL)
 STOICHIOMETRIC IONIC STRENGTH=.5934417E+00 OSMOTIC COEF.= .7542
 IONIC STRENGTH=.4373955E+00 ACTIVITY=.9853

EQ2 INPUT AS REDOX CONTROL

LOG EQ2=-15.10 LOG FH2=-10.26 LOG FH2O= 1.91 LOG FCO2= -.53
 LOG FH2S= N LOG FS2= N
 CALCULATED ACTIVITY HS= .5163E-35M LOG FH2S=-29.02 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FC2
H2(AQ) CM	.1660E-12	.1983E-12 .1104E+01	.3348E-09	.3719E-11	-10.2627
O2(AQ) CM	.2574E-17	.3073E-17 .1104E+01	.8236E-13	.5766E-16	

CM - MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))17	LOG(A/(A(H+))17)
1 H+	.1213E-02	-3.1621	.1827E-01	.1000E+01	0
2 H2O		-0.0064	.5551E+02		
3 EQ2		-15.1024ATM			
4 CL-	.4066E+00	-0.8556	.5452E+00	.9578E-04	-4.0187
5 SO4--	.1135E-04	-6.4687	.5621E-03	.1603E-12	-12.7950
6 HCO3-	.4449E-07	-7.7327	.1539E-01	.1271E-10	-10.8958
7 SiO2(AQ)	.2100E-01	-3.6007	.2100E-01	.2508E-01	-1.6007
8 AL+++	.2468E-17	-16.8317	.1149E-04	.4566E-10	-10.3423
9 CA++	.7831E-02	-3.2968	.7834E-02	.8500E+03	2.9294
10 MG++	.2051E-02	-3.7601	.2061E-02	.3683E+03	2.5662
11 FE++	.0700E-05	-6.2039	.4834E-04	.1053E+01	.0222
12 K+	.2205E-01	-2.1214	.2560E-01	.1101E+02	1.0418
13 NA+	.3244E+00	-0.8941	.4573E+00	.1858E+03	2.2690
14 MN++	.1984E-01	-3.3234	.2062E-01	.1007E+04	3.0028
15 ZN++	.2558E-05	-10.2131	.2142E-03	.1297E-03	-3.8869
16 BA++	.8137E-05	-6.5266	.8143E-05	.6304E+00	-2.0004
17 SR++	.7625E-04	-6.5549	.7761E-04	.5907E+01	.7714
18 AM+	.4032E-00	-9.8960	.1320E-04	.1850E-06	-6.7329

GPC2-300-5-3 HOURS = 210.5 PH(25) = 2.65
 300 DEGRFES C AT 500 BAPS AND W/P = 5
 81/02718.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.1213E-02	-2.9160	.6869E-03	-3.1631	.5661E+00
2 H2O			.9853E+00	-.0064	.9853E+00
3 F02			.7900E-15 ATM	-15.1024	
4 CL-	.4066E+00	-.3909	.1394E+00	-.8556	.3430E+00
5 SO4--	.1135E-04	-4.9452	.3399E-06	-6.4687	.2995E-01
6 HCO3-	.4449E-07	-7.3518	.1851E-07	-7.7327	.4160E+00
7 SI02(AQ)	.2100E-01	-1.6777	.2508E-01	-1.6007	.1194E+01
8 AL+++	.2468E-17	-17.6076	.1473E-19	-19.8317	.5969E-02
9 CA++	.7831E-02	-2.1062	.4010E-03	-3.3968	.5121E-01
10 MG++	.2051E-02	-2.6879	.1737E-03	-3.7601	.6469E-01
11 FF++	.9700E-05	-5.0132	.4967E-06	-6.3039	.5121E-01
12 V+	.2205E-01	-1.6566	.7562E-02	-2.1214	.3430E+00
13 NA+	.3244E+00	-.4889	.1276E+00	-.8941	.3933E+00
14 MN++	.1984E-01	-1.7024	.4749E-03	-3.3234	.2393E-01
15 ZN++	.2558E-08	-8.5921	.6122E-10	-10.2131	.2393E-01
16 BA++	.6137E-05	-5.0895	.2974E-06	-6.5266	.3655E-01
17 SP++	.7625E-04	-4.1178	.2787E-05	-5.5549	.7655E-01
18 AU+	.4032E-09	-9.3945	.1270E-09	-9.8960	.3151E+00
19 AU+++	.8566E-32	-32.0672	.1930E-35	-35.7145	.2253E-03
20 AUCL2-	.1253E-04	-4.9020	.4929E-05	-5.3072	.3933E+00
21 AUCL-	.6673E-06	-6.1757	.2625E-06	-6.5809	.3933E+00
22 FF+++	.7515E-12	-12.1241	.4486E-14	-14.3481	.5969E-02
23 OH-	.3628E-07	-7.4403	.1329E-07	-7.8733	.2690E+00
24 H3SIO4-	.5857E-08	-8.2323	.2304E-08	-8.6376	.3933E+00
25 H2SIO4--	.1401E-15	-15.8534	.2354E-17	-17.4745	.2393E-01
26 KSO4-	.1875E-04	-4.7271	.6917E-05	-5.1601	.3690E+00
27 FES04	.1864E-06	-6.7290	.2225E-06	-6.6526	.1194E+01
28 HCL	.1394E-02	-2.8557	.1464E-02	-2.7787	.1194E+01
29 HSO4-	.3044E-03	-3.5166	.1197E-03	-3.9218	.3933E+00
30 CADH+	.5822E-06	-6.2349	.2290E-06	-6.6402	.3933E+00
31 MGOH+	.0163E-06	-6.0881	.3211E-06	-6.4934	.3933E+00
32 FECL+	.3514E-04	-4.4542	.1382E-04	-4.8595	.3933E+00
33 FECL2	.3220E-05	-5.4921	.3845E-05	-5.4151	.1194E+01
34 FECL++	.3617E-07	-7.4417	.8655E-09	-9.0627	.2393E-01
35 FECL4-	.6942E-08	-8.1585	.1661E-09	-9.7795	.2393E-01
36 FECL3	.1946E-08	-8.7110	.2323E-08	-8.6339	.1194E+01
37 FECL2+	.2716E-07	-7.5661	.1068E-07	-7.9713	.3933E+00
38 FES04+	.7879E-11	-11.1036	.3099E-11	-11.5088	.3933E+00
39 ZNCL+	.2661E-07	-7.5435	.1125E-07	-7.9487	.3933E+00
40 ZNCL2	.1044E-07	-7.9814	.1246E-07	-7.9043	.1194E+01
41 ZNCL3-	.2115E-04	-4.6747	.8319E-05	-5.0799	.3933E+00
42 ZNCL4--	.1930E-03	-3.7145	.4618E-05	-5.3355	.2393E-01
43 ALSD4+	.1188E-18	-18.9252	.4673E-19	-19.2304	.3933E+00
44 CO3--	.3750E-16	-16.4260	.1123E-17	-17.9495	.2995E-01

GPC3-300-E-3 HCUPS = 310.5 PH(25) = 2.65

300 DEGREES C AT 500 BAPS AND W/P = F

01/02/19.

(CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 H2CO?	.1530E-01	-1.8128	.1827E-01	-1.7358	.1194E+01
46 AL(OH)4-	.1149E-04	-4.0397	.4519E-05	-5.3450	.3933E+00
47 FEOH++	.2278E-11	-11.6424	.5452E-13	-13.2634	.2393E-01
48 FEOH+	.2906E-07	-7.5519	.1104E-07	-7.9572	.3933E+00
49 ALOH++	.5194E-09	-9.2844	.2661E-10	-10.5750	.5121E-01
50 NaCl	.1328E+00	-.0768	.1566E+00	-.7997	.1194E+01
51 KCl	.2516E-02	-2.4540	.4198E-02	-2.3770	.1194E+01
52 KHSO4	.1697E-04	-4.7702	.2027E-04	-4.6932	.1194E+01
53 CaCO3	.3211E-13	-13.4934	.3834E-13	-13.4164	.1194E+01
54 MnSO4	.1782E-03	-3.7491	.2128E-03	-3.6721	.1194E+01
55 Na2CO3-	.2125E-04	-4.6726	.8653E-05	-5.0628	.4071E+00
56 MgSO4	.8398E-05	-5.0758	.1003E-04	-4.9568	.1194E+01
57 CaSO4	.2615E-05	-5.5826	.3122E-05	-5.5056	.1194E+01
58 NaCO3-	.5751E-15	-15.2403	.2401E-15	-15.6037	.4331E+00
59 MgHCO3+	.2408E-07	-7.4675	.1340E-07	-7.8728	.3933E+00
60 CaHCO3+	.2497E-06	-6.6043	.5783E-07	-7.0095	.3933E+00
61 MgCO3	.1982E-20	-20.7029	.2367E-20	-20.6259	.1194E+01
62 BaCO3	.1402E-19	-19.8532	.1674E-19	-19.7762	.1194E+01
63 BaHCO3+	.5571E-08	-8.2540	.2191E-08	-8.6593	.3933E+00
64 BaCO3	.3975E-00	-9.4007	.1738E-09	-9.7599	.4372E+00
65 BaSO4	.8662E-10	-10.0624	.1034E-09	-9.9853	.1194E+01
66 SrOH+	.1910E-10	-10.7189	.8352E-11	-11.0782	.4372E+00
67 SrCO3	.3300E-18	-18.4815	.3941E-18	-18.4044	.1194E+01
68 SrHCO3+	.1311E-05	-5.8823	.5158E-06	-6.2876	.3933E+00
69 SrSO4	.5121E-07	-7.2906	.6115E-07	-7.2136	.1194E+01

GPC3-300-5-4 HOURS =625.0 PH(25) = 3.52
 300 DEGPYES C AT 500 BARS AND W/P = 5
 81/02/18.

WATER 1.0000(KG.LIO.) 55.5082(MOLES LIO.) 55.5083(MOLES TOTAL)
 STOICHIOMETRIC IONIC STRENGTH=.5854712E+00 OSMOTIC COEF.= .7541
 IONIC STRENGTH=.4385525E+00 ACTIVITY=.9853

FO2 INPUT AS REDOX CONTROL

LOG FO2=-11.49 LOG FH2=-12.07 LOG FH2O= 1.91 LOG FCO2= -.54
 LOG FH2S= N LOG FS2= N
 CALCULATED ACTIVITY HS- = .8331E-43M LOG FH2S=-37.64 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY GAMMA	PPM	CC/G	LOG F CALC LOG FO2
H2(AQ) CM	.2608E-14	.3115E-14 .1195E+01	.5257E-11	.5841E-13	-12.0665
O2(AQ) CM	.1042E-13	.1245E-13 .1195E+01	.3335E-09	.2334E-12	

CM - MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))Z	LOG(A/(AH)Z)
1 H+	.1821E-03	-3.9868	.1547E-01	.1000E+01	0
2 H2O		-.0064	.5551E+02		
3 FO2		-11.4949ATM			
4 Cl-	.4076E+00	-.8549	.5458E+00	.1440E-04	-4.8416
5 SO4--	.2006E-04	-6.2222	.5101E-03	.6371E-14	-14.1958
6 HCO3-	.2002E-06	-6.9184	.1506E-01	.1244E-10	-10.9052
7 SiO2(AQ)	.2060E-01	-1.6088	.2060E-01	.2461E-01	-1.6088
8 Al+++	.1456E-20	-23.0617	.1334E-04	.7920E-11	-11.1013
9 Ca++	.8024E-02	-3.3870	.8034E-02	.3860E+05	4.5866
10 Mg++	.2000E-02	-3.7717	.2020E-02	.1592E+05	4.2019
11 Fe++	.7669E-05	-6.4066	.3850E-04	.3690E+02	1.5670
12 K+	.2116E-01	-2.1305	.2458E-01	.7036E+02	1.8473
13 Na+	.3266E+00	-.8915	.4604E+00	.1245E+04	3.0953
14 Mn++	.2002E-01	-3.3207	.2023E-01	.4496E+05	4.6529
15 Zn++	.2541E-08	-10.2170	.2142E-03	.5709E-02	-2.2434
16 Ba++	.7236E-05	-6.5784	.7271E-05	.2464E+02	1.3952
17 Sr++	.7074E-04	-5.5882	.7875E-04	.2429E+03	2.3853
18 Au+	.3781E-09	-9.9243	.1269E-04	.1155E-05	-5.9376

GPC3-300-5-4 HClPS =625.0 PH(25) = 3.52
 300 DEGREES C AT 500 BARS AND W/R = 5
 01/02/18.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.1821E-03	-3.7396	.1031E-03	-3.9868	.5660E+00
2 H2O			.9853E+00	-.0064	.9853E+00
3 FF2			.3200E-11ATM	-11.4949	
4 CL-	.4076E+00	-.3898	.1397E+00	-.8549	.3427E+00
5 SO4--	.2006E-04	-4.6977	.5995E-06	-6.2222	.2989E-01
6 HCO3-	.2902E-06	-6.5373	.1207E-06	-6.9184	.4158E+00
7 SiO2(AQ)	.2060E-01	-1.6861	.2461E-01	-1.6088	.1195E+01
8 AL+++	.1456E-20	-20.8267	.8676E-23	-23.0617	.5957E-02
9 CA++	.8024E-02	-2.0956	.4102E-03	-3.3870	.5113E-01
10 MG++	.2000E-02	-2.6990	.1692E-03	-3.7717	.8460E-01
11 FE++	.7669E-05	-5.1153	.3921E-06	-6.4066	.5113E-01
12 K+	.2116E-01	-1.6744	.7253E-02	-2.1395	.3427E+00
13 NA+	.3266E+00	-.4860	.1284E+00	-.8915	.3931E+00
14 MN++	.2002E-01	-1.6986	.4778E-03	-3.3207	.2367E-01
15 ZN++	.2541E-09	-8.5949	.6067E-10	-10.2170	.2367E-01
16 BA++	.7236E-05	-5.1405	.2640E-06	-6.5784	.3648E-01
17 SR++	.7074E-04	-4.1503	.2581E-05	-5.5882	.3648E-01
18 AU+	.3701E-09	-9.4224	.1190E-09	-9.9243	.3148E+00
19 AU+++	.1157E-21	-31.9366	.2592E-35	-35.5863	.2240E-03
20 AUCL2-	.1170E-04	-4.9285	.4634E-05	-5.3341	.3931E+00
21 AUCL2-	.9032E-06	-6.0442	.3550E-06	-6.4497	.3931E+00
22 FF+++	.7118E-12	-12.1476	.4241E-14	-14.3726	.5957E-02
23 OH-	.2419E-06	-6.6164	.8920E-07	-7.0496	.3688E+00
24 H3SiO4-	.3832E-07	-7.4165	.1506E-07	-7.8221	.3931E+00
25 H2SiO4--	.6121E-14	-14.2132	.1461E-15	-15.8353	.2367E-01
26 KSO4-	.3174E-04	-4.4984	.1170E-04	-4.9317	.3688E+00
27 FFSO4	.2594E-06	-6.5960	.3099E-06	-6.5088	.1195E+01
28 HCL	.2095E-03	-3.4789	.2502E-03	-3.6016	.1195E+01
29 HSO4-	.8064E-04	-4.0925	.3170E-04	-4.4990	.3931E+00
30 CAOH+	.3971E-05	-5.4011	.1561E-05	-5.8066	.3931E+00
31 MGOM+	.5299E-05	-5.2758	.2083E-05	-5.6813	.3931E+00
32 FECL+	.2780E-04	-4.5559	.1093E-04	-4.9614	.3931E+00
33 FECL2	.2550E-05	-5.5935	.3046E-05	-5.5163	.1195E+01
34 FECL++	.3433E-07	-7.4644	.8196E-09	-9.0864	.2387E-01
35 FECL4-	.6623E-08	-8.1789	.1581E-09	-9.8010	.2367E-01
36 FECL?	.1848E-08	-8.7324	.2207E-08	-8.6561	.1195E+01
37 FECL2+	.2578E-07	-7.5888	.1013E-07	-7.9943	.3931E+00
38 FFSO4+	.1314E-10	-10.8812	.5167E-11	-11.2868	.3931E+00
39 ZNCL+	.2942E-07	-7.5463	.1117E-07	-7.9519	.3931E+00
40 ZNCL?	.1038E-07	-7.9839	.1240E-07	-7.9067	.1195E+01
41 ZNCL3-	.2108E-04	-4.6761	.8288E-05	-5.0816	.3931E+00
42 ZNCL4--	.1930E-03	-3.7144	.4609E-05	-5.3364	.2387E-01
43 ALSO4+	.1235E-21	-21.9083	.4854E-22	-22.3139	.3931E+00
44 CO3--	.1632E-14	-14.7872	.4879E-16	-16.3117	.2989E-01

GPC3-200-5-4 HOURS = 625.0 PH(25) = 3.52
 300 DEGREES C AT 400 BARS AND W/R = 5
 81/02/18.
 (CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 H2CO3	.1508E-01	-1.8225	.1798E-01	-1.7452	.1195E+01
46 AL(OH)4-	.1334E-04	-4.8747	.5245E-05	-5.2803	.3931E+00
47 FE(OH)++	.1438E-10	-10.8421	.3424E-12	-12.4642	.2387E-01
48 FE(OH)+	.1477E-06	-6.8307	.5504E-07	-7.2362	.3931E+00
49 AL(OH)++	.2042E-11	-11.6900	.1044E-12	-12.9813	.5113E-01
50 NaCl	.1338E+00	-.8736	.1598E+00	-.7964	.1195E+01
51 KCl	.3376E-02	-2.4716	.4033E-02	-2.3943	.1195E+01
52 KHSO4	.4308E-05	-5.3657	.5147E-05	-5.2885	.1195E+01
53 CaCO3	.1426E-11	-11.8458	.1704E-11	-11.7686	.1195E+01
54 MnSO4	.3161E-07	-3.5001	.3777E-03	-3.4229	.1195E+01
55 NaSO4-	.3774E-04	-4.4232	.1536E-04	-4.8137	.4069E+00
56 MgSO4	.1442E-04	-4.8411	.1722E-04	-4.7638	.1195E+01
57 CaSO4	.4717E-05	-5.3264	.5634E-05	-5.2491	.1195E+01
58 NaCO3-	.2514E-13	-13.5996	.1088E-13	-13.9632	.4329E+00
59 MgHCO3+	.2165E-06	-6.6646	.8509E-07	-7.0701	.3931E+00
60 CaHCO3+	.1660E-05	-5.7799	.6525E-06	-6.1854	.3931E+00
61 MgCO3	.1887E-20	-20.7241	.2255E-20	-20.6469	.1195E+01
62 BaCO3	.5404E-18	-18.2673	.6455E-18	-18.1901	.1195E+01
63 BaHCO3+	.3226E-07	-7.4914	.1268E-07	-7.8969	.3931E+00
64 BaOH+	.2352E-09	-8.6286	.1028E-08	-8.9881	.4370E+00
65 BaSO4	.1356E-09	-9.8678	.1619E-09	-9.7906	.1195E+01
66 SrOH+	.1179E-09	-9.9284	.5154E-10	-10.2879	.4370E+00
67 SrCO3	.1327E-16	-16.8771	.1585E-16	-16.7999	.1195E+01
68 SrHCO3+	.7922E-05	-5.1012	.2114E-05	-5.5067	.3931E+00
69 SrSO4	.8363E-07	-7.0777	.9990E-07	-7.0004	.1195E+01

GPC3-200-5-F HOURS =1509.0 PH(25) = 4.02
 300 DEGREES C AT 500 BARS AND W/F = 5
 P1702718.

WATER 1.0000(KG.LIQ.) 55.5082(MOLES LIQ.) 55.5083(MOLES TOTAL)
 STOICHIOMETRIC IONIC STRENGTH=.5754519E+00 OSMOTIC COEF.= .7544
 IONIC STRENGTH=.4272956E+00 ACTIVITY= .9857

FD2 INPUT AS REDOX CONTROL

LOG FD2= -8.70 LOG FH2=-13.46 LOG FH2O= 1.91 LOG FCO2= -.34
 LOG FH2S= N LOG FS2= N
 CALCULATED ACTIVITY HS- = .9654E-49M LOG FH2S=-44.23 LOG FS2= I

SPECIES	MOLALITY	ACTIVITY CALC	PPM	CC/G	LOG F CALC LOG FD2
H2(AO) CM	.1048E-15	.1247E-15 .1189E+01	.2113E-12	.2348E-14	-13.4643
F2(AO) CM	.6543E-11	.7781E-11 .1185E+01	.2094E-06	.1466E-09	

CM - MOLALITY CALCULATED FROM REDOX EQUATION

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))Z	LOG(A/(AH)Z)
1 H+	.3958E-04	-4.4047	.2410E-01	.1000E+01	0
2 H2O		-.0063	.5551E+02		
3 FCO2		-8.6990ATM			
4 CL-	.3967E+00	-.8633	.5299E+00	.3076E-05	-5.5120
5 SO4--	.4083E-04	-5.9045	.8953E-03	.6281E-15	-15.2020
6 HCO3-	.2011E-05	-6.0544	.2413E-01	.1981E-10	-10.7032
7 SIO2(AO)	.1806E-01	-1.6681	.1806E-01	.2147E-01	-1.6681
8 AL+++	.2958E-23	-25.7454	.1223E-04	.1588E-11	-11.7992
9 CA++	.8837E-02	-3.3385	.8882E-02	.9098E+06	5.9590
10 MG++	.2032E-02	-3.7602	.2090E-02	.3446E+06	5.5373
11 FE++	.3522E-05	-6.7381	.1791E-04	.3625E+03	2.5594
12 K+	.1937E-01	-2.1745	.2251E-01	.2980E+03	2.4742
13 NA+	.3183E+00	-.9002	.4475E+00	.5605E+04	3.7485
14 MN++	.1888E-01	-3.3360	.1951E-01	.9152E+06	5.9615
15 ZN++	.2619E-08	-10.1938	.2050E-02	.1270E+00	-.8963
16 BA++	.6395E-05	-6.6240	.6616E-05	.4714E+03	2.6734
17 SR++	.4424E-04	-5.7841	.8103E-04	.2261E+04	3.5134
18 AU+	.3880E-09	-9.9092	.1269E-04	.5490E-05	-5.2605

GPC3-300-5-R HOURS =1508.0 PH(25) = 4.02
 300 DEGPRES C AT FCC BARS AND W/P = F
 81/02/1P.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.3958E-04	-4.4025	.2245E-04	-4.6487	.5672E+00
2 H2O			.9857E+00	-.0063	.9857E+00
3 FFP			.2000E-00 ATM	-8.6990	
4 CL-	.3947E+00	-.4015	.1370E+00	-.8633	.3454E+00
5 SO4--	.4083E-04	-4.3891	.1246E-05	-5.9045	.3052E-01
6 HCO3-	.2111E-05	-5.6756	.6822E-06	-6.0544	.4180E+00
7 SiO2(AQ)	.1806E-01	-1.7434	.2147E-01	-1.6681	.1189E+01
8 AL+++	.2958E-23	-23.5290	.1797E-25	-25.7454	.6076E-02
9 CA++	.8P37E-02	-2.0537	.4586E-03	-3.3385	.5190E-01
10 MG++	.2037E-02	-2.6920	.1737E-03	-3.7602	.8548E-01
11 FE++	.2522E-05	-5.4533	.1928E-06	-6.7381	.5190E-01
12 K+	.1937E-01	-1.7128	.6691E-02	-2.1745	.3454E+00
13 NA+	.3183E+00	-.4972	.1258E+00	-.9002	.3954E+00
14 MN++	.1888E-01	-1.7241	.4612E-03	-3.3260	.2444E-01
15 NH4+	.2619E-08	-8.5819	.6400E-10	-10.1938	.2444E-01
16 BA++	.6395E-05	-5.1941	.2377E-06	-6.6240	.3716E-01
17 SP++	.4424E-04	-4.3542	.1644E-05	-5.7841	.3716E-01
18 AM+	.3880E-09	-9.4112	.1233E-09	-9.9092	.3177E+00
19 AU+++	.1344E-31	-31.8716	.3175E-35	-35.4983	.2362E-03
20 ANCL2-	.1147E-04	-4.9328	.4616E-05	-5.3357	.2954E+00
21 ANCL4-	.1018E-05	-5.9924	.4024E-06	-6.3954	.3954E+00
22 FE+++	.3538E-12	-12.4513	.2150E-14	-14.6677	.6076E-02
23 OH-	.1104E-05	-5.9572	.4097E-06	-6.3875	.3712E+00
24 H3SiO4-	.1526E-06	-6.8164	.6024E-07	-7.2194	.3954E+00
25 H2SiO4--	.1100E-12	-12.9587	.2688E-14	-14.5706	.2444E-01
26 KSO4-	.6044E-04	-4.2187	.2244E-04	-4.6490	.3712E+00
27 FES04	.2524E-06	-6.5976	.3002E-06	-6.5226	.1189E+01
28 HCL	.4495E-04	-4.3473	.5346E-04	-4.2720	.1189E+01
29 HSO4-	.3628E-04	-4.4403	.1435E-04	-4.8432	.3954E+00
30 CAQH+	.2027E-04	-4.6931	.8016E-05	-5.0960	.3954E+00
31 MGQH+	.2485E-04	-4.6047	.9822E-05	-5.0077	.3954E+00
32 FECL+	.1264E-04	-4.8984	.4956E-05	-5.3014	.3954E+00
33 FECL2	.1148E-05	-5.9399	.1366E-05	-5.8647	.1189E+01
34 FECL++	.1667E-07	-7.7780	.4075E-09	-9.3899	.2444E-01
35 FECL4-	.3035E-06	-8.5178	.7418E-10	-10.1297	.2444E-01
36 FECL3	.8977E-09	-9.0517	.1056E-08	-8.9765	.1189E+01
37 FECL2+	.1250E-07	-7.9022	.4941E-08	-8.3062	.3954E+00
38 FES04+	.1377E-10	-10.8612	.5443E-11	-11.2642	.3954E+00
39 ZNCL+	.2924E-07	-7.5341	.1156E-07	-7.9371	.3954E+00
40 ZNCL2	.1058E-07	-7.9756	.1258E-07	-7.5003	.1189E+01
41 ZNCL3-	.2086E-04	-4.6806	.8240E-05	-5.0636	.3954E+00
42 ZNCL4--	.1841E-03	-3.7350	.4499E-05	-5.3460	.2444E-01
43 ALSP4+	.52P5E-24	-24.2770	.2090E-24	-24.6799	.3954E+00
44 CO3--	.5367E-13	-13.2702	.1638E-14	-14.7857	.3052E-01

GPC3-300-E-F HOURS =1508.0 PH(25) = 4.02

300 DEGREES C AT 500 BARS AND W/P = F

81/02/18.

(CONTINUED)

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
45 H2CO3	.2408E-01	-1.6184	.2863E-01	-1.5432	.1189E+01
46 AL(OH)4-	.1223E-04	-4.9125	.4826E-05	-5.3155	.3954E+00
47 FFOH++	.3271E-10	-10.4853	.7995E-12	-12.0972	.2444E-01
48 FEOH+	.3143E-06	-6.5027	.1243E-06	-6.9056	.3954E+00
49 ALOH++	.1914E-13	-13.7191	.9932E-15	-15.0029	.5190E-01
50 NaCl	.1292E+00	-.8887	.1536E+00	-.8135	.1189E+01
51 KCl	.3069E-02	-2.5130	.3649E-02	-2.4378	.1189E+01
52 KHSO4	.1807E-05	-5.7430	.2149E-05	-5.6677	.1189E+01
53 CaCO3	.5377E-10	-10.2695	.6394E-10	-10.1942	.1189E+01
54 MnSO4	.6372E-03	-3.1958	.7577E-03	-3.1205	.1189E+01
55 Na2CO4-	.7646E-04	-4.1176	.3128E-04	-4.5047	.4091E+00
56 MgSO4	.3091E-04	-4.5100	.2675E-04	-4.4347	.1189E+01
57 CaSO4	.1101E-04	-4.9583	.1309E-04	-4.8830	.1189E+01
58 NaCO3-	.8235E-12	-12.0943	.3582E-12	-12.4459	.4350E+00
59 MgHCO3+	.1616E-05	-5.7916	.6388E-06	-6.1946	.3954E+00
60 CaHCO3+	.1349E-04	-4.8700	.5334E-05	-5.2729	.3954E+00
61 MgCO3	.3100E-20	-20.5086	.3687E-20	-20.4333	.1189E+01
62 BaOH+	.1641E-16	-16.7850	.1951E-16	-16.7097	.1189E+01
63 BaHCO3+	.2111E-06	-6.6755	.8347E-07	-7.0785	.3954E+00
64 BaOH+	.9681E-08	-8.0141	.4250E-08	-8.3716	.4391E+00
65 BaSO4	.2548E-09	-9.5938	.3030E-09	-9.5186	.1189E+01
66 SrOH+	.3434E-09	-9.4641	.1508E-09	-9.8216	.4391E+00
67 SrCO3	.2851E-15	-15.5450	.3390E-15	-15.4698	.1189E+01
68 SrHCO3+	.2668E-04	-4.4355	.1450E-04	-4.8385	.3954E+00
69 SrSO4	.1112E-06	-6.9539	.1322E-06	-6.8786	.1189E+01

GPC3-300-446 HOURS = 3026.5 PH(25) = 4.54
 300 DEGREES C AT 500 BARS AND W/P = 5
 81/02/18.

WATER 1.0000(KG.LIQ.) 55.5082(MOLES LIQ.) 55.5083(MOLES TOTAL)
 STOICHIOMETRIC IONIC STRENGTH=.583715E+00 OSMOTIC COEF.= .7533
 IONIC STRENGTH=.4406835E+00 ACTIVITY=.9852

REFBOX OPTION = F

4 GOLD + O2(GAS,AQ) + 4 H+ == 4 AU+ + 2 H2O

SPECIES	MOLALITY	LOG(A)	TOT MOLES	A/(A(H+))Z	LOG(A/(A(H+))Z)
1 H+	.3282E-04	-4.7182	.6177E-04	.1000E+01	0
2 H2O		-.0065	.5551E+02		
3 F02		-9.6420ATM			
4 CL-	.4096E+00	-.8534	.5479E+00	.2682E-05	-5.5715
5 SO4--	.6435E-04	-5.7176	.1385E-02	.7015E-15	-15.1540
6 SiO2(AQ)	.1523E-01	-1.7398	.1523E-01	.1821E-01	-1.7398
7 CA++	.8470E-02	-3.3647	.8508E-02	.1179E+07	6.0717
8 MG++	.2457E-02	-3.6491	.2756E-02	.6127E+06	5.7873
9 K+	.1930E-01	-2.1801	.2248E-01	.3452E+03	2.5381
10 NA+	.3293E+00	-.8883	.4646E+00	.6758E+04	3.8298
11 MN++	.1550E-01	-3.3340	.2048E-01	.1266E+07	6.1023
12 AU+	.3956E-09	-9.9054	.1269E-04	.6497E-05	-5.1873

GPC3-300-5-6 PDURS = 3026.5 PH(25) = 4.54
 300 DEGREES C AT 500 PARS AND W/P = F
 P1/02718.

SPECIES	MOLALITY	LOG(M)	ACTIVITY	LOG(A)	GAMMA
1 H+	.3382E-04	-4.4708	.1914E-04	-4.7182	.5657E+00
2 H2O			.9852E+00	-.0065	.9852E+00
3 F2O			.2280E-09 ATM	-9.6420	
4 CL-	.4096E+00	-.3876	.1402E+00	-.6534	.3422E+00
5 SO4--	.6435E-04	-4.1915	.1916E-05	-5.7176	.2978E-01
6 STO2(AQ)	.1523E-01	-1.8174	.1821E-01	-1.7398	.1196E+01
7 CA++	.8470E-02	-2.0721	.4318E-03	-3.3647	.5099E-01
8 MG++	.2657E-02	-2.5756	.2244E-03	-3.6491	.8444E-01
9 K+	.1930E-01	-1.7144	.6605E-02	-2.1801	.3422E+00
10 NA+	.3293E+00	-.4823	.1293E+00	-.6883	.3926E+00
11 MN++	.1950E-01	-1.7100	.4634E-02	-3.3340	.2377E-01
12 NH4+	.2954E-00	-0.4029	.1243E-09	-9.9054	.2143E+00
13 NH4++	.3569E-22	-32.4475	.7917E-36	-36.1015	.2218E-03
14 AUCL2-	.1241E-04	-4.9062	.4874E-05	-5.3122	.3926E+00
15 AUCL4-	.2900E-06	-6.5529	.1099E-06	-6.9589	.2926E+00
16 OH-	.1305E-05	-5.8845	.4805E-06	-6.3183	.3683E+00
17 H3SIO4-	.1520E-06	-6.8156	.6003E-07	-7.2216	.3926E+00
18 H2SIO4--	.1320E-12	-12.8795	.2137E-14	-14.5034	.2377E-01
19 KSO4-	.9249E-04	-4.0330	.3406E-04	-4.4677	.3683E+00
20 HCL	.3898E-04	-4.4091	.4661E-04	-4.3315	.1196E+01
21 HSO4-	.4799E-04	-4.3198	.1880E-04	-4.7258	.3926E+00
22 CACH+	.2254E-04	-4.6470	.8852E-05	-5.0530	.3926E+00
23 MGOH+	.3700E-04	-4.4214	.1488E-04	-4.8274	.3926E+00
24 NAOL	.1351E+00	-.8693	.1615E+00	-.7917	.1196E+01
25 KCL	.3083E-02	-2.5111	.2686E-02	-2.4335	.1196E+01
26 KHSO4	.2325E-05	-5.6335	.2780E-05	-5.5559	.1196E+01
27 MNSO4	.9700E-03	-3.0092	.1170E-02	-2.9316	.1196E+01
28 NASO4-	.1214E-03	-2.9150	.4943E-04	-4.3060	.4065E+00
29 MGSO4	.6105E-04	-4.2143	.7300E-04	-4.1367	.1196E+01
30 CASO4	.1585E-04	-4.7909	.1855E-04	-4.7223	.1196E+01

Addenda 2

Mineral Saturation Data for Solution Samples.
Hydrolysis Constants (Log K) from Helgeson et al.
(1978) and Calculated from Thermodynamic Data from
Robie et al. (1978).

<u>Experiment</u>	<u>Code</u>
smectite-rich sediment - 200°C	SM2-200-5 (4 samples)
smectite-rich sediment - 300°C	SM3-300-5 (6 samples)
metalliferous sediment - 200°C	GPC3C-200-5 (5 samples)
metalliferous sediment - a) 200°C	GPC3B-200-5 (samples 1,2,3,4)
b) 300°C	GPC3B-200-5 (samples 5,6,7)
metalliferous sediment - 300°C	GPC3-300-5 (6 samples)

SM2-200-F-1 HOURS = 5.00 PH(25) = 4.86
200 DEGREES C AT 500 BARS AND W/P = 5
81702/17.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-14.49	3.06	17.55	-37993.98	-4469.88
MAGNETIT	-11.62	7.11	18.73	-40559.98	-3244.80
CHRYSOTI	17.79	18.90	1.11	-2399.56	-149.97
ANTIGORI	7.71	2.98	.27	-582.59	-226.69
TALC	11.20	14.12	2.92	-6330.85	-372.40
ANTHOPHY	35.24	36.15	.91	-1978.82	-53.48
FAYALITE	5.09	5.72	.63	-1374.05	-152.67
HAUSMANI	11.91	12.65	.74	-1591.39	-127.31
BIXBYITE	5.94	6.75	.81	-1750.29	-205.92

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	.19	-1.83	-2.02	4364.15	969.81
MC2OH-SO	-2.47	-4.20	-1.73	3751.94	1042.20
GOLD	-4.01	-4.16	-.15	324.63	7.64
ANHYDRIT	-6.70	-6.84	-.14	304.93	152.46
BARITE	-9.68	-10.85	-1.17	2538.91	1269.46
CELESTIT	-7.85	-9.17	-1.32	2860.36	1430.18
ARAGONIT	-.11	-2.52	-2.41	5211.31	1737.10
CALCITE	-.26	-2.52	-2.26	4885.91	1628.64
DOLOMITE	-2.06	-3.98	-1.92	4160.36	693.39
MAGNESIT	-.83	-1.46	-.63	1366.26	455.42
SIDERITE	-4.83	-5.30	-.47	1011.66	337.22
WITHERIT	-2.47	-6.53	-4.06	8794.74	2931.58
STRONTIA	-1.65	-4.85	-3.20	6923.05	2307.68
QUARTZ	-2.33	-2.39	-.06	125.09	125.09
AM STO2	-1.68	-2.39	-.71	1534.76	1534.76
ALBITE	-.20	-3.35	-3.15	6816.26	619.66
ANORTHIT	9.19	.88	-8.31	17996.12	1058.60
MICROCLI	-1.57	-4.85	-3.28	7101.46	645.59
ZOISITE	17.05	4.73	-12.32	26674.06	952.64
CLINOZOI	17.03	4.73	-12.30	26630.76	951.10
PREHNITE	14.81	5.31	-9.50	20557.42	893.80
WATRAKIT	4.24	-3.92	-8.16	17661.30	841.01
ANALCIME	2.39	-.97	-3.35	7261.21	660.11
LAUMONTI	3.43	-3.93	-7.37	15948.34	693.41
TREMOLIT	34.24	34.03	-.21	455.12	12.30
BRUCITE	9.68	7.89	-1.79	3871.26	774.27
FORSTERI	15.04	13.41	-1.63	3538.27	303.14

SM2-200-E-1 HOURS = 5.00 PH(25) = 4.86
 200 DEGREES C AT 500 BARS AND W/P = 5
 81702/17.

ENSTATIT	5.98	5.50	-.48	1036.91	172.82
DIOPSIDE	12.10	9.95	-2.15	4648.68	464.87
CA-AL-PY	15.19	3.27	-11.91	25790.57	1611.91
GTBRSITE	2.61	-.60	-3.22	6960.54	994.36
KAOLINIT	-.86	-5.97	-5.11	11069.26	737.95
PYROPHYL	-5.11	-10.75	-5.64	12204.92	762.81
MUSCOVIT	1.01	-6.04	-7.05	15257.61	663.37
ILLITE11	-2.29	-7.92	-5.63	12192.82	603.61
ILLITE12	-1.40	-6.68	-5.28	11427.22	564.31
ILLITE13	-.43	-5.43	-5.00	10834.81	533.73
14ACL-CH	31.85	31.11	-.74	1599.18	42.08
7A-CL-CH	34.45	31.11	-3.34	7228.16	190.21
PARAGONI	3.04	-4.54	-7.58	16403.25	713.18
PYROCHRO	9.37	5.89	-3.48	7526.90	1505.38
PYROLUST	1.19	.85	-.35	747.47	166.10
RHODACHR	-2.01	-3.46	-1.44	3125.70	1041.90
GRAPHITE	36.37	-4.31	-40.67	88058.01	25159.43

SOLID SOLUTIONS

MINERAL X SUM

SM2-200-5-2 H2O/P = 101.00 PH(25) = 4.47
 200 DFGPEFS C AT 500 BARS AND W/P = 5
 81/02/17.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LOG-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
GOLD	-4.01	-3.13	.88	-1905.62	-44.84
HEMATITE	-14.49	2.00	16.49	-35696.96	-4199.64
MAGNETIT	-11.62	5.62	17.24	-37326.87	-2986.15
QUARTZ	-2.33	-1.86	.47	-1023.27	-1023.27
TREMOLIT	34.24	34.50	.26	-571.41	-15.44
CHRYSOIT	17.79	18.28	.49	-920.40	-57.52
ANTIGORIT	2.71	2.88	.17	-368.89	-143.54
TALC	11.20	14.50	3.30	-7148.31	-420.49
ANTHOPHY	35.24	36.32	1.09	-2354.98	-63.65
FAYALITE	5.09	5.39	.30	-650.22	-72.25
HAUSMANI	11.91	14.20	2.28	-4944.08	-395.60
BITXPYITE	5.94	7.72	1.78	-3844.40	-452.28
PYROCLUST	1.19	1.23	.04	-87.16	-19.37

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LOG-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	.19	-2.39	-2.57	5567.55	1237.23
MG2OH-SO	-2.47	-4.58	-2.11	4577.70	1271.58
ANHYDRIT	-6.70	-6.95	-.26	553.84	276.92
BARITE	-9.68	-11.01	-1.33	2878.57	1439.28
CELESTIT	-7.85	-9.27	-1.42	3076.19	1538.10
ARAGONIT	-.11	-2.47	-2.35	5092.70	1697.57
CALCITE	-.26	-2.47	-2.20	4767.30	1589.10
DOLOMITE	-2.06	-4.02	-1.96	4248.32	706.05
MAGNEST	-.83	-1.55	-.73	1572.83	524.28
SIDEPITE	-4.82	-5.25	-.41	895.64	298.55
WITHEPIT	-2.47	-6.52	-4.05	8766.86	2922.29
STRONTIA	-1.65	-4.78	-3.13	6771.36	2257.12
AM SIO2	-1.68	-1.86	-.18	386.40	386.40
ALBITE	-.20	-1.92	-1.72	3723.24	338.48
ANORTHIT	9.10	1.67	-7.52	16272.29	957.19
MICROCLIT	-1.57	-3.27	-1.70	3677.90	334.35
ZOISITE	17.05	5.71	-11.34	24555.02	876.97
CLINOZOIT	17.03	5.71	-11.32	24511.72	875.42
PREHNITE	14.81	6.21	-8.60	18618.65	809.51
WAIPAKIT	4.24	-2.06	-6.30	13640.59	649.55
ANALCIME	2.39	-.07	-2.46	5316.46	483.31
LAUMONTI	3.43	-2.08	-5.51	11927.47	518.59
BPUCITE	9.68	7.31	-2.37	5129.96	1025.99

SM2-200-5-2 HOURS = 101.00 PH(25) = 4.47
 200 DEGREES C AT 500 BARS AND W/P = 5
 81702/17%

FORSTERI	15.04	12.77	-2.27	4907.28	545.25
ENSTATIT	5.98	5.45	-.53	1147.15	191.19
DIOPSIDE	12.10	10.00	-2.10	4544.14	454.41
CA-AL PX	15.12	3.53	-11.65	25215.09	1575.94
GIBBSITE	2.61	-.52	-3.13	6780.11	968.59
KADLINIT	2.86	-4.75	-3.89	8411.77	560.78
PYROPHYL	-5.11	-8.46	-3.35	7250.80	453.18
MUSCOVIT	1.01	-4.29	-5.30	11473.35	498.84
ILLITE11	-2.29	-5.96	-3.67	7940.63	393.10
ILLITE12	-1.40	-4.81	-3.41	7381.86	364.54
ILLITE13	-.43	-3.66	-3.23	6996.28	344.64
14ACL-CH	31.85	29.96	-1.89	4086.57	107.54
7A-CL-CH	34.45	29.96	-4.49	9715.55	255.67
PARAGONT	3.04	-2.94	-5.98	12949.53	563.02
PYROCHRO	9.37	6.47	-2.89	6267.34	1253.47
RHODACHP	-2.01	-2.39	-.38	814.11	271.37
GRAPHITE	36.37	-3.62	-39.99	66581.05	24737.44

SOLID SOLUTIONS

MINERAL	X	SUM
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SM2-200-F-2 PGLPS = 341.00 PH(25) = 4.39
 200 DEGREES C AT 500 BARS AND W/P = F
 81/07/18.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
GOLD	-4.01	-3.17	.84	-1811.01	-42.61
HEMATITE	-14.49	1.66	16.15	-34954.73	-4112.22
MAGNETIT	-11.62	5.16	16.78	-36324.00	-2905.92
QUARTZ	-2.33	-1.85	.48	-1044.30	-1044.30
ANTIGORIT	2.71	2.74	.03	-70.31	-27.36
TALC	11.20	12.66	2.46	-5321.64	-313.04
FAYALITE	5.00	5.15	.07	-149.99	-16.67
HAUSMANN	11.91	13.42	1.50	-3255.52	-260.44
BIXPYITE	5.94	7.16	1.22	-2644.44	-311.11

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-CH-SO	.19	-2.74	-2.93	6342.70	1409.49
MG2OH-SO	-2.47	-4.95	-2.38	5161.77	1433.93
ANHYDRIT	-6.70	-6.98	-.29	618.92	309.46
BARITE	-9.68	-10.92	-1.24	2686.51	1343.26
CELESTIT	-7.85	-9.30	-1.45	3145.12	1572.56
ARAGONIT	-.11	-2.59	-2.48	5364.08	1788.03
CALCITE	-.26	-2.59	-2.33	5038.69	1679.56
DOLOMIT	-2.06	-4.45	-2.39	5182.69	863.78
MAGNESIT	-.83	-1.86	-1.03	2235.81	745.27
SIDERITE	-4.82	-5.38	-.55	1182.32	394.11
WITHERIT	-2.47	-6.53	-4.06	6781.12	2927.04
STRONTIA	-1.65	-4.91	-3.25	7046.59	2348.86
AM-SIO2	-1.68	-1.85	-.17	365.37	365.37
ALBITE	-.20	-1.82	-1.62	3509.01	319.00
ANOPHTIT	9.19	1.97	-7.22	15629.42	919.38
MICROCLI	-1.57	-3.10	-1.53	3317.47	301.59
ZOISITE	17.05	6.10	-10.95	23713.38	846.91
CLINOZOI	17.02	6.10	-10.93	23670.08	845.26
PREHNITE	14.81	6.40	-8.41	16200.09	791.31
WATPAKIT	4.24	-1.75	-5.98	12955.67	616.94
ANALCIME	2.39	.02	-2.37	5123.26	465.75
LAUMONT	3.43	-1.76	-5.19	11242.56	488.81
TREMOLIT	34.24	32.88	-1.36	2935.66	79.34
BRUCITE	9.68	7.02	-2.66	5766.89	1153.38
CHRYSOTI	17.79	17.35	-.44	948.34	59.27
ANTHOPHY	35.24	34.35	-.89	1935.28	52.30
FORSTERI	15.04	12.19	-2.85	6160.11	664.46

SM2-200-5-2 POURS = 341.00 PH(25) = 4.39
 200 DEGREES C. AT 500 BARS AND W/P = F
 81/02/18.

ENSTATITE	5.98	5.16	-.81	1763.05	293.84
DIOPSIDE	12.10	9.61	-2.49	5384.34	539.43
CA-AL-PX	15.18	3.82	-11.36	24593.25	1537.08
GIBBSITE	2.61	-.32	-2.94	6357.04	908.15
KAOLINITE	-.86	-4.34	-3.48	7523.57	501.57
PYROPHYLL	-5.11	-8.03	-2.92	6320.55	395.03
MUSCOVITE	1.01	-3.73	-4.74	10266.78	446.38
ILLITE11	-2.29	-5.45	-3.16	6844.58	338.84
ILLITE12	-1.40	-4.37	-2.97	6423.66	317.22
ILLITE13	-.43	-3.26	-2.85	6175.93	304.23
14ACL-CH	31.85	28.91	-2.94	6362.00	167.42
7A-CL-CH	34.45	28.91	-5.54	11990.97	315.55
PARAGONI	3.04	-2.45	-5.49	11889.17	516.92
PYROCHRO	9.37	6.25	-3.12	6756.84	1351.37
PYROLUST	1.19	.91	-.29	623.30	138.51
RHODACHP	-2.01	-2.63	-.61	1329.66	443.22
GRAPHITE	36.37	-3.53	-39.90	86386.14	24681.76

SOLID SOLUTIONS

MINERAL X SUM

SM2-200-F-4 HOURS = 678.00 PH(25) = 4.35
200 DEGREES C AT 500 BARS AND W/P = 5
P1/02/18.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LOG-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
GOLD	-4.01	-3.28	.73	-1582.22	-37.23
HEMATITE	-14.49	1.96	16.45	-35608.98	-4189.29
MAGNETIT	-11.62	5.66	17.28	-37406.64	-2992.53
QUARTZ	-2.33	-1.83	.50	-1081.96	-1081.96
TALC	11.20	12.88	1.68	-2637.66	-213.98
FAYALITE	5.09	5.57	.48	-1044.43	-116.05
HAUSMANI	11.91	12.54	.63	-1354.16	-108.33
RIXPYITE	5.04	6.54	.60	-1309.36	-154.04

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LOG-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	.19	-2.87	-3.05	6504.57	1467.68
MG2OH-SO	-2.47	-4.89	-2.42	5240.24	1455.62
ANHYDRIT	-6.70	-6.88	-.18	393.46	196.73
BARITE	-9.68	-10.73	-1.05	2283.47	1141.74
CELESTIT	-7.85	-9.18	-1.34	2891.31	1445.65
ARAGONIT	-.11	-2.90	-2.78	6023.17	2007.72
CALCITE	-.26	-2.90	-2.63	5697.77	1899.26
DOLOMITE	-2.06	-5.14	-3.09	6682.38	1113.73
MAGNESIT	-.93	-2.25	-1.42	3076.42	1025.47
SIDEPITE	-4.83	-5.29	-.45	983.04	327.68
WITHERIT	-2.47	-6.75	-4.28	9262.62	3087.54
STRONTIA	-1.65	-5.20	-3.55	7677.31	2559.10
AM STO2	-1.68	-1.83	-.15	327.71	327.71
ALBIT	-.20	-1.71	-1.51	3269.63	297.24
ANORTHIT	9.19	2.13	-7.06	15274.26	898.49
NYCPOCLT	-1.57	-3.09	-1.52	3293.97	299.45
ZOISITE	17.05	6.24	-10.81	23395.70	835.56
CLINOZOI	17.03	6.24	-10.79	23352.40	834.01
PPEHNITE	14.81	6.39	-8.42	18237.37	792.93
WAIPAKIT	4.24	-1.55	-5.79	12525.45	596.45
ANALCIME	2.39	.11	-2.27	4921.68	447.43
LAUMONTI	3.43	-1.56	-4.99	10812.59	470.11
TREMOLIT	34.24	31.21	-3.03	6551.94	177.08
EPUCITE	9.68	6.73	-2.95	6378.52	1275.70
CHRYSOIT	17.70	16.54	-1.25	2767.77	169.24
ANTIGORI	2.71	2.61	-.10	210.44	81.89
ANTHOPHY	35.24	32.51	-2.73	5914.60	159.85
FORSTERI	15.04	11.65	-3.39	7346.44	814.14

SM2-200-5-4 HOURS = 678.00 PH(25) = 4.35
200 DEGREES C AT 500 BARS AND W/P = 5
P1/02/18.

FNSTATIT	5.98	4.90	-1.06	2337.02	389.50
DIOPSIDE	12.10	9.17	-2.93	6350.49	635.05
GA-AL PX	15.18	3.97	-11.21	24275.76	1517.24
GIBBSITE	2.61	-1.16	-2.77	6002.33	857.48
KAOLINIT	-1.86	-3.97	-3.11	6738.70	449.25
PYROPHYL	-5.11	-7.63	-2.52	5460.21	341.26
MUSCOVIT	1.01	-3.30	-4.40	9533.60	414.50
ILLITE11	-2.29	-5.09	-2.80	6060.54	300.03
ILLITE12	-1.40	-4.06	-2.66	5766.83	284.78
ILLITE13	-1.43	-3.04	-2.61	5646.32	278.14
14ACL-CH	31.85	27.88	-3.97	8597.21	226.24
7A-CL-CH	34.45	27.88	-6.57	14226.19	374.37
PARAGENT	3.04	-2.01	-5.05	10940.11	475.66
PYROCHRO	9.37	5.99	-3.38	7323.25	1464.65
PYROLUSI	1.19	.55	-1.64	1392.10	309.36
RHODACHR	-2.01	-2.99	-1.98	2125.05	708.35
GRAPHTTE	35.37	-3.55	-39.91	84412.72	24669.25

SOLID SOLUTIONS

MINERAL X SUM

SM3-300-5-1 HOURS = 2.0 PH(25) = 2.71
 300 DEGREES C AT 500 BARS AND W/P = F
 81/02/19.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
GOLD	-2.78	-2.66	.12	-307.95	-7.25
HEMATITE	-13.14	-5.14	8.00	-20980.69	-2468.32
MAGNETITE	-11.64	-3.81	8.15	-21375.52	-1710.04
QUARTZ	-1.91	-1.28	.52	-1390.19	-1390.19
AM STOR	-1.48	-1.38	.10	-249.53	-249.53
TALC	7.94	8.22	.28	-734.27	-43.19

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MC-OR-SO	-4.64	-5.64	-1.60	4191.98	931.55
MG-OR-SO	-5.90	-7.02	-1.11	2923.04	811.95
ANHYDRIT	-8.93	-9.05	-.12	314.32	157.16
BARITE	-11.14	-12.43	-1.29	3277.91	1688.95
CELESTITE	-8.77	-11.48	-1.70	4470.00	2235.00
ARAGONITE	-1.37	-7.71	-6.34	16614.05	5538.02
CALCITE	-1.54	-7.71	-6.17	16178.71	5292.90
OPLOMITE	-4.79	-14.29	-9.50	24922.54	4153.76
MAGNESITE	-2.48	-6.58	-4.10	10760.59	3586.86
SIDERITE	-6.23	-9.84	-3.51	9199.66	2066.55
WITHERITE	-3.02	-11.08	-8.06	21133.16	7044.39
STRONTIA	-2.50	-10.13	-7.64	20027.54	6675.85
ALBITE	-1.36	-12.64	-11.28	29590.68	2690.06
ANORTHITE	3.46	-21.85	-25.32	66390.71	3905.34
MICROCCLIN	-2.34	-13.88	-11.54	30260.11	2750.92
ZOISITE	8.57	-31.05	-39.62	103897.62	3710.63
CLINOZOISITE	8.54	-31.05	-39.61	102868.77	3709.60
PREHNITE	8.97	-19.78	-28.75	75286.00	3277.65
WAIPAKITI	-1.43	-24.63	-24.20	63463.72	3022.08
ANALCIME	.89	-11.27	-12.16	31888.39	2898.94
LAUNONTI	.02	-24.65	-24.68	64723.79	2814.08
TRIPOLITE	25.66	18.79	-6.87	18012.15	486.81
REPUCITE	7.75	4.58	-3.17	8318.99	1663.80
CHRYSOTILE	13.73	10.98	-2.75	7208.47	450.53
ANTYDORITE	2.08	1.73	-.35	907.66	253.17
ANTHOPHY	25.11	21.03	-4.08	10690.15	288.92
FORSTERITE	11.07	7.79	-3.28	8599.88	955.54
FAYALITE	1.96	1.28	-.69	1798.57	199.84
ENSTATITE	4.28	3.20	-1.08	2845.48	474.25
DIOPSIDE	9.35	5.29	-4.06	10653.02	1065.30

SM2-300-5-1 HOURS = 2.0 PH(25) = 2.71
 300 DEGREES C AT 500 BARS AND W/P = F
 81/02/18.

CA-AL OX	8.55	-20.47	-29.02	76099.66	4756.23
GIPPSITE	1.05	-11.29	-12.34	32353.40	4621.91
KACLINIT	-3.55	-25.33	-21.79	57136.45	3809.10
PYROPHYL	-7.37	-28.09	-20.72	54336.55	3396.03
MUSCOVIT	-3.42	-36.43	-33.01	86574.99	3764.13
ILLITE11	-5.98	-33.10	-27.12	71117.89	3520.69
ILLITE12	-5.19	-31.28	-26.09	68427.95	3379.16
ILLITE13	-4.33	-29.47	-25.14	65921.56	3247.37
14ACL-CH	20.78	-3.79	-24.57	64442.92	1695.87
7A-CL-CH	23.16	-3.79	-26.95	70684.62	1860.12
PARAGONT	-1.84	-35.20	-33.36	87492.20	3804.01
PYROCHPO	7.74	3.60	-4.14	10844.79	2168.96
HAUSMANI	9.48	3.02	-6.46	16929.12	1354.33
BIXBYITE	5.07	-5.59	-5.66	14835.47	1745.35
PYROCLUST	1.51	-4.16	-5.70	14958.86	3324.19
RHODACHP	-3.26	-7.56	-4.31	11294.52	3764.84
GRAPHITE	28.37	-3.37	-31.74	83251.29	23786.11

SOLID SOLUTIONS

MINERAL	X	SUM
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SM3-200-F-2 H2O/PS = 79.0 PH(25) = 2.34
 300 DEGREES C AT 500 BARS AND W/P = F
 P1/02/77P.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-13.14	-8.47	4.67	-12238.16	-1439.79
MAGNETIT	-11.96	-8.56	3.40	-8917.40	-713.39
QUARTZ	-1.91	-1.40	.52	-1352.07	-1352.07
AM STQ	-1.48	-1.40	.08	-211.42	-211.42

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	-4.04	-7.72	3.68	9839.30	2142.87
MG2OH-SO	-5.00	-8.56	-2.66	6964.59	1934.72
GOLD	-2.78	-3.02	-.24	522.42	14.65
ANHYDRIT	-8.93	-9.72	-.79	2060.35	1030.17
BARITE	-11.14	-13.08	-1.94	5099.42	2549.71
CELESTIT	-9.77	-12.17	-2.40	6266.19	3143.10
APACONIT	-1.37	-9.01	-7.64	20043.97	6661.32
CALCITE	-1.54	-9.01	-7.48	19608.62	6536.21
DOLOMIT	-4.76	-17.42	-12.64	32141.28	5523.55
MAGNESIT	-2.49	-8.41	-5.93	15549.40	5183.13
SIDERIT	-6.33	-11.20	-4.96	13019.42	4339.81
WITHERIT	-3.02	-12.38	-9.36	24536.56	8179.52
STRONTIA	-2.50	-11.47	-8.97	23527.63	7842.54
ALBIT	-1.76	-12.69	-11.23	29713.98	2701.27
ANORTHIT	3.46	-21.64	-25.10	65638.75	3872.87
MICROCLI	-2.34	-12.85	-11.51	30186.48	2744.23
ZONIT	8.57	-31.27	-39.94	104732.62	3740.45
CLINOZOY	8.56	-31.37	-39.92	104703.78	3739.42
PREHNIT	8.97	-20.85	-29.82	79198.04	3399.91
WATPAKIT	-1.43	-24.45	-24.02	62988.21	2999.44
ANALCIME	.69	-11.30	-12.19	31973.69	2906.70
LAUMONTI	.03	-24.47	-24.50	64248.49	2793.41
TREMOLIT	25.66	7.21	-18.45	48392.08	1307.89
BRUCITE	7.75	7.79	-4.96	12003.77	2600.75
CHRYSOIT	13.73	5.50	-8.14	21338.93	1333.68
ANTIGORI	2.08	.87	-1.21	3169.29	1233.19
TALC	7.94	2.80	-5.14	13472.31	792.49
ANTHOPHY	25.11	8.41	-16.70	43787.87	1183.46
FORSTERI	11.07	4.20	-6.87	16007.34	2000.82
FAYALITE	1.96	-1.57	-3.53	9267.91	1029.77
ENSTATIT	4.29	1.40	-2.89	7568.37	1261.40
DIOPSIDE	9.35	2.20	-7.15	16739.70	1873.97

SM3-300-E-2 HOURS = 79.0 DH(25) = 2.34
300 DEGREES C AT 500 PARS AND W/P = F
P1/02/18.

CA-AL PX	8.55	-20.24	-28.79	75509.59	4719.35
GIRPSITE	1.05	-10.53	-11.58	30376.58	4339.51
KAOLINIT	-3.85	-23.85	-20.31	52258.94	3550.60
PYROPHYL	-7.37	-26.64	-19.27	50535.16	3158.45
MUSCOVIT	-3.42	-34.90	-31.46	82547.51	3589.02
ILLITE11	-8.98	-31.60	-25.62	67110.85	3325.78
ILLITE12	-8.19	-30.12	-24.93	65291.30	3229.20
ILLITE13	-4.33	-28.65	-24.32	62785.34	3142.13
14ACL-CH	20.78	-11.26	-32.04	84027.10	2211.24
7A-CL-CH	23.16	-11.26	-34.42	90268.79	2375.49
PARAGONY	-1.84	-33.74	-31.90	83661.66	3637.46
PYPOCHRC	7.74	2.33	-5.41	14187.81	2837.56
HAUSMANI	9.48	-1.30	-10.78	28269.15	2261.53
BITRYITE	5.07	-3.63	-8.71	22832.58	2686.19
PYROLUST	1.51	-5.97	-7.48	19613.05	4258.46
RHODACHR	-2.26	-8.68	-5.62	14741.58	4013.86
GRAPHITE	28.37	-2.91	-31.28	82044.26	23441.22

SOLID SOLUTIONS

[illegible]

SM3-300-F-3 PCWFS =261.5 PH(25) = 2.73
 300 DEGREES C AT FCC BARS AND W/S = F
 81/02/18

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-13.14	-6.23	6.81	-17856.12	-2100.72
MAGNETIT	-11.96	-5.75	6.21	-16293.93	-1303.51
QUARTZ	-1.91	-1.42	.50	-1303.83	-1303.83
AM SI02	-1.48	-1.42	.06	-163.17	-163.17

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OR-SO	-4.04	-7.13	-3.09	8069.77	1793.28
MG2OH-SO	-5.90	-9.21	-2.31	6062.86	1684.13
GOLD	-2.78	-2.98	-.20	536.53	12.62
ANHYDRIT	-9.93	-9.53	-.40	1575.30	787.65
BARITE	-11.14	-12.77	-1.63	4275.33	2137.67
CELESTIT	-9.77	-11.91	-2.14	5603.55	2801.78
ARAGONIT	-11.37	-9.11	-6.74	17687.24	5895.75
CALCITE	-1.54	-8.11	-6.58	17251.89	5750.63
DOLOMITE	-4.79	-15.64	-10.85	26455.47	4742.58
MAGNESIT	-2.48	-7.52	-5.04	13220.32	4406.77
SIDERITE	-6.23	-10.59	-4.25	11156.22	3718.74
WITHERIT	-3.02	-11.25	-8.33	21842.79	7280.93
STRONTIA	-2.50	-10.45	-8.00	20973.31	6991.10
ALBITE	-1.26	-12.59	-11.23	29446.26	2676.93
ANORTHIT	3.46	-21.40	-24.86	65201.47	3935.38
NYCPOCLI	-2.24	-13.73	-11.39	29867.02	2715.18
ZONSITE	8.57	-30.57	-39.14	102850.75	3666.10
CLINOZOI	8.56	-30.57	-39.13	102621.90	3665.07
PREHNITE	9.07	-19.77	-28.73	75357.08	3276.39
WATERKIT	-1.43	-24.25	-22.81	62447.84	2973.71
ANALCIME	.89	-11.18	-12.07	31657.94	2877.99
LAUMONTIT	.03	-24.26	-24.29	63708.54	2769.94
TREMOLIT	25.66	13.02	-12.64	33151.55	895.99
BRUCITE	7.75	3.64	-4.11	10779.50	2155.90
CHRYSOIT	13.73	8.10	-5.63	14762.39	922.65
ANTIGORIT	2.08	1.27	-.81	2118.01	824.13
TALC	7.94	5.27	-2.67	6692.04	411.30
ANTHOPHY	25.11	14.20	-10.91	28602.64	773.04
FORSTERT	11.07	5.88	-5.19	13606.61	1511.85
FAYALITE	1.96	-7.25	-2.21	5798.96	644.33
ENSTATIT	4.28	2.23	-2.06	5392.34	898.72
DIOPSIDE	9.35	3.87	-5.48	14359.57	1435.96

SM3-300-F-3 HOURS = 261.5 PH(25) = 2.73
300 DEGREES C AT 500 BARPS AND W/P = F
81/02/18.

CA-AL-PY	8.55	-19.98	-28.53	74824.07	4676.50
GIBBSITE	1.05	-10.82	-11.87	31136.08	4448.01
KANLINIT	-3.55	-24.47	-20.92	54874.22	3658.28
PYROPHYL	-7.37	-27.30	-19.92	52246.71	3265.42
MUSCOVIT	-3.42	-25.36	-31.93	83746.62	3641.16
ILLITE11	-5.98	-32.13	-26.15	68584.94	3395.29
ILLITE12	-5.19	-30.50	-25.31	66365.80	3278.31
ILLITE13	-4.33	-28.87	-24.54	64370.25	3170.95
14AL-CH	20.78	-7.65	-28.43	74568.62	1962.33
7A-CL-CH	23.16	-7.65	-30.81	80810.32	2126.59
PARAGONI	-1.84	-34.22	-32.38	84912.51	3691.85
PYROCHRO	7.74	3.21	-4.53	11870.67	2374.13
HAUSMANI	9.48	2.15	-7.33	19216.34	1537.31
BIXBYITE	5.07	-1.07	-6.14	16097.13	1893.78
PYPOLUST	1.51	-4.25	-5.79	15194.95	2376.66
PHODACHR	-3.26	-7.95	-4.70	12319.43	4106.54
GRAPHITE	28.37	-3.67	-32.05	84040.41	24011.55

SOLID SOLUTIONS.

[illegible]

SM3-300-B-4 HCLPS = 575.3 PH(25) = 3.02
 300 DEGREES C AT 500 BARS AND W/P = 5
 81/02/1P.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MTNEPAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-13.14	-5.33	7.81	-20480.19	-2409.43
MAGNETIT	-11.96	-4.57	7.39	-19377.04	-1580.16
QUARTZ	-1.91	-1.40	.51	-1340.13	-1340.13
AM-SIO2	-1.48	-1.40	.08	-199.47	-199.47

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	-4.04	-6.75	-2.71	7116.94	1581.54
MG2OH-SO	-5.20	-8.03	-2.13	5579.41	1549.84
GOLD	-2.76	-2.94	-.16	423.55	9.97
ANHYDRIT	-8.93	-9.36	-.43	1132.54	566.27
BARITE	-11.14	-12.68	-1.54	4039.66	2019.83
CELESTIT	-9.77	-11.67	-1.90	4985.95	2492.97
ARAGONIT	-1.37	-7.43	-6.06	15900.59	5300.20
CALCITE	-1.54	-7.43	-5.90	15465.24	5155.08
DOLOMIT	-4.79	-14.38	-9.59	25154.31	4192.39
MAGNESIT	-2.48	-6.94	-4.46	11705.82	3901.94
SIDERITE	-6.33	-10.43	-4.10	10747.20	3582.40
WITHERIT	-3.02	-10.75	-7.73	20263.23	6754.41
STROMTIA	-2.50	-9.74	-7.25	19011.82	6337.27
ALBITE	-1.36	-12.54	-11.18	29330.03	2666.37
ANORTHIT	3.46	-21.36	-24.82	65094.46	3829.09
MTCROCLI	-2.34	-13.65	-11.31	29672.86	2697.53
ZOISITE	8.57	-30.16	-38.73	101571.95	3627.57
CLINOZOY	8.56	-30.16	-38.72	101543.11	3626.54
PREHNIT	8.07	-19.01	-27.98	73377.22	3190.31
WAIKAKIT	-.43	-24.18	-23.74	62268.44	2965.16
ANALCIME	.89	-11.15	-12.04	31578.11	2870.74
LAUMONTI	.03	-24.19	-24.22	63529.35	2762.15
TREMOLIT	25.66	17.51	-8.15	21365.43	577.44
BRUCITE	7.75	4.24	-3.51	9215.09	1843.02
CHRYSOIT	13.73	9.92	-3.81	9996.47	624.78
ANTIGOPH	2.08	1.56	-.52	1354.73	527.13
TALC	7.94	7.12	-.82	2153.42	126.67
ANTHOPHY	25.11	18.49	-6.62	17360.80	469.21
FORSTERI	11.07	7.09	-3.98	10441.30	1160.14
FAYALITE	1.96	.12	-1.85	4844.61	538.29
ENSTATIT	4.28	2.84	-1.45	3791.64	631.94
DIOPSIDE	9.35	5.20	-4.15	10885.81	1088.58

SM3-200-5-4 HPLPS = 575.3 PH(25) = 3.02
 200 DEGREES C AT 500 BARS AND W/P = 5
 81/02/1P.

CA-AL OX	8.55	-10.06	-28.50	74753.35	4672.08
GTBB SITE	1.05	-11.17	-12.22	32037.35	4576.76
KACLINIT	-3.55	-25.13	-21.58	56604.06	3773.60
PYROPHYL	-7.37	-27.93	-20.55	53903.86	3368.99
MUSCOVIT	-3.42	-35.97	-32.55	85354.80	3711.08
ILLITE11	-5.98	-32.75	-26.77	70212.71	3475.68
ILLITE12	-5.19	-31.00	-25.81	67688.78	3342.66
ILLITE13	-4.33	-29.25	-24.92	65348.44	3219.13
14ACL-CH	20.78	-5.32	-26.10	68439.82	1801.05
7A-CL-CH	23.16	-5.32	-28.48	74681.52	1965.30
PARAGONI	-1.84	-34.86	-33.02	86598.63	3765.16
PYROCHRO	7.74	3.91	-3.83	10037.42	2007.48
HAUSMANI	9.48	4.90	-4.58	12010.28	960.82
BIXPYITE	5.07	.98	-4.09	10724.41	1261.70
PYROCLUST	1.51	-7.93	-4.44	11655.59	2590.13
RHODACHP	-3.26	-7.27	-4.02	10536.29	3512.10
GRAPHITE	28.27	-4.34	-32.71	85796.43	24513.27

SOLID SOLUTIONS

MINERAL X SUM

SM3-300-F-F H2O/P = 1347.0 PH(25) = 4.08
 300 DEGREES C AT 500 BARS AND W/P = 5
 81/02/1P.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-13.14	-7.79	12.25	-32391.29	-3810.74
MAGNETIT	-11.96	-1.19	13.15	-34487.29	-2758.98
QUARTZ	-1.91	-1.61	.31	-804.40	-804.40
TREMOLIT	25.66	29.07	3.41	-8954.72	-242.02
CHRYSOIT	13.73	15.06	1.33	-3490.57	-218.16
ANTIGORI	2.08	2.38	.30	-792.48	-308.36
TALC	7.94	11.85	3.91	-10261.91	-603.64
ANTHOPHY	25.11	29.81	4.70	-12322.27	-333.03
FAYALITE	1.96	2.35	.39	-1017.98	-113.11
ENSTATIT	4.28	4.48	.20	-525.55	-87.59
HAUSMANI	9.48	12.64	3.16	-9077.09	-726.17
RIXBYITE	5.07	7.64	1.97	-5171.43	-608.40

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	-4.04	-5.69	-1.65	4844.22	1076.49
MG2OH-SO	-5.90	-7.72	-1.82	4762.42	1322.90
GPLC	-2.78	-3.00	-.22	566.44	13.33
ANHYDRIT	-8.93	-9.30	-.37	967.75	483.87
PARITE	-11.14	-12.56	-1.42	3733.70	1866.85
CELESTIT	-9.77	-11.70	-1.93	5065.96	2532.98
APACONIT	-1.37	-5.20	-3.83	10046.99	3349.00
CALCITE	-1.54	-5.20	-3.66	9611.64	3203.88
DOLOMITE	-4.79	-10.03	-5.24	13765.64	2294.27
MAGNESIT	-2.48	-4.93	-2.45	6170.75	2056.92
SIDERITE	-6.33	-8.95	-2.62	6865.64	2288.55
WITHERIT	-3.02	-8.46	-5.44	14268.46	4756.15
STRONTIA	-2.50	-7.61	-5.11	13403.01	4467.67
AM STC?	-1.48	-1.61	-.13	336.26	336.26
ALBITE	-1.26	-13.06	-11.70	30685.98	2789.63
ANORTHIT	3.46	-21.64	-25.10	65830.10	3872.36
MICROCLI	-2.34	-14.12	-11.78	30895.01	2808.64
ZOISITE	8.57	-29.60	-38.16	100089.68	3574.63
CLINCTOT	8.56	-29.60	-38.15	100060.83	3573.60
PHEHNITE	8.97	-17.52	-26.49	69477.13	3020.74
WATRAKIT	-4.43	-24.87	-24.43	64075.02	3051.19
ANALCIME	.89	-11.46	-12.35	32398.08	2945.28
LAIMONTI	.03	-24.88	-24.91	65335.43	2840.67
BPUCITE	7.75	6.09	-1.66	4362.17	872.43

SM3-300-5-F HOURS = 1347.0 PH(25) = 4.06
300 DEGREEFS C AT 500 BARS AND W/R = 5
81/02/1P.

FORSTPT	11.07	10.59	- .48	1271.70	141.30
DIOPSYDE	9.35	8.61	- .74	1933.41	193.34
CA-AL PX	8.55	-20.03	-28.58	74953.26	4684.58
GIBBSITE	1.05	-12.09	-13.14	34454.66	4922.09
KAO LINYT	-3.55	-27.38	-23.84	62510.39	4167.36
PYROPHYL	-7.37	-30.59	-23.21	60881.90	3805.12
MUSCOVIT	-3.42	-38.28	-34.86	91412.08	3974.44
ILLITF11	-5.98	-35.20	-29.22	76638.29	3793.97
ILLITF12	-5.19	-33.08	-27.89	73144.69	3612.08
ILLITF13	-4.33	-30.96	-26.63	69834.68	3440.12
T4ACL-CH	20.78	1.48	-19.30	50618.04	1332.05
7A-CL-CH	23.16	1.48	-21.68	56859.74	1496.31
PAPAGONI	-1.84	-37.22	-35.38	92789.70	4034.33
PYROCHRO	7.74	5.89	-1.85	4845.64	969.13
PYROCLUST	1.51	1.15	- .36	951.28	211.39
PHODACHR	-3.26	-5.03	-1.78	4662.35	1554.12
GRAPHITE	28.37	-6.18	-34.56	90626.80	25893.37

SOLID SOLUTIONS...

MINERAL X SLIM

SM3-200-5-6 HOURS = 2811.0 PH(25) = 4.17
 300 DEGREES C AT 500 BARS AND W/P = C
 P1/02/1R.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-13.14	.03	13.17	-34530.63	-4062.43
MAGNETIT	-11.96	2.32	14.28	-37438.98	-2995.12
QUARTZ	-1.91	-1.61	.30	-793.37	-793.37
TREMOLIT	25.66	30.41	4.75	-12445.47	-336.36
CHRYSOIT	13.73	15.61	1.88	-4939.09	-308.32
ANTIGORIT	2.08	2.47	.39	-1023.05	-398.08
TALC	7.94	12.39	4.45	-11682.18	-687.19
ANTHOPHY	25.11	31.08	5.97	-15650.68	-422.99
FAYALITE	1.96	2.97	1.00	-2631.65	-292.41
ENSTATIT	4.28	4.66	.38	-1002.78	-167.13
HAUSMANIT	9.48	13.85	4.37	-11474.34	-917.95
BIXBYITE	5.07	7.72	2.65	-6941.14	-816.60
PYROCLUST	1.51	1.58	.07	-190.90	-42.42

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SC	-4.04	-5.73	-1.69	4439.49	986.55
MG2OH-SC	-5.90	-7.62	-1.72	4504.05	1251.12
GOLD	-2.78	-2.96	-.18	474.06	11.15
ANHYDRIT	-8.93	-9.21	-.28	725.96	362.98
BARITE	-11.14	-12.38	-1.24	3260.75	1630.37
CELESTIT	-9.77	-11.66	-1.89	4959.34	2479.67
ARAGONIT	-1.37	-5.05	-3.68	9649.04	3216.35
CALCITE	-1.54	-5.05	-3.51	9213.69	3071.23
DOLOMITE	-4.79	-9.76	-4.98	13050.92	2175.15
MAGNESIT	-2.68	-4.71	-2.23	5853.97	1951.32
SIDFRITE	-6.23	-8.71	-2.37	6224.58	2074.86
WITHERIT	-3.02	-8.22	-5.20	13639.34	4546.45
STRONTIA	-2.50	-7.51	-5.01	12140.24	4380.08
AM-SIO2	-1.48	-1.61	-.13	347.29	347.29
ALBITE	-1.36	-13.13	-11.77	30874.57	2806.78
ANORTHIT	3.46	-21.83	-25.29	66329.04	3901.71
HYCROCLI	-2.34	-14.26	-11.92	31271.62	2842.87
ZOISITE	8.57	-29.77	-38.34	100553.38	3591.19
CLINOZOIT	8.84	-29.77	-38.33	100524.53	3590.16
PREHNITE	8.97	-17.50	-26.47	69417.67	3018.16
WAIPAKIT	-4.43	-25.07	-24.63	64595.64	3075.98
ANALCIME	.89	-11.53	-12.42	32575.45	2961.40
LAUMONTIT	.03	-25.08	-25.11	65955.66	2863.29

SM3-200-F-6 HOUFS =2811.0 PH(25) = 4.17
 300 DFGPEFS C AT FOC BARS AND W/O = F
 P1702718.

BRUCITE	7.75	6.28	-1.48	3873.92	774.78
FORSTERI	11.07	10.95	-.12	306.60	34.07
DIOPSIDE	9.35	9.01	-.34	898.16	89.82
CA-AL PY	8.55	-20.22	-28.77	75441.17	4715.07
GTBRSITE	1.05	-12.29	-13.34	34977.44	4996.78
KACLINIT	-3.55	-27.79	-24.24	63576.18	4238.55
PYROPHYL	-7.37	-31.01	-23.63	61971.94	3873.25
MUSCOVIT	-3.42	-38.82	-35.40	92834.61	4036.29
ILLITE11	-5.98	-35.69	-29.71	77927.82	3857.81
ILLITE12	-5.19	-33.52	-28.33	74308.72	3669.57
ILLITE13	-4.33	-31.35	-27.02	70873.19	3491.29
14ACL-CH	20.78	2.00	-18.78	49256.18	1296.22
7A-CL-CH	23.16	2.00	-21.16	55497.88	1460.47
PARAGONT	-1.84	-37.69	-35.85	94024.22	4088.01
PYROCHRO	7.74	6.13	-1.61	4217.92	843.58
RHODACHP	-3.26	-4.86	-1.60	4206.11	1402.04
GRAPHITE	28.37	-6.44	-34.82	91312.74	26089.35

SOLID SOLUTIONS

MINERAL X SUM

GPC3C-200-5-1 H2O/S = 1.0 PH(25) = 5.07
200 DEGREES C AT 500 BARS AND W/P = 5
P1702/18.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-14.40	2.92	17.41	-37669.35	-4434.04
MAGNETIT	-11.62	7.00	18.62	-40315.45	-3225.24
QUARTZ	-2.33	-2.11	.23	-489.12	-489.12
TREMOLIT	34.24	39.70	5.46	-11811.67	-319.23
CHRYSOIT	17.79	20.80	3.01	-6524.45	-467.78
ANTIGORI	2.71	3.29	.58	-1254.86	-488.27
TALC	11.20	16.60	5.40	-11684.51	-687.32
ANTHOPHY	25.24	41.55	6.31	-13652.23	-368.98
FAYALITE	5.09	6.06	.97	-2108.48	-234.28
ENSTATIT	5.98	6.23	.25	-542.68	-90.45
TAACL-CH	31.85	33.48	1.63	-3523.20	-92.72
HAUSMANI	11.01	13.00	1.99	-2357.03	-188.56
BIXYITE	5.94	6.92	.98	-2119.10	-249.31

THIS SOLUTION IS UNDESATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OP-SO	.19	-1.67	-1.86	4020.60	893.47
MG2OH-SO	-2.47	-4.18	-1.71	3698.20	1027.28
GOLD	-4.01	-4.06	-.05	110.34	2.60
ANHYDRIT	-6.70	-6.77	-.07	147.37	73.68
PARITE	-9.68	-10.52	-.85	1830.78	915.39
CLEFSTIT	-7.85	-9.06	-1.21	2623.00	1311.50
ARAGONIT	-.11	-1.86	-1.74	3770.83	1256.94
CALCITE	-.26	-1.86	-1.59	3445.44	1148.48
DOLOMITE	-2.06	-2.78	-.72	1576.09	262.68
MAGNESIT	-2.83	-.93	-.10	222.47	74.16
SIDERITE	-4.83	-5.19	-.36	773.48	257.83
WITHEPIT	-2.47	-5.61	-3.14	6803.69	2267.90
STRONTIA	-1.65	-4.15	-2.50	5402.78	1800.93
AM SID?	-1.68	-2.11	-.43	920.55	920.55
ALBITE	-.20	-2.58	-2.37	5141.61	467.42
ANORTHIT	9.19	1.31	-7.88	17052.74	1003.10
MICROCLI	-1.57	-4.02	-2.44	5290.92	480.99
ZOISITE	17.05	5.67	-11.38	24627.67	879.57
CLINOZOI	17.02	5.67	-11.36	24584.67	878.02
PREHNIT	14.81	6.62	-8.19	17737.78	771.21
WAIPAKIT	4.24	-2.92	-7.15	15490.21	737.63
ANALCIME	2.39	-.48	-2.86	6201.12	563.74
LAUMONTI	3.43	-2.93	-6.36	13777.97	599.04

QPC3C-200-F-1 HEURS = 1.0 PH(25) = 5.07
 200 DEGREES C AT 500 BARS AND W/P = 5
 01/02/16.

BRUCITE	0.68	8.34	-1.34	2905.99	581.20
FORSTERI	15.04	14.58	-0.46	992.61	110.29
DIOPSIDE	12.10	11.55	-0.55	1192.12	119.21
CA-AL PX	15.18	3.42	-11.76	25461.40	1591.34
GRANITE	2.61	-0.96	-3.57	7734.80	1104.97
KALINIT	-0.86	-6.12	-5.26	11389.01	759.27
PYROPHYL	-5.11	-10.33	-5.22	11295.69	705.99
MUSCOVIT	1.01	-5.92	-6.93	14994.86	651.95
ILLITE11	-2.29	-7.68	-5.39	11671.58	577.80
ILLITE12	-1.40	-6.33	-4.93	10683.74	527.59
ILLITE13	-0.43	-4.99	-4.56	9869.11	486.16
7A-CL-CH	34.45	32.48	-1.97	2105.78	55.42
PARAGONY	3.04	-4.48	-7.52	16276.42	707.67
PYROCHRO	9.37	6.08	-3.29	7130.42	1426.08
PYROLUSI	1.19	0.84	-0.36	775.49	172.32
RHODACHP	-2.01	-3.19	-1.18	2550.60	850.27
GRAPHITE	26.37	-4.02	-40.40	67455.09	24987.17

SOLID SOLUTIONS

MINERAL X SUM

GPC3C-200-5-2 PDUPS = 123.25 PH(25) = 4.0
 200 DEGREES C AT 500 BARS AND W/P = 5
 81/02/18.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-14.49	-.18	14.31	-30987.86	-3645.63
MAGNETIT	-11.62	2.64	14.26	-30862.49	-2469.00
QUARTZ	-2.33	-1.92	.41	-885.58	-885.58
TALC	11.20	12.79	1.59	-3440.12	-202.36

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	.10	-2.55	-2.73	5617.15	1314.92
MG2OH-SO	-2.47	-4.60	-2.13	4411.63	1281.01
GOLD	-4.01	-4.08	-.07	154.15	3.63
ANHYDRIT	-6.70	-6.94	-.25	232.26	266.18
BARITE	-9.68	-10.65	-.98	2116.40	1058.20
CELESTIT	-7.85	-9.14	-1.30	2809.12	1404.56
ARAGONIT	-.11	-2.22	-3.11	6728.85	2242.95
CALCITE	-.26	-3.22	-2.96	6403.45	2134.48
DOLOMITE	-2.66	-5.46	-3.40	7365.41	1227.57
MAGNESIT	-.83	-2.24	-1.41	3053.77	1017.92
STREPITE	-4.83	-6.26	-1.42	3079.44	1026.48
WITHERIT	-2.47	-6.93	-4.46	9662.33	3220.78
STRONTIA	-1.65	-5.42	-3.77	8161.92	2720.64
AM SiO2	-1.68	-1.92	-.24	524.09	524.09
ALBITE	-.20	-2.20	-2.00	4326.33	393.30
ANORTHIT	9.19	1.27	-7.92	17145.19	1008.54
HYDROCLI	-1.57	-2.63	-2.06	4454.02	404.91
ZOISITE	17.05	4.82	-12.23	26468.27	945.30
CLINOZOI	17.03	4.82	-12.21	26424.97	943.75
PREHNITE	14.81	5.19	-9.62	20837.04	905.96
WATPAKIT	4.24	-2.59	-6.83	14789.23	704.25
ANALCIME	2.29	-.28	-2.67	5782.04	525.64
LAUMONTI	3.43	-2.61	-6.04	13076.46	568.54
TREMOLIT	34.24	30.45	-3.79	8207.62	221.83
BRUCITE	9.68	6.82	-2.86	6182.55	1236.51
CHRYSOIT	17.79	16.63	-1.16	2512.58	157.04
ANTIGORI	2.71	2.62	-.08	183.14	71.26
ANTHOPHY	35.24	32.42	-2.82	6113.63	165.23
FORSTERI	15.04	11.74	-3.30	7149.80	794.42
FAYALITE	5.09	3.70	-1.38	2998.01	333.11
ENSTATIT	5.98	4.90	-1.08	2337.43	389.57
DIOPSIDE	12.10	8.83	-3.27	7079.56	707.96

81/02/18.

[illegible]

CPC30-200-5-3 HOURS = 292.0 PH(25) = 2.91
 200 DEGREES C AT 500 BARS AND W/P = F
 R1/02/19.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-14.49	-8.80	13.69	-29642.55	-3487.36
MAGNETITE	-11.62	1.80	13.42	-29059.91	-2324.79
QUARTZ	-2.33	-1.93	.40	-P67.93	-867.93
TALC	11.20	12.48	1.28	-2765.56	-162.68

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-CH-SO	.19	-2.60	-2.79	6027.96	1339.55
MC204-SO	-2.47	-4.62	-2.15	4662.06	1295.02
GOLD	-4.01	-4.06	-.05	103.42	2.42
ANHYDRITE	-6.70	-6.92	-.22	461.87	240.94
BARITE	-9.68	-10.83	-1.15	2489.33	1244.66
CELESTITE	-7.85	-9.10	-1.25	2711.11	1355.55
ARAGONITE	-.11	-3.33	-3.21	6953.65	2317.88
CALCITE	-.26	-3.33	-3.06	6628.25	2209.42
DOLomite	-2.06	-5.69	-3.64	7875.43	1312.60
MAGNESITE	-.83	-2.37	-1.54	3339.19	1113.06
SIDERITE	-4.92	-6.51	-1.67	3620.82	1206.94
WITHERITE	-2.47	-7.23	-4.76	10310.55	3436.85
STRONTIAN	-1.65	-5.50	-3.85	8339.19	2779.73
AM STO2	-1.68	-1.93	-.25	541.74	541.74
ALBITE	-.20	-2.23	-2.02	4383.54	398.50
ANORTHITE	9.19	1.27	-7.92	17137.60	1008.09
MICROCLIN	-1.57	-3.59	-2.02	4362.66	396.61
ZOISITE	17.05	4.80	-12.25	26527.26	947.40
CLINOZOIS	17.03	4.80	-12.23	26483.96	945.86
PREHNITE	14.81	5.12	-9.69	20967.84	912.51
WATPAKITE	4.24	-2.61	-6.84	14817.03	705.57
ANALCIME	2.29	-.30	-2.69	5821.65	529.24
LAUMONTITE	3.43	-2.62	-6.05	13104.36	569.75
TREMOLITE	24.24	29.79	-4.45	9636.74	260.45
EPIDOTE	9.68	6.73	-2.95	6383.90	1276.78
CHRYSOTILE	17.79	16.23	-1.46	3151.89	196.99
ANTIGORITE	2.71	2.57	-.13	285.76	111.20
ANTHOPHY	35.24	31.70	-3.54	7663.97	207.13
FORSTERITE	15.04	11.54	-3.50	7570.05	841.12
FAYALITE	5.09	3.27	-1.82	3930.20	436.69
ENSTATITE	5.98	4.90	-1.18	2556.43	426.07
DIOPTASE	12.10	8.66	-3.44	7456.85	745.69

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GPC3C-200-5-3 HOURS = 292.0 PH(25) = 3.91
 200 DEGREES C AT 500 BARS AND W/P = F
 81/02/18.

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CA-AL PX	15.18	3.21	-11.97	25025.07	1620.32
GIBBSITE	2.61	-0.33	-2.95	6383.61	911.94
KAOLINITE	-0.86	-4.52	-3.66	7929.22	528.61
PYROPHYL	-5.11	-8.38	-3.27	7078.70	442.42
MUSCOVIT	1.01	-4.24	-5.25	11264.66	494.12
ILLITE11	-2.29	-5.90	-3.61	7806.57	386.46
ILLITE12	-1.40	-4.85	-3.45	7475.54	369.16
ILLITE13	-0.43	-3.81	-3.38	7317.71	360.46
14ACL-CH	21.85	27.22	-4.63	10028.40	263.91
7A-CL-CH	34.45	27.22	-7.23	15657.38	412.04
PARAGONI	3.04	-2.88	-5.92	12816.39	557.23
PYROCHRO	9.37	4.84	-4.53	9797.06	1959.41
HAUSMANI	11.91	8.55	-3.36	7272.83	581.83
BIXBYITE	5.94	3.70	-2.24	4843.91	569.87
PYROCLUST	1.19	-1.15	-2.34	5071.66	1127.03
RHODACHR	-2.01	-4.26	-2.24	4856.24	1618.75
GRAPHITE	36.37	-2.11	-39.48	80464.37	24418.39

SOLID SOLUTIONS

MINERAL	X	SUM
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GPC2C-200-F-4 HOURS = 674.0 PH(25) = 4.74
 200 DEGREES C AT 500 BARS AND W/P = F
 81702/18.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-14.49	1.50	15.99	-34607.68	-4071.49
MAGNETIT	-11.62	4.54	16.16	-34992.48	-2799.40
QUARTZ	-2.33	-1.94	.39	-836.43	-836.43
TREMOLIT	34.24	36.68	2.44	-5274.47	-142.55
COPPERSY	17.79	19.28	1.49	-3220.09	-201.26
ANTIGONI	2.71	3.05	.34	-733.10	-285.25
TALC	11.20	15.39	4.19	-9074.41	-533.79
ANTHOPHY	35.24	38.52	3.28	-7098.45	-191.85
14ACL-CH	31.85	32.05	.20	-439.62	-11.57
HAUSMANI	11.91	13.23	1.32	-2646.96	-227.76
RIXPYITE	5.94	7.29	1.35	-2912.71	-342.67
PYROLUSI	1.10	1.34	.15	-321.79	-71.51

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	.19	-2.12	-2.30	4582.49	1107.22
MG2OH-SO	-2.47	-4.44	-1.97	4260.02	1183.34
GOLD	-4.01	-4.33	-.32	691.04	16.26
ANHYDRIT	-6.70	-6.90	-.20	434.53	217.27
BARITE	-8.68	-10.73	-1.06	2285.59	1142.80
CELESTIT	-7.85	-9.19	-1.34	2899.92	1449.96
ARAGONIT	-5.11	-2.32	-2.20	4770.41	1590.14
CALCITE	-4.26	-2.32	-2.05	4445.01	1481.67
DOLOMITE	-2.06	-3.71	-1.66	3583.53	597.26
MAGNESIT	-5.82	-1.40	-.57	1230.34	410.11
STIEPITE	-4.83	-6.08	-1.24	2689.44	896.48
WITHERIT	-2.47	-6.15	-3.68	7970.91	2656.97
STRONTIA	-1.65	-4.61	-2.95	6392.10	2130.70
AM STR	-1.68	-1.05	-.26	573.24	573.24
ALBITE	-4.20	-1.81	-1.61	3479.83	316.35
ANORTHIT	-9.19	2.19	-6.09	15143.84	890.81
MYCROCLIT	-1.57	-3.25	-1.67	3622.16	329.29
ZOISITE	17.05	6.69	-10.36	22426.91	800.96
CLINNOXY	17.03	6.69	-10.34	22383.61	799.41
PREHNITE	14.81	7.05	-7.76	16806.15	730.70
WATERKIT	4.24	-1.71	-5.95	12886.01	613.62
ANALCIME	2.39	.13	-2.26	4886.30	444.21
LAUMONTI	3.43	-1.73	-5.16	11173.07	485.79
BRUCITE	9.68	7.72	-1.96	4238.86	847.77

GPC3C-200-E-4 HOURS = 674.0 PH(25) = 4.74
 200 DEGREES C AT 500 BARS AND W/P = F
 81/02/18.

FORSTERT	15.04	13.51	-1.53	3211.75	367.97
FAYALITE	5.09	4.15	-.94	2026.84	225.20
ENSTATTIT	5.98	5.77	-.20	442.89	73.82
DIOPSIDE	12.10	10.64	-1.46	3155.66	315.57
CA-AL PY	15.18	4.14	-11.04	23899.80	1493.74
GIBBSITE	2.61	-.37	-2.99	6464.66	923.52
KAOINIT	-.86	-4.63	-3.77	6154.48	543.63
PYROPHYI	-5.11	-8.51	-3.40	7367.11	460.44
MUSCOVIT	1.01	-3.97	-4.98	10786.55	468.98
ILLITE11	-2.29	-5.79	-3.50	7575.07	375.00
ILLITE12	-1.40	-4.59	-3.19	6914.18	341.44
ILLITE13	-.43	-3.40	-2.97	6426.48	316.58
TA-CL-CH	34.45	32.05	-2.40	5180.35	136.56
PARACONT	3.04	-2.54	-5.58	12075.06	525.00
PYROCHPO	9.37	5.94	-3.43	7433.75	1486.75
RHODACHR	-2.01	-3.18	-1.17	2529.12	843.04
GRAPHITE	36.37	-4.52	-40.89	85530.69	25294.48

SOLID SOLUTIONS

MINERAL	Y	SUM
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GPC3C-200-F-F H2OPS = 1359.0 PH(25) = 4.05
 200 DEGREES C AT 500 BARS AND W/P = F
 81/02/18.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LOG-LK	AFFINITY CAL/M MIN	AFFINITY / STDT CAL/M SPECIES
HEMATITE	-14.49	-2.03	12.46	-26985.35	-3174.75
MAGNETIT	-11.62	-.01	11.61	-25129.53	-2010.36
QUARTZ	-2.33	-1.96	.37	-810.68	-810.68
TALC	11.20	12.88	1.68	-3631.19	-213.60

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LOG-LK	AFFINITY CAL/M MIN	AFFINITY / STDT CAL/M SPECIES
MG-OH-SO	.19	-2.53	-2.72	5887.59	1308.35
MG2OH-SO	-2.47	-4.51	-2.14	4631.20	1286.45
GRF	-24.01	-4.10	-.09	190.16	4.48
ANHYDRIT	-6.70	-6.93	-.23	454.17	247.09
PARITE	-9.68	-10.43	-.75	1625.25	812.63
CELESTIT	-7.85	-9.14	-1.30	2804.63	1402.31
ARAGONIT	-.11	-2.11	-2.00	6497.35	2165.78
CALCITE	-.25	-3.11	-2.85	6171.95	2057.32
DOLOMITE	-2.04	-5.29	-3.22	6992.76	1165.46
MAGNESIT	-.82	-2.17	-1.35	2912.62	970.87
SIDERITE	-4.93	-7.07	-2.23	4832.34	1610.78
WITHERIT	-2.47	-6.62	-4.15	8977.87	2992.62
STRONTIA	-1.65	-5.33	-3.68	7964.11	2654.70
AM STR2	-1.68	-1.96	-.28	598.99	598.99
ALBITE	-.20	-2.27	-2.07	4483.46	407.59
ANORTHIT	9.19	1.26	-7.93	17162.06	1009.53
MICROCCL	-1.57	-3.70	-2.13	4612.35	419.30
ZOISITE	17.05	4.97	-12.18	26366.69	941.67
CLINOZOI	17.03	4.97	-12.16	26323.39	940.12
PREHNITE	14.91	5.26	-9.55	20675.02	898.91
WATPAKIT	4.24	-2.67	-6.91	14556.20	712.20
ANALCIME	2.59	-.32	-2.71	5864.44	533.13
LAUMONTI	3.43	-2.69	-6.12	13243.76	575.82
TREMOLIT	24.24	30.78	-3.46	7481.02	202.19
BRUCITE	9.68	6.90	-2.78	6019.11	1203.87
CHRYSOIT	17.79	16.79	-1.00	2171.88	135.74
ANTIGORP	2.71	2.65	-.06	130.13	50.63
ANTHOPHY	35.24	32.67	-2.57	5567.72	150.48
FORSTERT	15.04	11.85	-3.19	6897.49	766.39
FAYALITE	5.09	2.07	-3.02	6533.82	725.98
ENSTATIT	5.98	4.64	-1.04	2248.88	374.81
DIOPSIDE	12.10	8.95	-3.15	6811.80	681.18

GPC3C-200-F-E HCLPS = 1389.0 PH(25) = 4.05
 200 DEGREES C AT 500 BARS AND W/P = .F
 R1/02/18.

CA-AL PX	15.18	3.22	-11.96	25892.28	1618.27
GIBBSITE	2.61	-.40	-3.02	6536.07	933.72
KAOLINIT	-.84	-4.72	-3.86	8348.53	556.57
PYROPHYL	-5.11	-8.63	-3.52	7612.40	475.77
MUSCOVIT	1.01	-4.50	-5.51	11919.06	518.22
ILLITE11	-2.29	-6.15	-3.86	8352.69	413.50
YLLITE12	-1.40	-5.07	-3.67	7951.70	392.68
ILLITE13	-.43	-4.00	-3.57	7723.90	380.49
14ACL-CH	21.85	27.84	-4.01	6680.65	228.44
7A-CL-CH	34.45	27.84	-6.61	14309.63	376.57
PARAGONI	3.04	-3.07	-6.11	13221.02	574.83
PYROCHPO	9.37	5.11	-4.26	9214.74	1842.95
HAUSMANI	11.91	9.31	-2.60	5636.36	450.91
BIXBYITE	5.94	4.19	-1.75	3789.88	445.87
PYROCLUST	1.19	-.93	-2.12	4600.05	1022.23
RHODACHR	-2.01	-3.96	-1.95	4212.15	1404.05
GRAPHITE	36.37	-3.03	-39.40	85291.89	24369.11

SOLID SOLUTIONS

MINERAL	X	SUM
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GPC3R-200-E-1 HOURS = 3.00 PH(25) = 4.6
200 DEGREES C AT 500 BARS AND W/R = 5
P1/02/18.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-14.49	.03	14.52	-31433.59	-3698.07
MAGNETIT	-11.62	3.29	14.91	-32287.73	-2583.02
QUARTZ	-2.33	-2.18	.15	-330.84	-330.84
TREMOLIT	34.24	35.45	1.21	-2622.70	-70.88
CHRYSOIT	17.79	19.00	1.21	-2625.00	-164.06
ANTIGORI	2.71	3.00	.29	-627.76	-244.27
TALC	11.20	14.65	3.45	-7466.86	-439.23
ANTHOPHY	35.24	37.10	1.86	-4019.94	-109.65

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	.19	-2.04	-2.23	4819.14	1070.92
MG2OH-SO	-2.47	-4.38	-1.91	4137.65	1149.35
GOLD	-4.01	-4.09	-.08	172.59	4.06
ANHYDRIT	-6.70	-6.76	-.06	127.38	63.69
BARITE	-9.68	-10.86	-1.18	2561.52	1280.76
CELESTIT	-7.85	-9.08	-1.23	2661.41	1330.70
ARAGONIT	-.11	-2.37	-2.26	4894.65	1631.55
CALCITE	-.26	-2.37	-2.11	4569.25	1523.08
DOLOMITE	-2.06	-3.93	-1.87	4045.38	674.23
MAGNESIT	-.83	-1.55	-.72	1567.94	522.65
SIDEPITE	-4.83	-6.08	-1.25	2695.55	898.52
WITHERIT	-2.47	-6.48	-4.01	8678.23	2892.74
STRONTIA	-1.65	-4.69	-3.04	6584.98	2194.99
AM SID2	-1.68	-2.18	-.50	1079.83	1078.83
ALBYTE	-.20	-2.80	-2.60	5631.36	511.94
ANORTHIT	9.19	1.44	-7.73	16739.32	984.67
MICROCLI	-1.87	-4.24	-2.66	5766.72	524.25
ZOISITE	17.05	5.67	-11.38	24643.88	880.14
CLINOZOI	17.03	5.67	-11.36	24600.58	878.59
PREHNITE	14.81	6.24	-8.57	18554.74	806.73
WATRAKIT	4.24	-2.92	-7.15	15490.12	737.62
ANALCIME	2.39	-.63	-3.02	6530.97	593.72
LAUMONTI	3.43	-2.93	-6.36	13774.63	598.90
APUCITE	9.68	7.79	-1.89	4099.74	819.95
FORSTERT	15.04	13.40	-1.64	3541.65	393.52
FAYALITE	5.09	4.35	-.74	1593.75	177.08
ENSTATIT	5.98	5.61	-.37	809.36	134.89
DIOPSIDE	12.10	10.40	-1.70	3677.78	367.78

GPC3R-200-F-1 HOURS = 3.00 PH(25) = 4.6
200 DEGREES C AT 500 BARS AND W/P = 5
P1702/JR.

CA-AL PX	15.18	3.64	-11.54	24989.70	1561.86
GIBBSITE	2.61	-5.59	-3.20	6930.51	990.07
KAGLINIT	-5.86	-5.53	-4.66	10098.62	673.24
PYROPHYL	-5.11	-9.88	-4.77	10323.70	645.23
MUSCOVIT	1.01	-5.39	-6.40	13865.35	602.84
ILLITE11	-2.29	-7.19	-4.90	10604.99	525.00
ILLITE12	-1.40	-5.96	-4.56	9876.64	487.74
ILLITE13	-1.43	-4.74	-4.31	9321.50	459.19
14ACL-CH	31.85	31.24	-0.61	1318.34	34.69
7A-CL-CH	34.45	31.24	-3.21	6947.31	182.82
PARAGONI	3.04	-3.96	-7.00	15160.84	659.17
PYROCHRO	9.37	4.12	-5.25	11365.70	2273.14
HAUSMANI	11.91	5.88	-6.02	13065.47	1045.24
BIXBYITE	5.94	1.75	-4.19	9066.50	1066.65
PYROLUST	1.19	-2.37	-3.57	7724.20	1716.49
RHODACHP	-2.01	-5.22	-3.20	6937.80	2312.60
GRAPHITE	36.37	-2.84	-39.21	84893.38	24255.25

SOLID SOLUTIONS

MINERAL	X	SUM
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GPC38-200-5-2 HOURS = 74.50 PH(25) = 5.1
 200 DEGREES C AT 500 BARS AND W/P = F
 81/02/18.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LOG-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-14.49	2.66	17.15	-37138.41	-4369.23
MAGNETIT	-11.62	6.57	18.19	-39384.15	-3150.73
MAGNESIT	-.83	-.79	.04	-85.75	-28.58
QUARTZ	-2.33	-1.98	.35	-760.49	-760.49
TREMOLIT	34.24	41.28	7.04	-15231.18	-411.65
CHRYSOTIL	17.79	21.24	3.45	-7469.87	-466.87
ANTIGORIT	2.71	3.36	.65	-1411.53	-549.23
TALC	11.20	17.28	6.08	-13170.51	-774.74
ANTHOPHY	25.24	42.98	7.74	-16754.89	-452.63
FAYALITE	5.09	5.83	.75	-1619.10	-179.90
ENSTATIT	5.98	6.42	.44	-948.96	-158.16
14ACL-CH	31.85	34.21	2.36	-5104.02	-134.32

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LOG-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	.19	-1.96	-2.14	4641.78	1031.51
MG?OH-SO	-2.47	-4.48	-2.01	4358.58	1210.72
GOLD	-4.01	-4.03	-.02	37.05	.87
ANHYDROIT	-6.70	-7.01	-.31	677.60	338.80
BARITE	-9.68	-11.65	-1.97	4264.63	2132.32
CELESTIT	-7.85	-9.55	-1.70	3690.43	1845.21
ARAGONIT	-.11	-1.64	-1.53	3304.19	1101.40
CALCITE	-.26	-1.64	-1.38	2978.79	992.93
DOLOMITE	-2.06	-2.43	-.37	801.23	133.54
SIDERITE	-4.83	-5.29	-.45	978.44	326.15
WITHERIT	-2.47	-6.28	-3.81	8240.66	2746.89
STRONTIA	-1.65	-4.18	-2.53	5473.32	1824.44
AM SID?	-1.68	-1.98	-.30	649.18	649.18
ALBITE	-.20	-2.25	-2.05	4433.42	403.04
ANOPHTIT	9.19	1.74	-7.45	16124.64	948.51
MICROCLI	-1.57	-3.65	-2.07	4491.17	408.29
ZOISITE	17.05	6.29	-10.66	23089.13	824.61
CLINOZOI	17.03	6.29	-10.64	23045.83	823.07
PREHNITE	14.81	7.31	-7.50	16244.94	706.30
WAIRAKIT	4.24	-2.24	-6.47	14015.09	667.39
ANALCIME	2.39	-.27	-2.66	5762.15	523.83
LAUMONTI	3.43	-2.25	-5.68	12298.56	534.72
BRUCITE	9.68	8.40	-1.28	2771.05	554.21
FORSTERI	15.04	14.83	-.21	455.65	50.63

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GPC3B-200-5-R HOURS = 74.50 PH(2F) = 5.1
 200 DEGREES C AT 500 BARS AND W/P = .5
 81/02/18.

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DIOPSIDE	12.10	12.00	-.10	225.36	22.54
CA-AL-PX	15.18	3.72	-11.46	24804.67	1550.29
GIBBSITE	2.61	-.93	-3.55	7684.51	1097.79
KAOLINIT	-.86	-5.83	-4.96	10747.84	716.52
PYROPHYL	-5.11	-9.78	-4.67	10114.15	632.13
MUSCOVIT	1.01	-5.50	-6.51	14098.84	612.99
ILLITE11	-2.20	-7.21	-4.92	10661.26	527.79
ILLITE12	-1.40	-5.86	-4.46	9658.21	476.95
ILLITE13	-.43	-4.51	-4.08	8828.36	434.89
7A-CL-CH	34.45	34.21	-.24	524.96	13.81
PARAGONI	3.04	-4.11	-7.15	15471.94	672.69
PYPOCHRO	9.37	5.32	-4.05	8765.79	1753.16
HAUSMANI	11.91	10.83	-1.08	2345.70	167.66
BIXBYITE	5.94	5.50	-.44	946.12	111.31
PYRCLUST	1.19	.18	-1.02	2203.20	489.60
RHODACHP	-2.01	-3.87	-1.85	4012.90	1337.63
GRAPHITE	36.37	-4.04	-40.41	87489.40	24997.00

SOLID SOLUTIONS

MINERAL	X	SUM
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GPC3B-200-5-3 HOURS = 267.50 PH(25) = 4.6
200 DEGREES C AT 500 BARS AND W/P = F
P1/02/18.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-14.49	1.06	15.55	-33666.57	-3960.77
MAGNETIT	-11.62	4.59	16.21	-35095.95	-2807.68
QUARTZ	-2.33	-1.95	.36	-831.17	-831.17
TREMOLIT	34.24	34.61	.37	-809.52	-21.88
CHRYSOIT	17.79	18.34	.55	-1199.31	-74.96
ANTIGORI	2.71	2.90	.19	-409.66	-159.40
TALC	11.20	14.45	3.25	-7041.66	-414.22
ANTHOPHY	35.24	26.33	1.09	-2360.43	-63.80
FAYALITE	5.09	5.11	.03	-57.07	-6.34

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	.19	-2.48	-2.67	5780.81	1264.62
MG-OH-SO	-2.47	-4.71	-2.24	4856.59	1349.05
GOLD	-4.01	-4.10	-.09	198.41	4.67
ANHYDRIT	-6.70	-7.05	-.35	761.52	380.76
BARITE	-9.68	-11.00	-1.32	2863.32	1431.66
CELESTIT	-7.85	-9.38	-1.53	3310.99	1655.50
APAGONIT	-.11	-2.61	-2.49	5395.10	1798.37
CALCITE	-.26	-2.61	-2.34	5069.70	1689.90
DOLOMITE	-2.06	-4.35	-2.30	4969.45	828.24
MAGNESIT	-.83	-1.75	-.92	1991.56	663.85
SIDEPITE	-4.83	-5.64	-.80	1735.01	578.34
WITHEPIT	-2.47	-6.56	-4.09	8846.34	2948.78
STRONTIA	-1.65	-4.93	-3.28	7100.88	2366.96
AM SIO2	-1.68	-1.95	-.27	578.50	578.50
ALRITE	-.20	-2.17	-1.97	4270.65	388.24
ANORTHIT	9.19	1.71	-7.48	16190.22	952.37
MICROCLY	-1.57	-3.57	-1.99	4318.10	392.55
ZOISITE	17.05	5.84	-11.21	24263.01	866.54
CLINOZOI	17.03	5.84	-11.19	24219.71	864.99
PPEHNIT	14.81	6.32	-8.49	18390.86	799.60
WAIPAKIT	4.24	-2.20	-6.44	13939.97	663.81
ANALCIME	2.39	-.23	-2.62	5670.41	515.49
LAUMONTI	3.43	-2.21	-5.65	12224.10	531.48
BRUCITE	9.68	7.41	-2.27	4908.47	981.69
FORSTERI	15.04	12.89	-2.15	4659.14	517.68
ENSTATIT	5.98	5.46	-.52	1117.75	186.29
DIOPSIDE	12.10	10.08	-2.02	4371.77	437.18

GPC3B-200-543 HQUPS = 267.50 PH(25) = 4.6
 200 DEGREES C AT 500 BARS AND W/P = F
 81/02/18.

CA-AL PY	15.18	3.66	-11.52	24940.93	1558.81
GIRRSITE	2.61	-4.49	-3.10	6713.14	959.02
KANLINT	-0.86	-4.86	-4.00	6663.40	577.56
PYROPHYL	-5.11	-9.75	-3.64	7688.00	493.00
MUSCOVIT	1.01	-4.52	-5.53	11982.37	520.97
ILLITE11	-2.29	-6.22	-3.93	8500.92	420.84
ILLITE12	-1.40	-5.06	-3.66	7915.62	390.69
ILLITE13	-0.43	-3.90	-3.47	7503.52	369.63
14AL-CH	31.85	30.27	-1.58	3426.96	90.18
7A-CL-CH	34.45	30.27	-4.18	9055.93	238.31
PARACONT	3.04	-3.13	-6.17	13365.77	581.12
PYROCHPO	9.37	4.37	-5.00	10821.73	2164.35
HAUSMANI	11.91	7.13	-4.78	10351.64	828.13
BIXPYITE	5.04	2.75	-3.19	6896.46	811.35
PYROLUST	1.19	-1.62	-2.82	6097.93	1355.10
RHODACHP	-2.01	-4.79	-2.78	6008.72	2002.91
GRAPHITE	36.37	-3.17	-39.53	85590.58	24454.45

SOLID SOLUTIONS

MINERAL	X	SUM
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GPC3R-200-F-4 PCURS = 602.50 PH(25) = 4.3
 200 DEGREES C AT 500 BARS AND W/P = 5
 #1702/19.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LOG-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-14.49	.68	15.17	-32838.56	-3863.36
MAGNETIT	-11.62	4.00	15.71	-34016.86	-2721.35
QUARTZ	-2.33	-2.00	.33	-711.79	-711.79
TALC	11.20	12.58	1.38	-2998.17	-176.26

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LOG-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	.19	-2.77	-2.95	6396.47	1421.44
MG2OH-SO	-2.47	-4.83	-2.36	5115.79	1421.05
GOLD	-4.01	-4.15	-.14	207.54	7.24
ANHYDRIT	-6.70	-7.01	-.31	670.64	335.32
BARITE	-9.68	-10.65	-.97	2115.23	1057.61
CELESTIT	-7.85	-9.31	-1.46	3169.37	1584.69
APAGONIT	-.11	-3.06	-2.94	6371.17	2123.72
CALCITE	-.26	-3.06	-2.79	6045.77	2015.26
DOLOMITE	-2.06	-5.31	-3.25	7033.68	1172.28
MAGNESIT	-.83	-2.25	-1.42	3079.72	1026.57
SIDEPITE	-4.83	-5.71	-.87	1885.71	628.57
WITHERIT	-2.47	-6.70	-4.23	9165.20	3055.07
STRONTIA	-1.65	-5.36	-3.71	8026.20	2675.40
AM SiO2	-1.68	-2.00	-.32	697.88	697.88
ALBITE	-.20	-2.43	-2.23	4820.88	438.26
ANOPHTIT	0.10	1.41	-7.78	16836.52	990.38
MICROCLI	-1.57	-3.85	-2.28	4926.93	447.90
ZOISITE	17.05	5.15	-11.90	25770.85	920.39
CLINOZOY	17.03	5.15	-11.88	25727.55	918.84
PREHNITE	14.81	5.46	-9.35	20233.33	879.71
WATRAKIT	4.24	-2.61	-6.85	14825.72	705.99
ANALCIME	-2.39	-.43	-2.82	6101.61	554.69
LAUMONTI	3.43	-2.62	-6.06	13110.56	570.02
TREMOLIT	24.24	30.43	-3.81	8241.47	222.74
RFUCITE	0.68	6.86	-2.82	6097.36	1219.47
CHRYSOIT	17.79	16.59	-1.20	2605.77	162.86
ANTIGORI	2.71	2.61	-.09	201.54	78.42
ANTHOPHY	35.24	32.05	-3.19	6914.75	186.89
FORSTERI	15.04	11.73	-3.31	7155.60	795.07
FAYALITE	5.09	4.82	-.26	564.46	62.72
ENSTATIT	5.98	4.86	-1.12	2426.02	404.34
DIOPSIDE	12.10	8.92	-3.18	6875.51	687.55

GPC3B-200-4 HOURS = 602.50 PH(25) = 4.3
 200 DEGREES C AT 500 BARS AND W/P = 5
 81702/186

CA-AL PX	15.18	3.42	-11.76	25467.85	1591.74
GIBBSITE	2.61	-3.33	-2.95	6379.21	911.32
KAOLINTT	-0.86	-4.66	-3.80	8233.95	548.93
PYROPHYL	-5.11	-8.67	-3.56	7696.95	481.06
MUSCOVIT	1.01	-4.50	-5.51	11922.64	518.38
ILLITE11	-2.29	-6.16	-3.87	8388.66	415.26
ILLITE12	-1.40	-5.10	-3.70	8015.09	395.81
ILLITE13	-0.43	-4.04	-3.61	7814.71	384.96
14ACL-CH	31.85	27.67	-4.18	9060.29	238.43
7A-CL-CH	34.45	27.67	-6.78	14689.27	386.56
PARAGONI	3.04	-3.08	-6.12	13247.43	575.98
PYROCHRO	9.37	3.99	-5.38	11641.67	2328.33
HAUSMANI	11.91	5.85	-6.07	13136.27	1050.90
BIXBYITE	5.94	1.85	-4.09	8861.49	1042.53
PYROLUST	1.19	-2.15	-3.35	7243.38	1609.64
RHODACHR	-2.01	-5.12	-3.11	6727.93	2242.64
GRAPHITE	36.37	-2.97	-39.34	85164.33	24332.67

SOLID SOLUTIONS

MINERAL	Y	SUM
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GPC38-200-5-5 HOURS = 648.00 PH(25) = 2.94
 300 DEGREES C. AT 500 BARS AND W/P = 5
 81/02/18.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG O	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-13.14	-2.29	10.85	-28456.03	-3347.77
MAGNETIT	-11.96	-.99	10.97	-28781.78	-2302.54
ANHYDIT	-8.93	-8.92	.01	-33.93	-16.96
QUARTZ	-1.91	-1.64	.28	-722.84	-722.84

THIS SOLUTION IS UNDESATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG O	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	-4.04	-5.69	-1.65	4330.84	962.41
MG2OH-SO	-5.90	-7.12	-1.21	3165.35	894.82
GOLD	-2.78	-3.27	-.49	1283.60	30.20
CELESTIT	-9.77	-11.09	-1.32	3461.41	865.35
APACCNIT	-1.37	-7.36	-5.99	15696.74	5232.25
CALCITE	-1.54	-7.36	-5.82	15261.39	5087.13
DOLOMITE	-4.79	-13.85	-9.07	23782.14	3963.69
MAGNESIT	-2.48	-6.50	-4.02	10537.50	3512.50
SIDERITE	-6.33	-9.94	-3.61	9458.54	3152.85
STRONTIA	-2.50	-9.53	-7.04	18449.89	3074.98
AM SIO2	-1.48	-1.64	-.16	417.82	417.82
ALBIT	-1.36	-12.50	-11.14	29210.19	2655.47
ANORTHIT	3.46	-20.19	-23.66	62037.83	3649.28
MICROCCL	-2.34	-13.84	-11.50	30171.51	2742.86
ZOISITE	8.57	-28.35	-36.92	96814.06	3457.65
CLINOZOIT	8.56	-28.35	-36.90	96785.22	3456.61
PREHNITE	8.97	-17.95	-26.92	70591.99	3069.22
WAIPAKIT	-1.43	-23.48	-23.05	60442.79	2878.23
ANALCIME	.00	-10.87	-11.76	30839.18	2803.56
LAUMONTIT	.03	-23.49	-23.53	61700.11	2682.61
TRIPICLIT	25.66	18.39	-7.27	19070.99	515.43
REPUCITE	7.78	4.74	-3.01	7904.74	1580.95
CHRYSOIT	13.73	10.95	-2.78	7301.80	456.36
ANTIGORT	2.08	1.72	-.36	935.95	364.18
TALC	7.94	7.67	-.27	695.13	40.89
ANTHOPHY	25.11	20.10	-5.01	13137.45	355.07
FORSTETI	11.07	7.85	-3.22	8441.48	937.94
FAYALITE	1.96	.97	-.99	2604.10	289.34
ENSTATIT	4.28	3.10	-1.18	3098.58	516.43
DIOPSIDE	9.35	5.36	-3.99	10467.74	1046.77
CA-AL PX	8.55	-18.56	-27.10	71079.43	4442.46
GTSSITE	1.05	-10.41	-11.46	30061.10	4294.44

GPC3R-200-5-E HELPS = 648.00 PH(25) = 2.94
 300 DEGREES C AT 500 BARS AND W/F = 5
 P1/02/18.

KADLINTT	-3.85	-24.09	-20.55	53887.93	3592.53
PYROPHYL	-7.37	-27.36	-19.99	52424.10	3276.51
MUSCOVIT	-3.42	-34.65	-31.23	81904.53	3561.07
ILLITE11	-5.98	-31.74	-25.76	67550.64	3344.09
ILLITE12	-5.19	-29.99	-24.80	65027.79	3211.25
ILLITE13	-4.33	-28.23	-23.90	62688.52	3089.10
14ACL-CH	20.78	-2.02	-22.80	59794.62	1573.54
7A-CL-CH	23.16	-2.02	-25.18	66036.32	1737.80
PARAGONT	-1.84	-33.31	-31.47	82529.87	3588.26
PYROCHPO	7.74	2.83	-4.91	12870.90	2574.18
HAUSMANI	9.48	3.61	-5.87	15398.05	1231.84
BIXBYITE	5.07	.77	-4.30	11276.92	1326.70
PYROLUST	1.51	-2.06	-3.57	9372.81	2082.85
RHODACHR	-2.26	-8.41	-5.15	13511.60	4503.93
GRAPHITE	28.37	-6.35	-34.72	91054.71	26015.63

SOLID SOLUTIONS

MINERAL	X	SUM
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GPC3B-200-E-6 HOURS = 743.50 PH(25) = 2.59
 300 DEGREES C AT 500 BARS AND W/P = F
 81/02/1P.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LOG-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-13.14	-2.04	11.10	-29114.49	-3425.23
MAGNETITE	-11.96	-2.71	11.25	-29508.56	-2360.68
QUARTZ	-1.91	-1.53	.39	-1010.18	-1010.18

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LOG-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	-4.04	-6.94	-2.90	7598.23	1688.50
MG2OH-SO	-5.90	-7.96	-2.06	5391.73	1497.70
GOLD	-2.78	-4.71	-1.93	5052.13	118.87
ANHYDROIT	-8.92	-9.33	-.40	1043.79	521.90
RAPITE	-11.14	-12.56	-1.42	3734.40	1867.20
CELESTITE	-9.77	-11.27	-1.59	4177.44	2088.72
ARAGONITE	-1.37	-8.47	-7.10	18623.03	6207.68
CALCITE	-1.54	-8.47	-6.94	18187.69	6062.56
DOLOMITE	-4.79	-16.25	-11.46	30055.49	5009.25
MAGNESITE	-2.48	-7.78	-5.29	13884.55	4628.18
SIDERITE	-6.33	-9.84	-3.51	9199.99	3066.66
WITHERITE	-3.02	-11.71	-8.68	22769.16	7589.72
STRONTIA	-2.50	-10.51	-8.01	21014.49	7004.83
AM SiO2	-1.48	-1.53	-.05	130.47	130.47
ALBITE	-1.36	-12.66	-11.30	29631.16	2693.74
ANORTHITE	3.46	-20.95	-24.42	64034.87	3766.76
MICROCLIN	-2.34	-13.75	-11.41	29933.94	2721.27
ZOISITE	8.57	-30.09	-38.65	101368.16	3620.29
CLINOZOIS	8.56	-30.09	-38.64	101339.21	3619.26
PREHNITE	8.97	-19.79	-28.76	75418.77	3279.08
WAIRAKITE	-.43	-24.02	-23.59	61866.27	2946.01
ANALCIME	.89	-11.14	-12.03	31548.07	2868.01
LAUMONTITE	.03	-24.04	-24.07	63124.73	2744.55
TREMOLITE	25.66	10.14	-15.52	40692.17	1099.79
BRUCITE	7.75	3.39	-4.36	11442.58	2288.52
CHRYSOTILE	13.73	7.12	-6.61	17340.06	1083.75
ANTIGORITE	2.08	1.11	-.97	2536.32	986.89
TALC	7.94	4.07	-3.87	10158.12	597.54
ANTHOPHYLITE	25.11	11.54	-13.57	35600.14	962.17
FORSTERITE	11.07	5.26	-5.81	15229.67	1692.07
FAYALITE	1.96	1.13	-.83	2180.11	242.23
ENSTATITE	4.28	1.86	-2.42	6349.07	1058.18
DIOPSIDE	9.35	3.04	-6.31	16546.84	1654.68

GPC3B-200-5-A HOURS = 743.50 PH(25) = 2.59
 300 DEGREES C AT 500 BARS AND W/P = "
 81/02/1P.

Ca-AL PX	8.55	-19.43	-27.97	73363.81	4585.24
GIBBSITE	1.05	-10.31	-11.36	29789.56	4255.65
KAOLINIT	-3.55	-23.67	-20.12	52769.59	3517.97
PYROPHYL	-7.37	-26.72	-19.34	50730.49	3170.66
MUSCOVIT	-3.42	-34.35	-30.93	81122.75	3527.08
ILLITE11	-5.98	-31.30	-25.32	66404.13	3287.33
ILLITE12	-5.19	-29.76	-24.57	64439.11	3182.18
ILLITE13	-4.33	-28.22	-23.89	62657.67	3086.58
14ACL-CH	20.78	-8.23	-29.01	76076.43	2002.01
7A-CL-CH	23.16	-8.23	-31.39	82318.13	2166.27
PARAGONI	-1.84	-33.26	-31.42	82406.62	3582.90
PYROCHRO	7.74	1.51	-6.23	16330.95	3266.19
HAUSMANI	9.48	-0.15	-9.63	25254.67	2020.37
BITBYITE	5.07	-1.67	-6.74	17674.06	2079.30
PYROLUSI	1.51	-3.18	-4.69	12310.48	2735.66
RHODACHP	-3.26	-9.66	-6.40	16761.05	5593.68
GRAPHITE	29.37	-4.47	-34.85	91386.30	26110.37

SOLID SOLUTIONS

MINERAL	X	SUM
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GPC38-200-5-7 HOURS = 1017.5 PH(25) = 2.50
300 DEGREES C AT 500 BARS AND W/P = 5
P1/02/18.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-13.14	-7.48	5.66	-14855.61	-1747.72
MAGNETIT	-11.94	-6.29	5.67	-14874.00	-1189.92
QUARTZ	-1.91	-1.51	.40	-1054.50	-1054.50

THIS SOLUTION IS UNDEPSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	-4.04	-7.44	-3.40	8906.64	1979.25
MG2OH-SO	-5.90	-8.32	-2.42	6236.00	1760.00
GOLD	-2.78	-3.11	-.33	862.40	20.29
ANHYDRIT	-8.92	-9.56	-.63	1654.19	827.09
BARITE	-11.14	-13.52	-2.38	6251.79	3125.89
CELESTIT	-9.77	-11.66	-1.88	4938.04	2469.02
APAGCNIT	-1.37	-9.02	-7.65	20075.09	6691.70
CALCITE	-1.54	-9.02	-7.49	19639.74	6546.58
DOLOMIT	-4.79	-17.39	-12.60	33051.09	5508.52
MAGNESIT	-2.48	-8.36	-5.88	15428.10	5142.70
SIDERITE	-6.32	-10.11	-3.78	9905.81	3301.94
WITHERIT	-3.02	-12.99	-9.96	26128.21	8709.40
STRONTIA	-2.50	-11.12	-8.62	22616.75	7538.92
AM STN2	-1.48	-1.51	-.03	86.16	86.16
ALBITE	-1.26	-12.69	-11.33	29717.15	2701.56
ANOPHTIT	3.46	-21.06	-24.53	64321.98	3783.65
MICROCLI	-2.34	-13.75	-11.41	29922.07	2720.19
ZONISITE	8.57	-30.46	-39.03	102359.60	3655.70
CLINOZOY	8.54	-30.46	-39.02	102330.75	3654.67
PPEHNTTE	8.97	-20.31	-29.28	76783.10	3338.40
WATPAKIT	-4.43	-24.10	-23.67	62064.00	2955.43
ANALCIME	.89	-11.19	-12.08	31677.99	2879.82
LAUMONTI	.03	-24.11	-24.14	63321.70	2753.12
TREMOLIT	25.66	7.11	-18.55	48648.17	1314.82
BRUCITE	7.75	2.93	-4.83	12655.61	2531.12
CHRYSOIT	13.73	5.76	-7.97	20890.90	1305.68
ANTIGORT	2.08	.89	-1.18	3103.57	1207.62
TALC	7.94	2.75	-5.19	13620.72	801.22
ANTHOPHY	25.11	8.43	-16.68	43739.13	1182.14
FORSTERT	11.07	4.35	-6.72	17611.18	1956.80
FAYALITE	1.96	.86	-1.10	2887.14	320.79
ENSTATIT	4.28	1.42	-2.87	7517.79	1252.96
DIOPSIDE	9.35	2.19	-7.17	18793.54	1679.35

GPC3B-200-5-7 HOURS = 1017.5 PH(25) = 2.50
 300 DEGREES C AT 500 BARS AND W/P = F
 81/02/18.

CA-AL PX	8.55	-19.55	-28.10	73695.24	4605.95
GIBBSITE	1.05	-10.17	-11.22	29415.90	4202.27
KAOLINIT	-3.55	-23.35	-19.80	51934.03	3462.27
PYROPHYL	-7.37	-26.37	-18.99	49806.69	3112.92
MUSCOVIT	-3.42	-34.07	-30.64	80364.33	3494.10
TILLITE11	-5.98	-30.99	-25.01	65579.56	3246.51
TILLITE12	-5.19	-29.52	-24.34	63833.86	3152.29
TILLITE13	-4.33	-28.07	-23.74	62271.73	3067.57
14ACL-CH	20.78	-10.21	-30.99	81262.85	2138.50
7A-CL-CH	23.16	-10.21	-33.37	87504.54	2302.75
PARAGONI	-1.84	-33.01	-31.17	81746.06	3554.18
PYROCHRO	7.74	1.11	-6.63	17362.70	3476.54
HAUSMANI	9.48	-6.51	-15.98	41918.63	3353.49
RIXBYITE	5.07	-7.62	-12.69	33285.88	3915.99
PYPOLUST	1.51	-8.74	-10.25	26670.16	5971.15
RHODACHR	-2.26	-10.18	-6.93	18163.34	6054.45
GRAPHITE	28.37	-1.45	-29.82	78208.90	22345.40

SOLID SOLUTIONS

MINERAL	X	SUM
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GPC3-200-5-1 HOURS = 3.0 PH(25) = 3.35
 200 DEGREES C AT 500 BARS AND W/P = 5
 P1/02/1P.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG C	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	-4.04	-3.99	.05	-129.17	-28.70
HEMATITE	-13.14	4.80	17.94	-47054.42	-5535.81
MAGNETITE	-11.96	9.34	21.30	-55848.21	-4467.86
MAGNESITE	-2.48	-2.45	.03	-89.32	-29.77
ALBITE	-1.36	4.52	5.88	-15424.81	-1402.26
ANORTHITE	2.46	15.94	12.48	-32728.57	-1925.21
MICROCLIN	-2.34	3.40	5.74	-15043.06	-1367.55
ZOISITE	8.57	27.90	19.33	-50697.20	-1810.61
CLINOZOISITE	8.54	27.90	19.34	-50726.05	-1811.64
PREHNITE	8.97	21.99	13.03	-34159.76	-1485.21
WATPAKITE	-7.43	12.10	12.54	-32878.71	-1565.65
ANALCIME	.80	6.44	5.55	-14549.33	-1322.67
LAUMONTITE	.03	12.10	12.07	-31652.46	-1376.19
TEPICALITE	25.66	43.76	18.10	-47466.47	-1282.88
BOUCITE	7.75	8.63	.88	-2312.82	-462.56
CHRYSOITE	13.73	22.07	8.34	-21859.40	-1366.21
ANTICORITE	2.08	3.49	1.42	-3714.93	-1445.50
TALC	7.94	18.23	10.29	-26974.58	-1586.74
ANTHOPHYLLITE	25.11	45.09	19.98	-52388.47	-1415.90
FORSTERITE	11.07	15.35	4.28	-11224.60	-1247.18
FAYALITE	1.94	7.15	5.18	-13594.00	-1510.44
ENSTATITE	4.20	6.72	2.42	-6381.01	-1063.50
DIOPTASE	9.35	12.77	3.42	-8966.13	-896.61
CA-AL-PX	8.55	17.86	9.31	-24424.95	-1526.56
GIBBSITE	1.05	5.90	4.85	-12729.48	-1818.50
KADLITE	-2.55	7.07	11.52	-30201.73	-2013.45
PYROPHYLITE	-7.37	4.13	11.51	-30174.06	-1885.88
MUSCOVITE	-3.42	15.21	18.63	-48860.12	-2124.35
ILLITE11	-5.98	10.78	16.76	-43947.41	-2175.61
ILLITE12	-5.19	11.48	16.67	-43723.84	-2159.20
ILLITE13	-4.33	12.19	16.52	-43316.69	-2133.83
14ACL-CH	20.78	49.22	28.44	-74598.28	-1963.11
7A-CL-CH	23.16	49.22	26.06	-68356.58	-1798.86
PAPAGONITE	-1.84	16.33	18.17	-47655.21	-2071.97
PYROCHLORE	7.74	8.42	.68	-1794.81	-358.96
HAUSMANNITE	9.48	21.00	11.52	-30214.79	-2417.18
RIXYITE	5.07	12.58	7.51	-19685.75	-2315.97
PYROCLUST	1.51	4.16	2.65	-6939.67	-1542.15
RHODACHLORE	-3.26	-2.66	.60	-1563.16	-521.05

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

GPCR-200-5-1 HDUPS = 3.0 PH(25) = 3.35
 200 DEGREES C AT 500 BARS AND W/P = 5
 P1/02/18.

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG2OH-SO	-5.90	-6.58	-.68	1781.29	494.80
GOLD	-2.78	-2.78	-.00	.13	.00
ANHYDPIT	-8.93	-8.97	-.04	109.07	54.54
BARITE	-11.14	-12.53	-1.39	3644.29	1822.15
CELESTIT	-9.77	-12.15	-2.38	6237.37	3118.69
ARAGONIT	-1.37	-3.11	-1.74	4564.14	1521.38
CALCITE	-1.54	-3.11	-1.57	4128.80	1376.27
DOLOMITE	-4.79	-5.56	-.77	2022.74	337.12
SIDERITE	-6.33	-6.55	-.22	565.71	188.57
WITHERIT	-3.02	-6.67	-3.64	9554.89	3184.96
STPONTIA	-2.50	-6.29	-3.79	9950.26	3316.75
QUARTZ	-1.91	-1.92	-.01	15.14	15.14
AM STO	-1.46	-1.92	-.44	1155.80	1155.80
GRAPHITE	28.37	-6.82	-35.19	92292.23	26369.21

SOLID SOLUTIONS

MINERAL	X	SIIM
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GPC3-300-5-2 HOURS = 93.0 PH(25) = 2.38
 200 DEGREES C AT 500 BARS AND W/P = 5
 P17027JR.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LOG-LK	AFFINITY CAL/M MIN	AFFINITY / STGT CAL/M SPECIES
HEMATITE	-13.14	-7.21	5.93	-15544.86	-1828.81
MAGNETIT	-11.96	-6.87	5.09	-12348.86	-1067.91
QUARTZ	-1.91	-1.65	.26	-689.65	-689.65

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LOG-LK	AFFINITY CAL/M MIN	AFFINITY / STGT CAL/M SPECIES
MC-CH-SO	-4.04	-9.12	-5.07	13308.55	2957.46
MG2OH-SO	-5.90	-9.77	-3.87	10140.55	2816.82
GOLD	-2.78	-3.11	-.33	853.04	20.07
ANHYDRIT	-8.93	-10.04	-1.10	2896.21	1448.10
BARITE	-11.14	-13.32	-2.18	5724.50	2862.25
CELESTIT	-6.77	-12.23	-2.45	6435.32	3217.66
ARAGONIT	-1.37	-8.65	-7.28	19086.16	6362.05
CALCITE	-1.54	-8.65	-7.11	18650.82	6216.94
DOLOMITE	-4.79	-17.46	-12.67	33234.25	5539.38
MAGNESIT	-2.48	-8.81	-6.33	16602.22	5534.07
SIDERITE	-6.33	-10.64	-4.31	11301.89	3767.30
WITHERIT	-3.02	-11.04	-8.01	23369.96	7789.99
STRONTIA	-2.50	-10.84	-8.34	21883.10	7294.37
AN STO2	-1.48	-1.65	-.17	451.01	451.01
ALBIT	-1.36	-13.00	-11.64	30527.91	2775.26
ANORTHIT	3.46	-20.97	-24.43	64080.59	3769.45
MICROCLI	-2.34	-14.30	-11.96	31371.51	2851.96
ZOISITE	8.57	-30.29	-38.86	101912.85	3639.74
CLINOCOI	8.56	-30.29	-38.85	101884.00	3638.71
PREHNITE	8.97	-20.29	-29.26	76737.22	3336.40
WATRAKIT	-.43	-24.29	-23.65	62554.83	2978.80
ANALCIME	.89	-11.36	-12.25	32125.16	2920.47
LAUMONTI	.03	-24.30	-24.33	63815.03	2774.57
TREMOLIT	25.66	2.33	-23.33	61189.19	1653.76
BRUCITE	7.75	2.17	-5.59	14649.31	2929.86
CHRYSOTI	13.73	3.21	-10.52	27600.43	1725.03
ANTIGORI	2.08	.48	-1.60	4184.38	1628.16
TALC	7.94	-.09	-8.03	21058.68	1238.75
ANTHOPHY	28.11	2.00	-23.11	60606.24	1638.01
FORSTERT	11.07	2.70	-8.37	21960.91	2440.10
FAYALITE	1.96	-.97	-2.93	7680.78	853.42
ENSTATIT	4.28	.52	-3.77	9876.33	1646.06
DIOPSIDE	9.35	1.21	-8.14	21345.06	2134.51

GPC3-300-F-7 HOURS = 93.0 PH(25) = 2.38
 200 DEGREES C AT 500 BARS AND W/P = 1 F
 P1702778.

CA-AL PY	8.55	-19.32	-27.87	73089.01	4568.06
GIPPSITE	1.05	-10.01	-11.06	29017.55	4145.36
KADLINTT	-3.55	-22.32	-19.78	51865.76	3457.72
PYROPHYL	-7.37	-26.62	-19.24	50466.86	3154.18
MUSCOVIT	-3.42	-34.31	-30.89	81014.55	3522.37
ILLITE11	-5.98	-31.24	-25.26	66233.76	3278.90
ILLITE12	-5.18	-29.91	-24.72	64826.94	3201.33
ILLITE13	-4.33	-28.58	-24.25	62603.71	3133.19
I4ACL-CH	20.79	-14.12	-34.90	91524.13	2408.53
7A-CL-CH	23.16	-14.12	-37.28	97765.83	2572.78
PARAGONI	-1.84	-33.02	-31.17	81757.60	2554.68
PYPOCHRC	7.74	2.37	-5.36	14069.63	2813.93
HAUSMANI	9.48	-0.76	-10.24	26857.60	2148.61
BIYRYITE	5.07	-3.14	-8.21	21529.18	2534.02
PYROLUSI	1.51	-5.52	-7.03	16437.79	4097.29
RHODACHR	-3.26	-8.61	-5.35	14030.69	4676.90
GRAPHITE	29.37	-3.09	-31.46	82508.63	22573.90

SOLID SOLUTIONS

MINERAL	Y	SUM
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GPC3-300-5-3 HOURS = 310.5 PH(25) = 2.65
 300 DEGREES C AT 500 BARS AND W/P = F
 81/02/18.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-13.14	-7.52	5.62	-14740.49	-1734.18
MAGNETIT	-11.96	-7.50	4.46	-11687.61	-935.01
QUARTZ	-1.91	-1.60	.31	-221.62	-221.62

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	-4.04	-8.95	-4.91	12879.79	2862.18
MG2OH-SO	-5.90	-9.72	-3.82	10015.55	2782.10
GOLD	-2.78	-2.96	-.18	473.46	11.14
ANHYDRIT	-9.93	-9.27	-.66	2450.93	1225.46
RAPITE	-11.14	-13.00	-1.86	4865.75	2432.87
CELESTIT	-9.77	-12.02	-2.25	5902.22	2951.16
APAGONIT	-1.37	-7.97	-6.60	17299.43	5766.48
CALCITE	-1.54	-7.97	-6.43	16864.09	5621.36
DOLOMITE	-4.79	-16.30	-11.51	30185.73	5030.96
MAGNESIT	-2.26	-6.33	-4.07	15338.29	5117.80
SIDERITE	-6.33	-10.27	-4.94	11907.57	3969.19
WITHEPIT	-3.02	-11.10	-8.07	21169.77	7056.59
STRONTIA	-2.50	-10.12	-7.62	20008.64	6669.55
AM SIO2	-1.48	-1.60	-.12	319.04	319.04
ALPITE	-1.34	-12.80	-11.46	30231.21	2748.29
ANDRTPIT	3.46	-20.96	-24.42	64107.07	3771.00
MICROCLI	-2.34	-14.12	-11.78	30890.07	2808.19
ZOISITE	8.67	-30.02	-38.69	101184.73	3613.74
CLINOZOI	8.56	-30.02	-38.57	101155.88	3612.71
PREHNITE	8.07	-19.67	-27.74	75096.07	3265.05
WATRAKIT	-4.43	-24.20	-23.76	62317.14	2967.48
ANALCIME	.89	-11.29	-12.19	31960.32	2905.48
LAUMONT	.03	-24.21	-24.24	63577.13	2764.22
TREMOLIT	25.66	5.23	-19.83	51999.07	1405.38
BRUCITE	7.75	2.55	-5.20	13636.56	2727.31
CHRYSOIT	13.73	4.46	-9.27	24298.35	1518.65
ANTIGORI	2.08	.68	-1.39	3653.41	1421.56
TALC	7.94	1.27	-6.67	17492.78	1028.99
ANTHOPHY	25.11	5.11	-20.00	52461.91	1417.89
FORSTPFI	11.07	3.52	-7.55	19803.66	2200.41
FAYALITE	1.96	-1.57	-3.53	9262.57	1029.17
ENSTATIT	4.22	.95	-3.33	8731.61	1455.27
DIOPSIDE	9.35	2.28	-7.07	18532.95	1853.30

GPC3-300-5-3 HOURS = 310.5 PH(25) = 2.65
 300 DEGPFFS C AT 500 BARS AND W/P = .F
 81/02/18.

CA-AL PX	8.55	-19.38	-27.93	73247.45	4577.97
GTBR SITE	1.05	-10.36	-11.41	29930.35	4275.76
KAOLINIT	-3.55	-23.92	-20.37	53427.55	3561.84
PYROPHYL	-7.37	-27.11	-19.74	51764.83	3235.30
MUSCOVIT	-3.42	-34.83	-31.40	82358.94	3580.82
ILLITF11	-5.98	-31.74	-25.76	67559.58	3344.53
ILLITE12	-5.19	-30.32	-25.13	65909.57	3254.79
ILLITE13	-4.33	-28.90	-24.57	64443.15	3174.54
14ACL-CH	20.78	-12.73	-33.51	87890.53	2312.91
7A-CL-CH	23.16	-12.73	-35.89	94132.22	2477.16
PARAGONI	-1.84	-33.60	-31.76	83286.73	3621.16
PYROCHRO	7.74	2.99	-4.75	12448.21	2489.64
HAUSMANI	9.48	1.44	-8.04	21084.28	1686.74
BIXBYITE	5.07	-1.56	-6.63	17387.17	2045.55
PYPOLUST	1.51	-4.55	-6.07	15907.09	3534.91
PHODACHP	-3.26	-7.89	-4.64	12158.18	4052.73
GRAPHITE	28.37	-3.34	-31.71	83166.82	23761.95

SOLID SOLUTIONS:

MINERAL	Y	SUM
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GPC3-300-5-4 HOURS = 625.0 PH(25) = 3.52
 200 DEGREES C AT 500 BARS AND W/R = 5
 P1/02/1P.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-13.14	-2.63	10.51	-27572.78	-3243.86
MAGNETITE	-11.96	-1.07	10.89	-28570.81	-2285.66
QUARTZ	-1.91	-1.61	.31	-800.28	-800.28

THIS SOLUTION IS UNDEPSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LO-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	-4.04	-7.90	-3.86	10118.69	2248.60
MG2OH-SO	-5.90	-9.16	-3.26	8541.42	2372.62
GOLD	-2.78	-3.07	-.29	752.83	17.71
ANNHYDRIT	-8.92	-9.61	-.68	1778.48	889.24
RARITE	-11.14	-12.80	-1.66	4355.09	2177.54
CELESTITE	-9.77	-11.81	-2.04	5343.28	2671.64
APACONIT	-1.37	-6.32	-4.95	12978.03	4326.01
CALCITE	-1.54	-6.32	-4.78	12542.68	4180.89
DOLomite	-4.79	-13.02	-8.24	21599.20	3599.87
MAGNESITE	-2.48	-6.70	-4.22	11073.27	3691.09
STREPITE	-6.33	-9.34	-3.01	7881.44	2627.15
WITHERITE	-3.02	-9.51	-6.49	17010.16	5670.05
STRONTIA	-2.50	-8.52	-6.02	15800.64	5266.88
AM SiO2	-1.48	-1.61	-.13	340.38	340.38
ALBITE	-1.36	-12.05	-11.48	30118.70	2738.06
ANOPHTHIT	3.46	-20.86	-24.32	63784.37	3752.02
MICROCLIT	-2.34	-14.09	-11.76	30831.86	2802.90
ZOTSITE	8.57	-29.00	-37.57	98527.59	3518.84
CLINOZOI	8.56	-29.00	-37.56	98498.75	3517.81
PREHNITE	9.97	-17.29	-26.86	70448.54	3062.98
WAIPAKIT	-.43	-24.09	-23.66	62037.15	2954.15
ANALCIME	.80	-11.24	-12.14	31826.48	2893.32
LAUMONTITE	.03	-24.10	-24.14	63297.17	2752.05
TREMOLITE	25.66	17.26	-8.40	22027.90	595.35
BRUCITE	7.75	4.19	-3.56	9346.67	1869.33
CHRYSOITE	13.73	9.36	-4.37	11471.35	716.96
ANTIGORITE	2.08	1.46	-.61	1601.52	623.16
TALC	7.94	6.14	-1.80	4708.44	276.97
ANTHOPHY	25.11	16.49	-8.62	22603.31	610.90
FORSTERITE	11.07	6.78	-4.29	11245.20	1249.47
FAYALITE	1.96	1.51	-.45	1162.08	131.34
ENSTATITE	4.28	2.52	-1.70	4463.07	743.84
DIOPSIDE	9.35	5.56	-3.79	9939.54	993.95

GPC3-300-5-4 HOURS = 625.0 PH(25) = 3.52
 200 DEGREES C AT 500 BARS AND W/P = F
 P1/O2/IP.

CA-AL PY	8.55	-19.25	-27.80	72903.41	4556.46
GIRASITE	1.05	-11.12	-12.17	31920.79	4560.11
KADLINT	-3.55	-25.45	-21.91	57451.07	3830.07
PYROPHYL	-7.37	-28.66	-21.29	55831.00	3489.44
MUSCOVIT	-4.42	-36.32	-32.90	66281.57	3751.37
ILLITE11	-5.98	-33.26	-27.26	71539.62	3541.57
ILLITE12	-5.19	-31.52	-26.33	69047.09	3409.73
ILLITE13	-4.33	-29.78	-25.45	66738.14	3287.59
14ACL-CH	20.78	-6.10	-26.88	70485.92	1854.89
7A-CL-CH	23.16	-6.10	-29.26	76727.61	2019.15
PARAGONI	-1.84	-35.07	-33.23	87155.05	3789.35
PYROCHRO	7.74	4.64	-3.10	8120.93	1624.19
HAUSMANI	9.48	8.19	-1.79	3371.92	269.75
BIXBYITE	5.07	3.55	-1.53	4002.10	470.84
PYROCLUST	1.51	-1.10	-2.61	6849.32	1522.07
PHODACHR	-3.26	-6.25	-3.00	7855.67	2618.56
GRAPHITE	28.37	-5.15	-33.53	87922.08	25120.59

SOLID SOLUTIONS

MINERAL	X	SUM
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GPC3-300-5-5 HOURS = 1500.0 PH(25) = 4.02
 300 DEGREES C AT 500 BARS AND W/P = 5
 P1/02/19.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
HEMATITE	-13.14	.74	13.90	-36445.02	-4287.65
MAGNETIT	-11.94	3.31	15.27	-40046.08	-3203.69
QUARTZ	-1.91	-1.67	.25	-644.87	-644.87
TREMOLIT	25.64	26.21	.55	-1441.02	-38.95
ANTIGORIT	2.08	2.09	.01	-27.61	-10.51
TALC	7.94	9.91	1.97	-5178.04	-304.59
ANTHOPHY	25.11	25.37	.26	-671.74	-18.16
FAYALITE	1.96	3.44	1.48	-3868.57	-429.84
HAUSMANN	9.48	13.52	4.04	-10591.51	-847.32
BIXPYITE	5.07	7.56	2.49	-6528.91	-768.11
PYROCLUST	1.51	1.61	.10	-249.28	-55.39

THIS SOLUTION IS UNDERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LQ-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MC-OH-SO	-4.04	-6.90	-2.86	7503.94	1667.54
MCZCH-SO	-5.90	-8.56	-2.66	6977.30	1938.14
GOLD	-2.78	-3.09	-.31	809.98	19.06
ANHYDRIT	-8.93	-9.24	-.31	818.31	409.15
PARITE	-11.14	-12.53	-1.39	3641.56	1820.78
CELESTIT	-9.77	-11.69	-1.92	5023.80	2511.90
ARAGONIT	-1.37	-4.74	-3.37	8849.04	2949.68
CALCITE	-1.54	-4.74	-3.21	8413.69	2804.56
DOLOMITE	-4.79	-9.91	-5.12	13438.16	2239.69
MAGNESIT	-2.48	-5.17	-2.69	7041.22	2347.07
SIDERITE	-6.33	-8.14	-1.81	4748.91	1582.97
WITHERIT	-3.02	-8.03	-5.01	13127.81	4375.94
STRONTIA	-2.50	-7.19	-4.69	12312.34	4104.11
AM-SIG2	-1.48	-1.67	-.19	495.78	495.78
ALBITE	-1.36	-13.07	-11.71	30701.00	2791.00
ANOPHTIT	3.46	-21.00	-24.46	64154.90	3773.82
MICROCLI	-2.34	-14.24	-12.00	31483.32	2862.12
ZONISITE	8.57	-29.53	-37.09	97263.42	3474.41
CLINOZOI	8.56	-28.53	-37.08	97254.57	3473.38
PREHNITE	8.97	-16.72	-25.69	67374.52	2929.33
WAIRAKIT	-.43	-24.35	-23.91	62717.55	2986.55
ANALCIME	.89	-11.41	-12.30	32252.91	2932.08
LAUMONTI	.03	-24.36	-24.39	63976.63	2781.59
BRUCITE	7.75	5.52	-2.23	5843.65	1168.73
CHPYSOTI	13.73	13.24	-.49	1273.56	79.60

GPC3-300-F-5 HOURS = 1500.0 PH(25) = 4.02
 300 DEGREES C. AT 500 BARS AND W/P = 5
 P1702710

FORSTERT	11.07	9.39	-1.68	4395.51	488.39
ENSTATIT	4.28	3.86	-.42	1115.45	185.91
DIOPSID	9.35	8.15	-1.20	3148.32	314.83
CA-AL PX	8.55	-19.33	-27.88	73118.53	4569.91
GIBBSITE	1.05	-11.82	-12.87	33749.68	4821.38
KAOINIT	-3.55	-26.97	-23.42	61420.14	4094.68
PYROPHYL	-7.37	-30.30	-22.92	60111.36	3756.96
MUSCOVIT	-3.42	-37.97	-34.54	90501.75	3938.77
ILLITE11	-5.98	-34.90	-28.92	75837.88	3754.35
ILLITE12	-5.19	-32.89	-27.70	72637.01	3587.01
ILLITE13	-4.33	-30.86	-26.53	69619.71	3429.54
14ACL-CH	20.78	-.99	-21.77	57096.71	1502.54
7A-CL-CH	22.16	-.99	-24.15	63338.40	1666.80
PARAGMT	-1.84	-36.69	-34.85	91396.08	3973.74
PYROCHRO	7.74	5.95	-1.79	4688.04	937.61
PHODACHP	-3.26	-4.74	-1.48	3893.75	1297.92
GRAPHITE	28.37	-6.35	-34.72	91058.75	26016.79

SOLID SOLUTIONS

MINERAL	X	SUM
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GPC-300-5-6 HClFS = 3026.5 PH(25) = 4.54
300 DEGPFS C AT 500 BARS AND W/P = 5
81702/18.

THIS SOLUTION IS SUPERSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LOG-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
QUARTZ	-1.01	-1.74	.17	-456.91	-15.76
TREMOLIT	25.66	27.11	1.45	-3801.93	-18.10
CHRYSOPT	13.73	13.85	.12	-314.46	-19.65
ANTIGORIT	2.08	2.19	.11	-277.35	-107.92
TALC	7.94	10.38	2.44	-6390.71	-375.92
ANTHOPHY	25.11	26.54	1.43	-3752.63	-101.42
HAUSMANIT	9.48	13.47	3.99	-10461.37	-836.91
BIXBYITE	5.07	7.37	2.30	-6029.95	-709.41

THIS SOLUTION IS UNDEPSATURATED WITH THE FOLLOWING MINERALS

MINERAL	LOG K	LOG Q	LOG-LK	AFFINITY CAL/M MIN	AFFINITY / STOT CAL/M SPECIES
MG-OH-SO	-4.04	-6.48	-2.44	6395.21	1421.16
MG2OH-SO	-7.90	-8.22	-2.31	6065.24	1684.79
GOLD	-2.78	-2.78	-0.00	.00	.00
AMHYDRIT	-8.93	-9.08	-.15	396.80	17.25
AM STOT	-1.48	-1.74	-.26	683.74	683.74
BRUCITE	7.75	5.77	-1.98	5189.18	1037.84
FORSTESI	11.07	9.82	-1.25	3273.44	363.77
ENSTATIT	4.28	4.03	-.25	648.94	43.26
DIOPSIDE	9.35	8.37	-.98	2574.20	257.42
PYROCHRO	7.74	6.09	-1.65	4319.77	17.87
PYROCLUST	1.54	1.27	-.24	618.50	137.45

SOLD TO SOLUTIONS

MINERAL ... Y ... SIRM

Appendix F

Temperature and pH Effects on
Sorption Properties of Subseabed Clay

B. T. Kenna

TEMPERATURE AND pH EFFECTS ON SORPTION PROPERTIES OF SUBSEABED CLAY

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INTRODUCTION

A waste package, i.e. nuclear waste contained within a canister, emplaced in the subseabed could produce elevated temperature and therefore, pH changes in the area immediately surrounding the waste package [1]. These changes could possibly alter the sorption properties [2,3] of the clay to serve as a barrier to radionuclide migration away from the waste form [4]. Therefore, the possible influence of temperature and pH must be evaluated before appropriate modeling studies can be completed. The present study addressed the sorption of Cs, Sr, Eu and Ba by subseabed "smectite" clay (composed of quartz, illite, clinoptilolite and montmorillonite [5,6,7] at two temperatures (20 C and 60C) in the pH range of 2-10. Erickson [8] has studied the sorption properties of these elements by smectite clay at the nominal temperature of undisturbed seabed sediment (4 C).

The sorption properties of materials are generally represented mathematically by the equilibrium sorption distribution coefficient ($K_{d,i}$) for each of the species involved, viz.

$$K_d = C_{s,i} / C_{l,i}$$

where $C_{s,i}$ is the equilibrium solid-phase concentration (mMol/gm) of species i and $C_{l,i}$ is the equilibrium solution-phase concentration (mMol/mL) of species i . The general technique of batch equilibration can be readily used to determine $K_{d,i}$ values for specific experimental conditions.

EXPERIMENTAL

Batch equilibration under controlled temperature and pH conditions was used to study the sorption behavior of smectite clay for Cs, Sr, Eu and Ba. The procedure is delineated below.

The smectite clay was provided by G. R. Heath, University of Rhode Island from core LL44-CPC-2, collected in the Pacific Ocean October 11, 1976, at 30°20.9'N, 157°57.85'W, water depth 5821 meters, and was representative of the smectite-rich region which occurs in the sediment at depths below 10 meters. This material contains 5-6 w/o leachable iron and manganese in the form of hydrous oxides and the minerals, illite, clinoptilolite (a zeolite) and montmorillonite.

Duplicate samples for each temperature and/or pH were prepared by suspending 0.25 gm of the clay in 50 mL of 0.68 N NaCl solution (approximate salinity of sea water). Each sample pair had 1 $\mu\text{Ci/mL}$ of ^{137}Cs , ^{85}Sr , ^{154}Eu , or ^{133}Ba and a known amount of the corresponding stable element added, and the pH was adjusted to a preselected value with HCl or NaOH. They were then placed in a constant temperature shaker batch and maintained at temperature with agitation for various time periods. A second suite of sample pairs also were made in which the pH of the 0.68 N NaCl-smectite solution was permitted to remain at its initial value of 7.5-7.8.

After various time periods, a sample pair was removed from the constant temperature batch, the solutions filtered through 0.2 μ filters and a 5 mL aliquot taken for counting. Duplicate standards for each pH were prepared by adding a known spike of radionuclide plus stable element to 50 mL of 0.68 N NaCl and adjusting the pH to a preselected value. These standards were subjected to the same treatment as the other samples.

RESULTS AND DISCUSSION

Figures 1 and 2 summarize the effect of time, temperature, and pH on the sorption of Cs, Sr, Eu and Ba by subseabed smectite clay. For Cs, the sorption equilibrium appears to be established in 3-4 days at 20 C and sooner at 60 C with pH contributing little effect. This is in accord with previous work [8,9]. Ion exchange has been suggested as a primary sorption mechanism for Cs [8], and the inverse relationship between sorption and temperature (Fig. 1) might be consistent with this, but further work is required before a definite statement can be made.

In the case of Sr, sorption equilibrium is established in 1-2 days at both 20 C and 60 C. At both temperatures, a marked increase in K_d accompanies an increase in pH. This is not due to precipitation of strontium since the initial strontium concentration in the samples (ca. 10^{-6} mMol/mL) was well below the solubility limits of sparingly soluble compounds such as $\text{Sr}(\text{OH})_2$ (10^{-3} mMol/mL) and SrCO_3 (10^{-5} mMol/mL). A possible explanation for the increase is that, in basic solutions, the apparent capacity of the smectite clay increases in terms of Sr^{+2} sorption. This could be caused either by the Sr^{+2} reacting with OH^- to form species such as $\text{Sr}(\text{OH})^+$, thereby halving the capacity demand compared to Sr^{+2} , or by sites, which are normally not available for Sr^{+2} sorption, reacting with OH^- to produce additional sorption sites, e.g., Eqs. 1 and 2. In either case, Sr^{+2} sorption would increase with increasing pH because of a change in sorption mechanism. A similar phenomenon and explanation has been reported previously [10] for titanate materials.

Sorption equilibrium for both Eu and Ba appear to be established within 2-3 days, and temperature does not appear to have a significant effect. However, the sorption of both seems to be pH dependent, and the changes in slope of the $\log K_d$ vs. pH curves may indicate a change in sorption mechanism, perhaps due to processes similar to those suggested for Sr^{+2} or to polymeric complex formation. Sorption K_d values obtained for samples exposed at 20 C for 8 days and then after the samples were exposed at 60 C for 8 days showed the sorption processes to be insensitive to temperature and possibly irreversible. Similar results were obtained for samples exposed to 60 C for 8 days and then exposed to 20 C for 8 days. The $\log K_d$ values determined were: Eu 20 C initial and 60 C final, $\log K_d = 7.0$ and 6.8, respectively; Eu 60 C initial and 20 C final, $\log K_d = 6.9$ and 6.8, respectively; Ba 20 C initial and 60 C final, $\log K_d = 4.9$ in both cases; Ba 60 C initial and 20 C final, $\log K_d = 4.9$ and 5.1, respectively.

The change of K_d as a function of temperature for Cs, Sr, Eu and Ba exhibits trends as shown in Figure 3 (data at 4 C determined previously [8]). Cesium sorption steadily decreases as the temperature increases. Strontium is similar between 4 and 20 C, but then exhibits a possible slight increase as temperature increases. The sorption of Eu and Ba apparently is much greater at temperatures above 20 C than below 20 C. The explanation for these trends is not clear at the present time. It is sufficient to say at the moment that, if these trends are valid, then subseabed smectite can be considered a geological barrier to radionuclide release in general, regardless of the pH, at temperatures below 60 C.

SUMMARY

The radionuclide sorption properties of a smectite subseabed clay for Cs, Sr, Eu, and Ba were studied as functions of time, pH, and temperature using batch equilibration techniques. All of the elements reached sorption equilibrium within four days and Cs was the only one not to exhibit pH dependence. Sorption of Cs is inversely dependent on temperature whereas the others show little or no dependence. Table I lists the K_d for the elements indicated at 20 C and 60 C. The initial concentrations are also denoted to allow intercomparison with other work. The values appear to be consistent with those reported in the literature

for Cs [3,9,11], Sr [3,9,11,12], Eu [3,9], and Ba [3,9,11,12]. Ion exchange may be the primary sorption mechanism for Cs, but there appear to be other mechanisms for the sorption of Ba, Sr, and Eu on subseabed sediments. Significant pH effects were measured for the sorption of the latter elements on subseabed sediments.

Table I

Summary of K_d (mL/gm) for Cs, Sr, Eu, Ba

T (°C)	Cs	Sr	Eu	Ba
20	1180 $\pm$ 24	126 $\pm$ 4	(1 $\pm$ 0.2) $\times 10^7$	(9.3 $\pm$ 0.7) $\times 10^4$
60	343 $\pm$ 10	170 $\pm$ 21	(1.1 $\pm$ 0.3) $\times 10^7$	(5.5 $\pm$ 0.3) $\times 10^4$
*	3 $\times 10^{-7}$	7 $\times 10^{-7}$	5 $\times 10^{-6}$	1.7 $\times 10^{-7}$

* Initial concentration in mMol/mL; solution pH 7.5 - 7.8.

REFERENCES

1. J. L. Bischoff and W. E. Seyfried, "Hydrothermal Chemistry of Seawater from 25 to 350 C," *Am. Jour. Sci.*, 278, 838-860 (1978).
2. O. P. Mehra and M. L. Jackson, "Specific Surface Determination by Glycerol Sorption for Vermiculite and Montmorillonite," *Surf. Sci. Soc. Am. Proc.*, 23, 351 (1959).
3. G. R. Heath, G. Epstein and R. A. Prince, in "Seabed Disposal Program Annual Report - Part II," Appendix E, D. M. Talbert ed., SAND77-1270, Oct., 1977.
4. K. L. Erickson, W. E. Seyfried, G. R. Heath, J. L. Krumhansl, and V. T. Bowen, "Geochemical Studies Supporting the U. S. Subseabed Disposal Program," in 16th Annual Marine Technology Conference, Marine Technology Society, Washington, D.C., pp. 500-509, Oct. 6-8, 1980, Washington, D.C.
5. B. T. Kenna, Unpublished results (1980).
6. D. B. Talbert, ed., "Seabed Disposal Program, Annual Report," Jan. to Dec. 1977, Vol. I and II, SAND78-1359, Sandia Laboratories Albuquerque, New Mexico, January, 1979.
7. D. B. Talbert, ed., "Seabed Disposal Program Annual Report," Jan. to Dec. 1978, Vol. I & II, SAND79-1618, Sandia Laboratories, Albuquerque, New Mexico, October, 1979.
8. K. L. Erickson, "Radionuclide Sorption Studies on Abyssal Red Clays," Symposium on Radioactive Waste in Geologic Storage, Amer. Chem. Soc. meeting, Miami, Florida, Sept. 11-15, 1978; *Scientific Basis for Nuclear Waste Management*, Vol. II, C. J. Northrup, ed., Plenum Press, N.Y. (1980).

9. H. Hamaguchi, "Studies on the Sorption of Radionuclides on Marine Sediments," IAEA Contract No. i11R2/RB, Japan Analytical Research Institute, Tokyo, Dec. 28, 1963.
10. R. G. Dosch, "Final Report on the Application of Titanates, Niobates, and Tantalates to Neutralized Defense Waste Decontamination," SAND80-1212 (1980).
11. J. R. Elliason, "Montmorillonite Exchange Equilibria with Sr-Na-Cs," Amer. Mineral., 51, 324-335 (1966).
12. R. J. Lewis and H. C. Thomas, "Adsorption Studies on Clay Minerals: VIII Consistency Test of Exchange in the Systems Na-Cs-Ba Montmorillonite," J. Phys. Chem., 67, 1781-1783 (1963).

FIGURE 1. EFFECT OF TIME, TEMPERATURE AND pH ON SORPTION OF Cs AND Sr BY SUBSEABED SMECTITE CLAY.

FIGURE 2. EFFECT OF TIME, TEMPERATURE AND pH ON SORPTION OF Eu AND Ba BY SUBSEABED SMECTITE CLAY.

FIGURE 3. EFFECT OF TEMPERATURE ON SORPTION OF Cs, Sr, Eu AND Ba BY SUBSEAMED SMECTITE CLAY.

ACKNOWLEDGEMENT

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Appendix G

Effect of Radiolysis on the Oxidation
State of Neptunium ²³⁷Seawater

K. L. Nash, S. Fried, A. M. Friedman

EFFECT OF RADIOLYSIS ON THE OXIDATION STATE OF NEPTUNIUM
IN SEAWATER*

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INTRODUCTION

In a previous study of the effect of radiolysis on plutonium oxidation states in environmental solutions several interesting results, some expected and some unexpected, were reported.¹ For example, it was found that by far the most stable form of plutonium in contact with distilled water and seawater was highly insoluble Pu(IV) hydrolytic polymer. In seawater small amounts of Pu(V) were identified spectrophotometrically in the solution phase. Both of these results are in agreement with the previously reported predictions of Polzer² and the experimental observations of Bondietti,³ among others. In a saturated brine solution radiolysis apparently produced a highly oxidizing medium in which Pu(V) was stable to reduction and the Pu(IV) hydrolytic polymer was slowly oxidized to Pu(VI). Reasons for this result have not been conclusively established but calculations indicate that Cl^- may act as a scavenger for OH radical prohibiting formation of H_2O_2 and leading to the production of Cl_2^- , a potent oxidizing agent.

Neptunium also represents a potential long-term hazard in radioactive waste disposal. Because its redox chemistry is different from the redox chemistry of plutonium a similar study of neptunium radiolysis in solution has been carried out. The principal difference between the solution chemistries of plutonium and neptunium is the relative stability of neptunium in the pentavalent state as opposed to the near equal stability of plutonium in its four valence states. The pentavalent neptunium exists in aqueous solution as the singly charged NpO_2^+ cation. Its low charge

implies relatively high stability and a low tendency to interact with complexing or absorbing species. These characteristics may make neptunium the most difficult long-lived cationic species to be immobilized in waste disposal schemes. What follows are the results of a study of neptunium radiolysis in distilled water and seawater.

EXPERIMENTAL

Experimental methods have been described in detail in the previous report on plutonium radiolysis¹ so the discussion of the experimental methods will be limited to a brief outline with emphasis on differences between the neptunium and plutonium studies. Solid samples of Np(IV), Np(V), or Np(VI) chlorides were prepared by drying solutions under a stream of N₂. Excess alpha doping at the same level as in the plutonium experiments (6×10^9 d/m/ml) was provided by ²⁴⁴Cm.

The concentration of Np in the experiments was between 0.010 M and 0.018 M depending on the starting oxidation state. Samples of 50 μ l of the solutions undergoing radiolysis were taken and diluted with 200 μ l of 1 M HCl for spectroscopic determination. Distribution of Np between its various oxidation states was monitored spectrophotometrically at $\lambda = 960, 723$ nm for Np(IV), $\lambda = 980$ nm for Np(V), and $\lambda = 1223$ nm for Np(VI). In addition Np(VI) was determined by reduction of Np(VI) to Np(V) with NaNO₂ and then measuring the concentration of Np(V) produced. Potentials were measured and pH monitored and adjusted as before. The atmosphere was maintained at 1-2 ppm O₂ with the balance of N₂.

RESULTS AND DISCUSSION

Experiments were performed in distilled water and seawater with neptunium in the (IV), (V) and (VI) valence states initially. Figures 1-4 represent those experiments in which an observable change in the neptunium oxidation state distribution occurred. When Np(IV) was present initially in distilled water (Figure 1), it was oxidized by a complex process. When the metal distribution was 65% Np(IV) + 35% Np(V), about 25% of the Np(IV) was oxidized to Np(V) in the first three days of the experiment. The remaining 40% of the Np(IV) was slowly oxidized to Np(V) ($t_{1/2} \sim 100$ days). When the starting neptunium species was primarily Np(VI), it was reduced to Np(V) with a half-life of seven days (Figure 2). Such a relative rate is understandable since the Np(VI) $\rightarrow$ Np(V) reduction involves only an electron transfer between species in solution or readily soluble, while the Np(IV) $\rightarrow$ Np(V) transition requires molecular rearrangement and is limited by the low solubility of Np(IV) hydroxides.⁴ As these experiments would suggest, when neptunium is present initially as Np(V), it remains as Np(V).

In a similar series of experiments in seawater both oxidation of Np(IV) and reduction of Np(VI) were observed. When the initial distribution of neptunium was 80% Np(IV), 20% Np(V), the Np(IV) was oxidized by an apparent first-order process (Figure 3). The product Np(V) grew into the solution via a zero order process linear in [Np(V)]. It should be noted that, in contrast to the experiment in distilled water, Np(IV) in seawater was apparently

rendered more soluble on subsequent 1 M HCl treatment than the corresponding Np(IV) from the distilled water experiments. When the starting distribution of neptunium was 60% Np(VI), 40% Np(V). Figure 4, reduction of Np(VI) to Np(V) in seawater was observed to take place at a rate slightly faster than Np(IV) oxidation in seawater. In an experiment which began as 100% Np(V), the Np(V) exhibited no tendency toward oxidation or reduction.

Table 1 is a summary of the kinetics analysis of the data in Figures 1-4. As was the case in the plutonium experiments, neptunium is radiolyzed in distilled water (under the conditions of these experiments) according to a zero-order rate law. This result implies that the process which determines whether neptunium is oxidized or reduced is independent of the concentration of neptunium in solution and gives very little information pertinent to elucidation of a mechanism. The half-life for the oxidation of $\text{Np(IV)} \rightarrow \text{Np(V)}$ in distilled water is a factor of 15 slower than the reduction of $\text{Np(VI)} \rightarrow \text{Np(V)}$ in the same medium. This result is in contrast with results obtained in the plutonium system in which oxidation processes were generally faster than reduction.

In the seawater experiments there was considerably greater scatter in the data than in the distilled water experiments. As a consequence of this scatter, the rate constants (particularly in the Np(IV) experiment) are of low precision. The results in Table 1 represent the best fit of the data. The half-lives for each of the reactions studied are very similar with the reduction of Np(VI) fractionally faster than

the oxidation of Np(IV). The disappearance of Np(IV) by a first-order rate law and concomittant zero-order growth of Np(V) implies that the product Np(V) is not involved in the radiolysis reaction (i.e. the oxidation is essentially irreversible). The zero order kinetics of Np(VI) reduction match up fairly well (disappearance of Np(VI) vs. appearance of Np(V)) but give little useful information concerning the mechanism.

When the solutions were judged to have reached a steady-state condition, the experiments were analyzed for soluble, slightly insoluble or adsorbed, and highly insoluble material as in the plutonium experiments. Table 2 contains the results of the steady state analysis of the various experiments. In distilled water neptunium is present only as Np(V) independent of the starting oxidation state. At least 80 percent of this Np(V) is soluble at pH 6.6 while the remaining 1-20 percent is present as a readily soluble pale green solid, probably Np(V) hydroxide.

In contrast only 14-31 percent of the neptunium in contact with seawater was soluble (as Np(V)). The majority of the remaining neptunium was insoluble Np(V) species. This low solubility may be attributable to the higher pH of the seawater though it also may be due to sparingly soluble Np(V) salts with seawater anions. In addition, small amounts of Np(IV) and Np(VI) were found in an acid resistant solid which dissolved in 12 M HCl in the experiment which was predominantly Np(IV) initially. The existence of Np(VI) implies that some oxidation of Np(V) has occurred in this experiment.

One of the most significant discoveries of these experiments is the existence of Np(V) as the stable oxidation state. As mentioned in the introduction, Np(V) exists in aqueous solution as the

monovalent dioxocation NpO_2^+ . Being a monovalent ion it does not interact as strongly with the surrounding medium as higher charged ions and so has higher mobility. In addition, in distilled water, which can be taken as representative of ground waters containing few dissolved salts, most of the neptunium was soluble. The existence of NpO_2^+ as the stable oxidation state implies that barriers around the emplacement site must be designed specifically to retain this potentially highly mobile species. In this respect, neptunium may represent a much greater hazard than plutonium as most of the plutonium was found to be insoluble at near neutral pH.

Table 1. Neptunium Radiolysis: Kinetics Results

<u>System</u>	<u>k</u>	<u>Order</u>	<u>Correlation</u>	<u>t_{1/2}</u>
Np(VI) in distilled water	0.00105 M ⁻¹ d ⁻¹ (a)	zero	0.9929	7 days
	0.00086 M ⁻¹ d ⁻¹ (b)	zero	0.9930	7 days
Np(IV) in distilled water	1.94x10 ⁻⁴ M ⁻¹ d ⁻¹	zero	0.9951	100 days
Np(V) in distilled water	No reaction			
Np(IV) in seawater	0.0663 d ⁻¹ (c)	first	0.9289	10.4 days
	0.00070 M ⁻¹ d ⁻¹ (d)	zero	0.9925	8 days
Np(V) in seawater	No reaction			
Np(VI) in seawater	0.00032 M ⁻¹ d ⁻¹ (e)	zero	0.9314	7 days
	0.00040 M ⁻¹ d ⁻¹ (f)	zero	0.9931	7 days

(a). Rate constant determined monitoring the disappearance of Np(VI).

(b). Rate constant determined monitoring the appearance of Np(V).

(c). Rate constant determined monitoring the disappearance of Np(IV).

(d). Rate constant determined monitoring the appearance of Np(V).

(e). Rate constant determined monitoring the disappearance of Np(VI).

(f). Rate constant determined monitoring the appearance of Np(V).

Table 2. Steady State Distribution of Neptunium

<u>Experiment</u>	<u>E_{Ag/AgCl}</u>	<u>pH_{av}</u>	<u>Solution</u>	<u>1 M HCl</u>	<u>12 M HCl</u>
Np(IV), Distilled Water	80 mv	6.60	0.78 Np(V)	0.22 Np(V)	---
Np(V), Distilled Water	250 mv	6.60	0.99 Np(V)	0.01 Np(V)	---
Np(VI), Distilled Water	150 mv	6.65	0.93 Np(V)	0.07 Np(V)	---
Np(IV), Seawater	-145 mv	8.55	0.14 Np(V)	0.74 Np(V) 0.01 Np(IV)	0.07 Np(IV) 0.03 Np(VI) 0.01 Np(V)
Np(V), Seawater	110 mv	8.40	0.17 Np(V)	0.83 Np(V)	---
Np(VI), Seawater	-360 mv	8.26	0.31 Np(V)	0.69 Np(V)	---

REFERENCES

1. "Study of Radiolytic Oxidation and Reduction of Plutonium in Environmental Solutions," Nash, K., Fried, S., and Friedman, A., Annual Report to Sandia Laboratory, 1979.
2. Polzer, W. L.: in, "Proceedings of a Symposium on Safety in Plutonium Handling Facilities" CONF-710401, Rocky Flats, Colorado, 13-16 April 1971.
3. Bondietti, E. A., and Trabalka, J.R., *Radiochem. Radioanalyt. Letters*, 42, 169 (1980).
4. Baes, C. F., and Messmer, R. E., "The Hydrolysis of Cations," Wiley-Interscience, New York, N.Y. (1976), P. 169-192.

FIGURE 1
Np(IV) in Distilled Water

FIGURE 2
Np(VI) in Distilled Water

FIGURE 3
Nd(IV) in Seawater

FIGURE 4
Nd(VI) in Seawater

Appendix H

A Study of the Mobility of Plutonium
and Americium in Marine Sediments

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A STUDY OF THE MOBILITY OF PLUTONIUM AND AMERICIUM IN
MARINE SEDIMENTS*

Annual Report
Submitted to Sandia National Laboratory

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Erratum for inclusion in the Subseabed Annual Report of December, 1980

The second sentence on page 2 of the report should read:

"In order to judge the effectiveness of this geological barrier it is necessary to collect information on the mobility behavior of important radionuclides in the sediment."

SNL-SDP ANNUAL REPORT

Purpose

The sediments covering the floor of the deep ocean form the last barrier with respect to the release of radionuclides from a subseabed repository. In order to judge the effectiveness of this geological information on the mobility behavior of important radionuclides in the sediment. Over the past year a method has been developed and measurements have been begun to study the diffusion of transuranium elements in samples of sediment from various locations. The purpose of these measurements is the determination of effective diffusion coefficients of the radionuclides in the absence of interstitial flow through the sediment and at ambient pressure and temperature. Data obtained under these conditions will provide valuable information on the retardation characteristics of the sediment. It must be pointed out, however, that in order to assess the merits of the subseabed disposal with confidence the measurements must be extended to regimes of pressure and temperature typical for the subseabed environment both in the near and in the far field of repositories.

By designing and implementing a procedure by which the concentration profile of tracer amounts of radionuclides can be measured in cylindrical samples of sediment after allowing time for diffusion, limiting values have been determined for plutonium and for americium. Samples that have been processed to date include two different types of sediment, and application of plutonium both in the tetravalent and hexavalent state as well as ^{241}Am . A listing of the samples is given in Table I. A sample of bentonite clay

containing ^{22}Na as a tracer nuclide is included because it was used to demonstrate the capability of the experimental procedure of yielding effective diffusion coefficients for a species of known mobility. For americium and plutonium the spread of the tracer by diffusion did not exceed a thickness of 1 mm in the sediment. This thickness is the approximate limit of resolution of the experimental method. It is therefore only possible to set an upper limit of $10^{-14} \text{ m}^2 \text{ sec}^{-1}$ for the effective coefficients of diffusion of the two actinide elements.

EXPERIMENTAL PROCEDURE

Preparation of Samples

The sediment samples used to measure the diffusion of the various tracer nuclides have the shape of right cylinders with a diameter of 14.4 mm and a height of 12.25 mm. In making up the samples it proved convenient to use disposable polyethylene syringes of 10 cm^3 volume the tips of which were cut off on a lathe. Figure 1 shows schematically how the sediment was packed into the syringe bodies. To begin with, an appropriate amount of tracer is mixed with the sediment. An amount equal to 1 cm^3 of the sediment-tracer mixture is packed into a syringe where it is backed by a plunger. The open-end face of the sediment is smoothed to make a plane surface with a roughness estimated not to exceed a few tenths of a millimeter. This surface is contacted with gentle

pressure with a similar surface of sediment that does not contain tracer and is brought up against it from a second syringe. After good contact of the two flat surfaces is established the sediment is pushed upward in the first syringe to the extent that an additional volume of 1 cm^3 of tracer-free sediment is introduced. At this point the second syringe is removed by shearing and the sediment is smoothed. The sample is now contained in the first syringe body and consists of a cylindrical plug of 2 cm^3 volume, 1 cm^3 of which contains the tracer nuclide joined to the tracer-free sediment by a sharp boundary plane. For storage the plunger is removed from the syringe and replaced by a rubber stopper. At the sediment end a closed end tube with a small amount of seawater is attached with a rubber sleeve. The water keeps the sediment from drying out during storage. The configuration of the sample during storage is shown in Figure 2.

The radioisotopes chosen for the mobility study, ^{241}Am and ^{237}Pu , are characterized by emission of 59.5 keV γ -rays and 97 and 100 keV X-rays, respectively. They were added to the sediment in amounts bringing the level of activity to approximately 10^4 d/s ($0.3\text{ }\mu\text{Ci}$) per cubic centimeter. The penetrating nature of the X- and γ -radiation permits assay of the samples with GeLi scintillation counting equipment without prior chemical separation. The radioactive tracers are added to the clay from a stock solution containing the carrier free chlorides. These stock solutions which were made up by dissolving americium and plutonium chlorides in distilled water are slightly acidic as a consequence of hydrolysis of the actinide salts. However, since the maximum tracer concentration in

the sediment is the order of 5×10^{-7} molar for americium and 2×10^{-9} molar for plutonium no change of the pH in the sediment is observed. The valence state of the actinide ions in the tracer solution is +3 for americium and normally +4 for plutonium. In the case of sample #170401 the plutonium was oxidized to the hexavalent state with ozone before it was added to the sediment. The higher valence state was verified by showing the plutonium not to be co-precipitated on LaF_3 .

Determination of the Tracer Activity Distribution

The activity samples were stored at ambient temperature, i.e. $T = 298 \pm 5$ K, for time periods ranging from several hours to the better part of a year. At the end of the storage period the variation of the tracer radioactivity along the axis of the sample cylinders was measured in order to evaluate the extent of the diffusion. The concentration profile of the radionuclide in the sample is determined by rubbing the sediment off on strips of filter paper moistened with a solution of 20% caramelized sucrose. The rubbing is done with the apparatus shown schematically in Figure 3. First, a plunger is re-inserted into the syringe containing the sediment sample after the rubber stopper and the bottom tube have been removed. The plunger has notches cut along side the tip allowing the escape of air so that it can be placed in contact with the back side of the sample. A 0.2 cm^3 volume of the sample is extruded and the syringe is mounted in the holder attached to an electrically driven carriage as shown in the diagram. The holder is lowered until the sediment is in contact with the moistened paper strip at a light (approximately 0.1-0.4 N)

force and the carriage is put in motion to generate a streak of the sediment of fairly uniform thickness. By rubbing off a known thickness of the sample, usually 2.25 mm, and noting the length of the deposit on the paper the axial coordinate of the sample is correlated with the distance on the paper strip measured from the point at which the sample is first set down.

After deposition of the sample the strips are left to dry and are cut into square pieces 2 cm on edge. The sediment will adhere to the paper after drying because of the caramelized sucrose contained in the solution with which the paper was treated.

The amount of sediment deposited on the paper squares may vary from 1 to 10 mg and corresponds to a thickness of approximately 5-10 μm in the original sample. It is determined by a conductivity measurement. After assay of tracer activity the square pieces are inserted in a special conductivity cell containing 0.80 cm^3 of conductivity grade water. The electrolyte content stemming from the seawater increases the electrical conductivity and is proportional to the quantity of moist sediment originally deposited. The measured conductivity is correlated to the amount electrolyte and the quantity of sediment by means of a calibration curve based on mixtures of seawater with pure water.

The amount of radionuclide associated with the sediment is assayed by pulse height analysis of the radioactivity with Ge(Li) γ -ray counting equipment. This is done directly on the paper squares since the 56 keV γ -ray activity accompanying the decay of ^{241}Am and the 97 and 100 keV X-ray

activity stemming from the ^{237}Pu is only insignificantly attenuated by the associated material and chemical isolation of the radionuclide is therefore unnecessary. For a given sample many more paper squares are obtained than are needed for the mapping of the concentration profile. In general, therefore, only every 4th paper slip is assayed, except in regions of no activity or maximum activity, where even fewer spot checks are adequate.

RESULTS

Before presentation of the results obtained with sediment samples containing americium and plutonium two tests of the experimental method must be mentioned. The first test was designed to assess the practical limit of resolution, i.e. the degree of spreading of the radionuclide in the sample that is attributable to experimental uncertainty. The second test involves the diffusion of a mobile species, viz. ^{22}Na , in the sediment and demonstrates the suitability of the method for the measurement of effective diffusion parameters.

For the first test a sample was rubbed off on filter paper that was made up by sandwiching a 0.1 mm thick layer of Prussian blue between two 1 cm^3 sections of the sediment. The blue dye is not expected to diffuse because it is insoluble and should therefore be deposited along a section of the filter paper reflecting the interface between the two halves of the

sediment core. Its intensity was judged visually and rated on a scale of 1 to 100. The results of this Prussian blue test with illitic sediment from MPG-III is shown in Figure 4. The main portion of the blue dye is distributed roughly in a bell-shaped curve over a distance of the paper strip corresponding to a thickness of the sample cylinder of 0.5 mm. There are two obvious reasons for the spread of the dye in excess of its natural thickness: despite efforts of creating a smooth, plane interface between the two cylindrical sections, there will be an unevenness of the two surfaces that is estimated to be of the order of several tenths of a millimeter. In addition an out-of-parallel alignment error during rub-off will result in additional spreading of the interfacial material. Figure 4 also shows small amounts of dye appearing at irregular locations several millimeters before the interface is reached. The reason for this behavior became obvious during preparation of the sample. When the second portion of the sediment was forced into the syringe tube, uneven friction at the wall caused a distortion of the perimeter causing small amounts of blue dye to be left more than a millimeter behind the interfacial plane. The conclusion from the dye test is a resolution limit of circa 0.75 mm thickness equivalent in the sample cylinder. Unless the diffusive spread of the activity exceeds this value substantially, movement of the tracer during a storage cannot be inferred conclusively. To demonstrate the suitability of the rub-off procedure for the measurement of effective diffusion coefficients sample #130501 was prepared containing the mobile radionuclide ^{22}Na in a commercial clay (bentonite) saturated with a concentrated NaCl-MgCl_2 brine. It was rubbed off 12120 seconds

(=3 hours 22 minutes) after preparation and yielded the activity data presented in Table II. The last column of the table lists specific activities converted to a relative scale in order to facilitate comparison of different samples with different absolute counting rates. Conversion to the relative scale is accomplished simply by division of the specific activity measured for the sediment on the individual paper slips by the maximum specific activity observed for the sample. The data from column 6 of Table II are plotted in Figure 5 as a function of distance from the front end (the originally inactive end) of the sample. Also plotted in Figure 5 are two curves representing the calculated concentration profile for values of the product of effective diffusion coefficient and time, $D_{\text{eff}} \cdot t$, of $3.0 \times 10^{-7} \text{ m}^2$ and $4.0 \times 10^{-7} \text{ m}^2$, respectively. These curves were calculated from the equation

$$\frac{C(z,t)}{C_0} = \frac{1}{2} - \frac{2}{\pi} \sum_{n=1}^{\infty} e^{-\left(\frac{n\pi}{h}\right)^2 D_{\text{eff}} \cdot t} \cdot \sin \frac{n\pi}{2} \cdot \cos \frac{n\pi z}{h} \quad (1)$$

Equation 1 is the solution of the linear, bounded diffusion problem for a region of height h and for a diffusion coefficient D . $C(z,t)$ is the concentration as a function of distance z and time t . C_0 represents the initial concentration in the upper half of the region at the beginning of the experiment, i.e. at time zero.

The known contact time of 12120 seconds of sample #130501 yields values of $3.30 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$ and $2.48 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$ for the effective coefficient of diffusion represented by the upper and lower curves,

respectively. The best approximation to the data points seems to fall between the two curves, so that the average of the two numbers emerges as a reasonable estimate for the effective coefficient of diffusion of sodium-22 in the bentonite clay-brine mixture. This average value is

$$D_{\text{eff}}(\text{Na}) = 3.0 \cdot 10^{-10} \text{ m}^2 \text{ s}^{-1}.$$

When compared with the coefficient of self-diffusion for Na in electrolyte solutions up to 3 mol/l of electrolyte, for which values near $1.0 \cdot 10^{-9} \text{ m}^2 \cdot \text{s}^{-1}$ are reported (Ref. 1,2), the diffusion coefficient in the clay indicates a reduction of the mobility of sodium by a factor of 3. The lowered mobility of the sodium can be accounted for by the combined effects of tortuosity and sorption. It has been shown that in marine sediments tortuosity and a potential structural change of the interstitial fluid reduces the diffusion coefficient to 55% of its value in seawater (Ref. 3). The effect of sorptive interaction with the clay further lowers the diffusion coefficient by a factor known as retardation factor defined as

$$R = \frac{1}{1 + \frac{\rho}{\theta} K_d} \quad (2)$$

ρ is the density of the dry clay and θ is the volume ratio of liquid to solid phase. The density of the clay is around $2 \text{ g} \cdot \text{cm}^{-3}$ and θ has a value near unity. In order to produce an overall lowering of the diffusion coefficient by a factor of 3, the retardation factor must also reduce the

mobility to 55% of the unretarded value. A value of 0.55 for the retardation factor implies a value of 0.4 for the distribution constant K_d . As judged from batch measurements of alkali ion sorption this number is quite reasonable.

The data obtained from the ^{22}Na tracer experiment verify the validity of the rub-off method for the determination of practical effective diffusion coefficients. Parenthetically it may be mentioned here that the same data also reflect the usefulness of the gross conductivity measurements for the determination of the amount of deposited material. The scatter of the raw data uncorrected for the variation of the mass of clay is approximately three times as large as the scatter of the specific activities. The residual scatter of the specific activities is consistent with the expected statistical error of the counting procedure.

The activity data for the samples containing ^{241}Am and ^{237}Pu are listed in Tables III through VII. Plots of the data points are shown in Figures 6 through 10. In all cases the increase of activity forms background levels to an averaged maximum above the interface occurs over a narrow range that does not exceed 1.5 mm (sample 170401). Even for as long a storage time as eight months for sample 210104 the transition from the inactive to the active part of the sediment spans an interval of only 0.95 mm and is not far outside the estimated resolution limit of the method of 0.75 mm. There appears to be progressive spreading with increasing storage time in the sediment samples containing americium. If it is assumed that the diffusion coefficient in the illite-rich sediment from MPG-III and in the

smectite-rich sediment from MPG-I is of the same magnitude, the variation of the slope of the activity curves depicted in Figures 6, 7, and 8 is consistent with a value of $9.6 \times 10^{-16} \text{ m}^2 \cdot \text{s}^{-1}$. This interpretation must be regarded with caution. Since the region over which the activity increase is observed does not substantially exceed the estimated experimental uncertainty, and since the scatter of the data points is substantial, the indication of a variation of the slopes in accordance with contact times may be fortuitous. If this is the case, the value of $9.6 \times 10^{-16} \text{ m}^2 \cdot \text{s}^{-1}$ is only an upper limit for the effective coefficient of diffusion of americium in the sediment.

Inspection of Figure 9 indicates the diffusion coefficient of tetravalent plutonium to be of the same order of magnitude as that of americium. In fact, the rather large scatter of the data points in the region where a constant specific activity is expected suggests that the mobility of the plutonium in the sediment is less than that characterized by a diffusion coefficient of $10^{-15} \text{ m}^2 \cdot \text{s}^{-1}$. The scatter may be attributed to imperfect mixing of the tracer with the sediment in conjunction with an inability of the plutonium to equilibrate the concentration over distances of the order of $10 \text{ } \mu\text{m}$ during a period of 28 days.

The data points for sample #170401 (Table VII and Figure 10) indicate a potentially higher mobility for hexavalent plutonium than is observed for the tetravalent species. The width of the transition region from background to maximum activity is 1 to 1.5 mm. With a contact time of $5.182 \times 10^6 \text{ s}$ the effective diffusion coefficient becomes $1.9 \times 10^{-15} \text{ m}^2 \cdot \text{s}^{-1}$.

CONCLUSIONS

The diffusion data obtained to date reflect an extremely low mobility of the transuranium elements americium and plutonium in marine sediments. The effective diffusion coefficients for both elements are of the order of $10^{-15} \text{ m}^2 \cdot \text{s}^{-1}$, i.e. smaller by five orders of magnitude than the diffusion coefficient of a mobile species such as sodium. There is no evidence of a significant difference of the mobility between smectite-rich sediment from MPG-I and the illitic sediment from MPG-III. However, there may be a difference in the effective diffusion coefficients of tetravalent and hexavalent plutonium. But even the more mobile hexavalent species is characterized by the exceedingly small value of $2 \times 10^{-15} \text{ m}^2 \cdot \text{s}^{-1}$ for the effective diffusion coefficient. These conclusions reflect a conservative interpretation of the experimental data. The actually observed diffusive spread of the tracers was within the estimated limits of the experimental uncertainty of the method, or of comparable magnitude. The calculations of diffusion coefficients are based on the trend of progressive spreading for similar samples stored over different time periods.

The results obtained from this study of actinide element mobility in marine sediments can be compared with the results of a parallel study of mobilities in bentonite and in hectorite clay saturated with NaCl-MgCl_2 brines (Ref. 5). From this latter study results are available for seven test samples made up of different combinations of clay type and brines. With storage times of up to four months it was concluded that the observed spread of the tracer was entirely within the limits of resolution of the

method, and that diffusion of trivalent americium and of plutonium, both, as tetravalent and as hexavalent species, had not been demonstrated. As a consequence, only an upper limit of $2 \times 10^{-14} \text{ m}^2 \cdot \text{s}^{-1}$ was placed on the magnitude of the effective coefficient of diffusion of the two actinide elements. This value suggests a common underlying aspect determining the mobility behavior of americium and plutonium in clay-like materials of different origin.

As regards the assessment of the effectiveness of marine sediments as a geological barrier the small values for the effective diffusion coefficients of americium and plutonium are encouraging. The root mean square displacement of a nuclide for which the diffusion coefficient has a value of $2 \times 10^{-15} \text{ m}^2 \cdot \text{s}^{-1}$ is only 3.6 cm after 10,000 years have elapsed.

While the data at hand are favorable for the subseabed disposal concept, they present only part of the mobility information needed for a thorough assessment of barrier effectiveness. Mobility studies must be made for other important nuclides, notably neptunium and technetium. Uranium, too, must be considered. Samples with neptunium and technetium as tracers have already been prepared. Preliminary results suggest a low mobility for neptunium in the pentavalent state, - perhaps as low as that of other transuranium elements - and they indicate high mobility for the pertechnetate ion in both, aerated and reducing sediments, the latter stemming from the east Pacific ocean.

It must be remembered, too, that the results of diffusion measurements obtained in the laboratory at ambient temperature and pressure may not faithfully reflect the diffusion properties in the regime of temperature

and pressure prevailing in the subseabed environment. It will be necessary to complement the present results by experimental data obtained in the field or in the laboratory under simulated subseabed conditions.

Furthermore it is desirable to support the gross diffusion observations with the investigation of the mechanism and the processes that are fundamentally responsible for the retention of slow-moving species. Confident extrapolation and short-term measurements over the time span of repository lifetimes can be made only on the basis of a good understanding of the physico-chemical processes determining the mobility behavior of the radionuclides.

12/30/80-jmb

TABLE I. Summary of Samples.

Sample Ident. Number	Sediment Type	Tracer Nuclide	Valence State at Application	Contact Time 10^6 s	Effective Coefficient of Diffusion $m^2 \cdot s^{-1}$
210102	MPG III illite	^{241}Am	+3	11.587	$0.96 \cdot 10^{-15}$
210104	MPG III illite	^{241}Am	+3	20.747	$0.96 \cdot 10^{-15}$
280104	MPG I smectite	^{241}Am	+3	3.101	$0.96 \cdot 10^{-15}$
110204	MPG I smectite	^{237}Pu	+4	2.433	$1.0 \cdot 10^{-15}$
170401	MPG I smectite	^{237}Pu	+6	5.182	$1.9 \cdot 10^{-15}$
130501	Bentonite clay	^{22}Na	+1	0.01212	$3 \cdot 10^{-10}$

TABLE II. Activity Distribution in Sample No. 130501: Bentonite Clay with 80%
by Wt. WIPP A Brine. Tracer Nuclide: ^{22}Na - Contact Time: 12120 s

Distance from front end of sample mm	Mass of moist clay on 4 cm ² paper slip mg	Counting rate corrected for background d per 100 s	Specific activity ^a 10 ⁶ d per s per kg	Relative specific activity ^b
0.24	4.08	4	0.098	0.01
0.63	4.69	7	1.49	0.16
1.46	3.96	16	4.03	0.043
1.59	4.08	18	4.41	0.047
1.84	3.68	10	2.72	0.029
1.96	3.58	20	5.59	0.060
2.68	3.90	19	4.87	0.052
2.80	3.28	22	6.72	0.072
3.07	4.48	47	10.5	0.11
3.19	12.85	138	10.7	0.12
3.32	8.94	74	8.28	0.088
3.46	7.38	91	12.3	0.13
3.53	4.33	66	15.2	0.16
3.59	8.56	114	13.3	0.14
3.71	3.35	60	17.9	0.19
3.85	4.58	105	22.9	0.24
4.10	3.02	65	21.5	0.23
4.32	4.33	96	22.2	0.24
4.63	7.91	182	23.0	0.25
4.76	4.53	132	29.1	0.310
4.81	4.79	130	27.2	0.29
5.01	3.58	120	33.5	0.36
5.15	3.17	105	33.1	0.35
5.54	5.14	222	43.2	0.46
5.91	4.41	191	43.3	0.46
6.38	4.74	239	50.5	0.54
7.89	4.41	202 ± 15	45.8	0.49

^aNo correction has been included for counting efficiency and geometry.

^bRelative specific activities were calculated by dividing the specific activities by 93.8×10^6 d/s/kg, twice the estimated activity at 6.25 mm distance from the front end of the sample.

TABLE III: Activity Distribution in Sample No. 280104: Smectite-rich Marine
Sediment from MPG I. Tracer Nuclide: ^{241}Am - Contact Time: $3.1008 \times 10^6 \text{ s}$

Distance from front end of sample	Mass of moist clay on 4 cm^2 paper slip ^a	Counting rate corrected for background	Specific activity ^b $10^4 \text{ d} \cdot \text{s}^{-1} \cdot \text{kg}^{-1}$	Relative specific activity ^c
mm	mg	d per 100 s		
0.03	0.8	background level	zero	zero
0.06	0.8	background level	zero	zero
0.22	0.4	background level	zero	zero
0.37	0.9	background level	zero	zero
0.53	0.8	background level	zero	zero
0.68	0.6	background level	zero	zero
0.84	2.0	background level	zero	zero
1.00	1.8	background level	zero	zero
1.15	0.5	background level	zero	zero
1.46	1.0	background level	zero	zero
1.78	0.8	background level	zero	zero
2.40	0.8	background level	zero	zero
3.02	0.8	background level	zero	zero
3.65	0.6	background level	zero	zero
4.27	0.6	background level	zero	zero
4.89	0.6	background level	zero	zero
4.95	0.5	background level	zero	zero
5.51	0.4	background level	zero	zero
5.54	0.5	background level	zero	zero
5.57	0.5	background level	zero	zero
5.60	0.5	background level	zero	zero
5.61	0.5	9	18	0.21
5.62	0.6	16	27	0.03
5.62	0.7	133	190	0.23
5.63	0.7	150	214	0.25
5.64	0.7	128	183	0.22
5.64	0.7	201	287	0.34
5.66	0.9	197	219	0.26
5.67	0.9	194	216	0.26
5.68	0.9	302	336	0.40
5.70	0.9	246	273	0.33
5.71	0.9	276	307	0.37
5.72	0.8	160	200	0.24
5.74	0.8	256	320	0.38
5.75	0.8	294	368	0.44

TABLE III. Continued.

Distance from front end of sample	Mass of moist clay on 4 cm ² paper slip ^a	Counting rate corrected for background	Specific activity ^b	Relative specific activity ^c
mm	mg	d per 100 s	10 ⁴ d·s ⁻¹ ·kg ⁻¹	
5.77	0.8	455	569	0.68
5.77	1.2	494	412	0.49
5.79	1.2	776	647	0.77
5.80	0.8	391	489	0.58
5.81	0.8	455	569	0.68
5.83	0.8	503	629	0.75
5.84	0.6	258	430	0.51
5.85	0.6	264	440	0.52
5.87	0.6	238	397	0.47
5.88	0.8	726	908	1.08
5.89	1.2	1549	1291	1.54
5.91	1.2	1761	1468	1.75
5.93	1.4	1970	1407	1.68
5.96	1.4	1218	870	1.04
5.98	1.0	785	785	0.93
6.01	1.0	564	564	0.67
6.04	0.6	301	502	0.60
6.06	0.3	297	990	1.18
6.08	0.5	314	628	0.75
6.11	0.3	182	607	0.72
6.14	0.3	213	710	0.85
6.29	0.4	323	808	0.96
6.48	0.8	424	530	0.63
6.61	1.0	416	416	0.50
6.92	1.2	626	522	0.62
7.38	1.4	704	503	0.60
7.70	0.6	390	650	0.77
7.85	1.0	870	870	1.04
8.01	0.6	489	815	0.97
8.09	0.8	884	1105	1.32

^aAmount of deposited sediment estimated by visual inspection.

^bNo correction has been included for counting efficiency and geometry.

^cRelative specific activities were calculated by dividing the specific activities by 840 10⁴ d·s⁻¹·kg⁻¹.

TABLE IV: Activity Distribution in Sample No. 210102: Illite-rich Marine Sediment from
MPG-III. Tracer Nuclide: ^{241}Am - Contact Time: 11.5866×10^6 s

Distance from front end of sample mm	Mass of moist sediment on 4 cm paper slip mg	Counting rate adjusted for background $\text{d}\cdot\text{min}^{-1}$	Specific activity ^a $\text{d}\cdot\text{min}^{-1}\cdot\text{g}^{-1}$	Relative specific ^b activity
0.12		4.97	Zero	Zero
0.37		2.96	Zero	Zero
0.61		2.85	Zero	Zero
0.86		3.91	Zero	Zero
1.35		3.34	Zero	Zero
1.60		3.57	Zero	Zero
1.84		background level	Zero	Zero
2.09		1.39	Zero	Zero
2.57		background level	Zero	Zero
2.82		background level	Zero	Zero
3.06		1.05	Zero	Zero
3.31		background level	Zero	Zero
3.80		background level	Zero	Zero
4.05		background level	Zero	Zero
4.29		background level	Zero	Zero
4.54		background level	Zero	Zero
5.02		background level	Zero	Zero
5.27		0.87	Zero	Zero
5.51		background level	Zero	Zero
5.76		background level	Zero	Zero
6.25		1.12	Zero	Zero
6.50		background level	Zero	Zero
6.74		background level	Zero	Zero
6.99		1.87	Zero	Zero
7.14		background level	Zero	Zero
7.22		background level	Zero	Zero
7.31		background level	Zero	Zero
7.39		0.91	Zero	Zero
7.48		0.45	Zero	Zero
7.56		background level	Zero	Zero
7.62		background level	Zero	Zero
7.71		background level	Zero	Zero
7.79		0.44	Zero	Zero
7.88	(4.0)	2.09	Zero	0.01
7.96		0.27	Zero	Zero
8.02		background level	Zero	Zero
8.11		1.24	Zero	Zero
8.19		0.85	Zero	Zero

TABLE IV. Continued.

Distance from front end of sample	Mass of moist sediment on 4 cm ² paper slip	Counting rate adjusted for background	Specific activity ^a	Relative specific activity ^b
mm	mg	d·min ⁻¹	d·min ⁻¹ ·g ⁻¹	
8.28		background level	0	0.
8.36	(4.0)	6.95	1738	0.04
8.44		1.55	0	0.
8.51		0.83	0	0.
8.59		background level	0	0.
8.67		0.58	0	0.
8.76	5.41	8.80	1627	0.04
8.84		0.31	0	0.
8.93	3.99	2.58	647	0.02
8.99		background level	0	0.
9.16	3.90	97.92	25108	0.64
9.33	5.74	92.05	16037	0.41
9.41	3.18	19.96	6277	0.16
9.64	5.35	240.37	44929	1.14
9.89	4.17	140.30	33645	0.86

^aNo correction was applied for counting efficiency and geometry.

^bRelative specific activities were calculated by dividing specific activities by 39287 d·min⁻¹·g⁻¹.

TABLE V: Activity Distribution in Sample No. 210104: Illite-rich Marine Sediment
from MPG-III. Tracer Nuclide: ^{241}Am - Contact Time: 20.747×10^6 s

Distance from front end of sample mm	Mass of moist sediment on 4 cm ² paper slip mg	Counting rate corrected for background d per min	Specific activity ^a d·min ⁻¹ ·g ⁻¹	Relative specific activity ^b
0.08		background level		
0.21		background level		
1.32		background level		
1.50		background level		
2.54		background level		
2.72		background level		
3.77		background level		
3.95		background level		
4.93	0.76	20.6	27105	0.11
4.99	0.54	5.9	10926	0.04
5.05	3.45	31.8	9217	0.04
5.11	3.16	20.5	6487	0.03
5.17	2.76	59.4	21522	0.08
5.23	3.25	35.1	10800	0.04
5.29	2.40	77.8	32417	0.13
5.35	2.52	69.0	27381	0.11
5.41	2.36	11.5	4873	0.02
5.47	4.54	15.4	3392	0.01
5.53	2.18	36.2	16606	0.07
5.59	3.81	18.1	4751	0.02
5.72	4.21	21.7	5154	0.02
5.78	3.72	87.3	23468	0.09
5.84	4.21	20.0	4751	0.02
5.90	1.23	17.5	14228	0.06
5.96	3.34	13.5	4042	0.02
6.02	2.54	54.8	21575	0.08
6.07	1.96	8.6	4388	0.02
6.13	1.43	57.8	40420	0.16
6.19	1.09	40.8	37431	0.15
6.25	2.81	58.9	20961	0.08
6.31	1.63	101.9	62515	0.25
6.38	1.23	122.4	99512	0.39
6.49	1.36	126.3	92868	0.37
6.61	0.71	146.4	206197	0.81
6.73	0.94	140.9	149894	0.59

TABLE V. Continued.

Distance from front end of sample	Mass of moist sediment on 4 cm ² paper slip	Counting rate corrected for background	Specific activity ^a	Relative specific activity ^b
mm	mg	d per min	d·min ⁻¹ ·g ⁻¹	
6.84	1.42	239.3	168521	0.66
6.95	1.27	273.8	215591	0.85
7.08	3.78	737.2	195026	0.77
7.44	1.00	421.8	421800	1.66
7.62	2.36	150.0	119153	0.47
7.80	2.63	668.6	254220	1.00
7.98	2.50	463.0	185200	0.73

^aNo correction was applied for counting efficiency and geometry.

^bRelative specific activities were calculated by dividing specific activities by 254220 d·min⁻¹·g⁻¹.

TABLE VI: Activity Distribution in Sample No. 110204: Smectite-rich Marine Sediment
from MPG I. Tracer Nuclide: ^{237}Pu Applied as PuCl_4 - Contact Time: 2.4331×10^6 s

Distance from front end of sample	Mass of moist sediment on 4 cm ² paper slip	Counting rate corrected for background	Specific activity ^a	Relative specific activity ^b
mm	mg	d per 100 s	d·s ⁻¹ ·g ⁻¹	
0.10		background level	zero	
0.30		background level	zero	
1.40		background level	zero	
1.61		background level	zero	
2.65		background level	zero	
2.65		background level	zero	
2.80		background level	zero	
3.85		background level	zero	
4.07		background level	zero	
5.03		background level	zero	
5.29		background level	zero	
5.51		background level	zero	
5.72		background level	zero	
5.76	0.12	4	333	0.38
5.80	0.39	4	103	0.12
5.83	0.73	2	27	0.03
5.87	0.72	18	250	0.28
5.91	0.60	12	200	0.23
5.95	0.31	6	194	0.22
5.97	0.56	18	321	0.36
6.01	0.66	16	242	0.27
6.05	1.19	35	294	0.33
6.08	1.64	34	207	0.23
6.12	0.36	9	250	0.28
6.16	0.30	24	800	0.91
6.19	4.11	72	175	0.20
6.22	0.37	47	1270	1.44
6.26	0.90	47	522	0.59
6.30	0.65	57	877	0.99
6.33	0.53	53	1000	1.13
6.37	0.32	93	2906	3.29
6.40	0.38	58	1526	1.73
6.44	0.62	31	500	0.57
6.47	1.14	71	623	0.71
6.51	1.05	73	695	0.61
6.55	1.08	76	704	0.80
6.58	0.78	77	987	1.12

TABLE VI. Continued.

Distance from front end of sample	Mass of moist 222 sediment of 4 cm ² paper slip	Counting rate corrected for background	Specific activity ^a	Relative specific activity ^b
mm	mg	d per 100 s	d·s ⁻¹ ·g ⁻¹	
6.61	2.59	28	108	0.12
6.65	0.55	31	564	0.64
6.68	1.86	69	371	0.42
6.72	0.78	56	718	0.81
6.76	0.82	93	1134	1.28
6.80	0.04	34		
6.82	0.15	46	3067	3.47
6.86	0.18	30	1667	1.89
6.90	0.84	29	345	0.39
6.93	0.22	26	1182	1.34
6.97	0.36	64	1778	2.01
7.01	0.53	45	849	0.96
7.04	0.72	13	181	0.21
7.07	0.48	29	604	0.68
7.11	0.87	73	839	0.95
7.15	0.82	57	695	0.79
7.18	0.65	36	554	0.63
7.22	0.53	45	849	0.96
7.25	0.27	30	1111	1.26
7.29	0.66	54	818	0.93
7.32	1.08	67	620	0.70
7.36	0.40	14	350	0.40
7.40	0.84	39	464	0.53
7.43	0.10	17	1700	1.93

^aNo correction was applied for counting efficiency and geometry.

^bRelative specific activities were calculated by dividing specific activities by 882 d·s⁻¹·g⁻¹.

TABLE VII: Activity Distribution in Sample No. 170401 Smectite-rich Marine Sediment from
MFG-I. Tracer Nuclide: ^{237}Pu Applied as PuO_2Cl_2 - Contact Time: 5.1823×10^6 s

Distance from front end of sample mm	Mass of moist sediment of 4 cm paper slip mg	Counting rate corrected for background d per min	Specific activity ^a d·min ⁻¹ ·g ⁻¹	Relative specific activity ^b
0.04		background level		zero
0.12		background level		zero
1.26		background level		zero
1.34		background level		zero
2.49		background level		zero
2.57		background level		zero
3.71		background level		zero
3.79		background level		zero
4.94		background level		zero
5.02		background level		zero
5.09		background level		zero
5.14		background level		zero
5.24		background level		zero
5.32		background level		zero
5.40		background level		zero
5.45		background level		zero
5.50		background level		zero
5.55		background level		zero
5.60		background level		zero
5.66		background level		zero
5.70		background level		zero
5.76		background level		zero
5.81		background level		zero
5.83		background level		zero
5.86		background level		zero
5.88		background level		zero
5.91		background level		zero
5.94		background level		zero
5.96		background level		zero
5.98		background level		zero
6.01		background level		zero
6.04	4.51	0.81	179.6	0.076
6.06	6.73	1.25	185.7	0.079
6.09	6.72	1.62	241.1	0.103
6.12	3.72	0.48	129.0	0.055
6.14	4.42	1.08	244.3	0.104

TABLE VII. Continued.

Distance from front end of sample	Mass of moist sediment of 4 cm paper slip	Counting rate corrected for background	Specific activity ^a	Relative specific activity ^b
mm	mg	d per min	d·min ⁻¹ ·g ⁻¹	
6.16		background level		zero
6.19	3.22	1.15	357.1	0.152
6.22	2.13	0.79	370.9	0.158
6.24	2.34	0.58	247.9	0.106
6.27	1.62	1.32	814.8	0.347
6.29		background level		zero
6.32	2.19	1.24	566.2	0.241
6.34	2.42	1.25	516.5	0.220
6.37	2.80	2.38	850.0	0.362
6.40	2.27	2.42	1066.1	0.454
6.42	1.36	0.32	235.3	0.100
6.47	1.97	1.28	649.7	0.277
6.58	2.09	2.32	1110.0	0.473
6.62	2.81	2.30	818.5	0.349
6.70	2.75	2.88	1047.3	0.446
7.39	4.08	7.07	1732.8	0.738
7.47	2.98	5.13	1721.5	0.733
8.61	3.27	6.27	1917.4	0.817
8.69	3.54	8.31	2347.5	1.000

^aNo correction is included for counting efficiency and geometry.

^bRelative specific activities were calculated by dividing specific activities by 2347.5 d·min⁻¹·g⁻¹.

REFERENCES

1. R. Mills, J. Amer. Chem. Soc. 77, 6116 (1955).
2. R. Mills, and E. W. Godbole, J. Amer. Chem. Soc. 82, 2395 (1960).
3. Yuan-Hui Li and S. Gregori, Geochimica et Cosmochimica Acta 38, 703 (1974).
4. J. F. Relyea, Doctoral Dissertation, University of Arkansas, 1977.
5. S. Fried, A. Friedman, and F. Schreiner, "A study of the Mobility of Plutonium and Americium in Clay", Annual Report submitted to Sandia National Laboratory, September, 1980.

LEGENDS TO THE FIGURES

- Fig. 1. Schematic of sample preparation.
- Fig. 2. Schematic of sample prepared for storage.
- Fig. 3. Schematic of apparatus for depositing clay samples on strips of filter paper.
- Fig. 4. Intensity distribution of the thin layer of Prussian blue deposited on filter paper.
- Fig. 5. Relative concentration of ^{22}Na in sample No. 130501 (bentonite clay + WIPP A brine + ^{22}Na as tracer; storage time: 12120 s). Upper curve: concentration curve expected for a diffusion coefficient $D_{\text{eff}} = 3.3 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$; Lower curve: concentration curve expected for a diffusion coefficient $D_{\text{eff}} = 2.5 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$.
- Fig. 6. Relative concentration of Am in sample 280104 (smectite-rich sediment from MPG-I with ^{241}Am -chloride; storage time: 3.1008×10^6 seconds); dashed line: slope of activity front at the interface.
- Fig. 7. Relative concentration of Am in sample 210102: (Illite-rich sediment from MPG-III with ^{241}Am -chloride; storage time: 11.5866×10^6 seconds); dashed line: estimated slope of activity front at the interface.
- Fig. 8. Relative concentration of Am in sample 210104: (Illite-rich sediment from MPG-III with ^{241}Am -chloride; storage time: 20.7474×10^6 seconds); dashed line: estimated slope of activity front at the interface.
- Fig. 9. Relative concentration of Pu in sample 110204: (Smectite-rich sediment from MPG-I with Pu(IV)-chloride; storage time: 2.43306×10^6 seconds).
- Fig. 10. Relative concentration of Pu in sample 170401: (Smectite-rich sediment from MPG-I with Pu(VI)-chloride; storage time: 5.18232×10^6 seconds) dashed line: estimated slope of the activity front at the interface.

Figure. 1

Figure. 2

Figure. 3

Figure. 4

Figure. 5

Figure. 6

Figure. 7

Figure. 8

Figure. 9

Figure. 10

Appendix I
Radionuclide Sorption and
Diffusion Studies

K. L. Erickson

SUBSEAED DISPOSAL PROGRAM

Annual Report for January through December 1980

RADIONUCLIDE SORPTION AND DIFFUSION STUDIES .

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RADIONUCLIDE SORPTION AND DIFFUSION STUDIES

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ABSTRACT

Experimental and theoretical analyses of radionuclide sorption by and diffusion in abyssal red clays are being conducted in support of activity C-2, Far-Field Ion Transport, and more specifically in support of subactivities C.2.1.1, Property Acquisition and Model Development and C.2.1.2, Laboratory and/or Field Verification. During the current reporting period, priority of effort has been given to conducting and interpreting data from one-dimensional diffusion experiments involving smectite-rich sediment and radionuclides such as ^{22}Na , ^{137}Cs , ^{133}Ba , ^{144}Ce , and ^{152}Eu . Most data from the diffusion experiments appear consistent with results predicted using appropriate mathematical models and independently measured sorption equilibrium data. In particular, experiments with ^{22}Na indicated that when small effects due to sorption were accounted for, the diffusion coefficient for sodium in the sediment samples was on the order of $3 \times 10^{-6} \text{ cm}^2/\text{sec}$ (at about 23°C), which appears consistent with previously reported results. Experiments with ^{137}Cs , ^{133}Ba , and ^{152}Eu indicated effective diffusion coefficients of 7×10^{-10} , 8×10^{-11} , and $7 \times 10^{-11} \text{ cm}^2/\text{sec}$, respectively, for those nuclides in the sediment. Such results are consistent with the effective diffusion coefficients which would be expected from the sorption equilibrium data for those nuclides at the solution-phase concentrations involved. However, some deviations from expected behavior have been observed and are currently under investigation to determine if such deviations represent significant phenomena or are artifacts of the experimental technique.

RADIONUCLIDE SORPTION AND DIFFUSION STUDIES

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INTRODUCTION

In order for the U. S. Subseabed Disposal Program to assess the feasibility of emplacing radioactive wastes in sub-seafloor geologic formations, mathematical models will be required which can reliably predict the rates of radionuclide transport through those formations. In order to develop and employ such models, the dominant mechanisms for nuclide sorption and migration must be understood and described by suitable mathematical expressions. Furthermore, it is necessary to experimentally evaluate the resulting models and to obtain matrices of data such that the critical parameters appearing in those models can be determined for all anticipated conditions. Such analyses and data collection requirements, as they pertain to the far field, are addressed in this report, and are part of activity C.2, Far-Field Ion Transport, as given in the Subseabed Disposal Program Plan (SAND80-007/I). More specifically, the projects and results described below provide substantial input to sub-activities C.2.1.1, Property Acquisition and Model Development, and C.2.1.2, Laboratory and/or Field Verification.

For the geologic materials and samples selected for study, the specific tasks and projects which are in progress or are being planned in support of the above activities are as follows:

- (1) Identification, analysis, and mathematical description of the important radionuclide sorption mechanisms at ambient pressure and temperatures near 4°C.
- (2) Experimental acquisition and mathematical analysis of one-dimensional radionuclide diffusion data, at ambient pressure and temperatures in the range of 4 to 25°C, in order to define and describe radionuclide migration mechanisms and evaluate proposed radionuclide transport models.
- (3) Physical and chemical characterization of the geologic materials studied (such as bulk chemical composition, mineralogy, etc.) and possible correlation of the sorption and migration properties of the materials with the characterization, so that the experimental results from a given sample can be applied to other similar materials obtained from different locations.

- (4) Evaluation of other mass transport parameters, such as ionic diffusion coefficients.
- (5) Identification and evaluation of mechanisms and scenarios which could lead to anomalous radionuclide migration rates in the geologic formation.
- (6) Coordination of plans for and results from sorption and diffusion studies with investigators whose experimental programs impact on or are affected by sorption and diffusion results and with investigators who are developing and evaluating radionuclide transport models.

With regard to the above tasks and projects, priority of effort has been given to conducting and interpreting data from one-dimensional radionuclide diffusion experiments involving smectite-rich sediment and selected radionuclides. The amount of effort allocated to the remaining tasks and projects has been very limited, due to manpower constraints and/or the nature of the activity.

A brief description of, the status of, and a summary of current experimental or other results from each of the above tasks and projects are given in the next section.

TASK/PROJECT DESCRIPTION, STATUS, AND SUMMARY OF EXPERIMENTAL RESULTS

Geologic Material and Samples Being Studied

The formations being studied are the abyssal red clays. The specific sediment samples being used in the work described herein were obtained from core LL44-GPC-2 collected at 30°20.9'N, 157°50.85'S, water depth 5821 meters, on October 11, 1976. Samples of the red clay having uniform physical and chemical characteristics were provided by G. R. Heath (then of the University of Rhode Island).

Analysis of Radionuclide Sorption Mechanisms at Ambient Pressure and 4°C

In the sediments being studied, it is believed that nuclide migration away from the waste form will primarily be due to molecular diffusion. The rates of diffusion of the various nuclides which might be released can be decreased as a result of sorption by the solid-phase constituents of the sediment. The magnitude of such decreases depends on the sorption equilibria which, for a given nuclide, are functions of temperature, pressure, and the equilibrium concentration of the given nuclide, and of the equilibrium concentration of all other competing species. For modeling purposes, sorption equilibria are conveniently represented by distribution coefficients (K_{D_i}), which are defined as the ratio of the

nuclides equilibrium solid-phase concentration ($\bar{C}_i$) to its equilibrium solution-phase concentration (C_i). Assuming that local equilibrium exists between solid and interstitial solution phases of the sediment, and that diffusion of radionuclides occurs only through the interstitial solution, then the simpler mathematical analyses of diffusion indicate that the migration rate of a given nuclide is inversely proportional to its distribution coefficient [1]. Hence, the adequacy of the sediment to serve as a barrier to radionuclide migration depends, in an inversely proportional manner, on the values of the various distribution coefficients.

The purpose of conducting sorption experiments at 4°C and ambient pressure is to obtain data matrices which are applicable to the nuclides of interest and which can be used to evaluate the radionuclides distribution coefficients as functions of solution composition in the "undisturbed" sediment. Here it has been assumed that in the "undisturbed" sediment the temperature will be very close to 4°C and that the effects due to differences between the local pressure and the ambient laboratory pressure will generally be small.

Sorption equilibria for fifteen selected nuclides have been reported previously [2,3,4,5]. Data were obtained from batch equilibration experiments in which samples of smectite-rich sediment from core LL44-GPC-2 were contacted with 0.68 N NaCl solutions containing a single sorbing species of either rubidium, cesium, strontium, barium, silver, cadmium, technetium, cerium, promethium, europium, gadolinium, uranium, plutonium, americium, or curium. Distribution coefficients were evaluated as functions of the nuclides concentration, solution pH, and hydrous metal oxide content of the sediment sample. With the exception of technetium, the sorption equilibria for the nuclides studied were very favorable. The distribution coefficients (under mildly oxidizing conditions) for technetium were essentially zero at a solution-phase concentration of about 2.5×10^{-5} M and at solution pH values of both 2.6 and 8.2. However, for the other fourteen nuclides, the distribution coefficients (for solution pH values of 6 and greater) generally varied nonlinearly from about 10 to greater than 10^4 ml/gm as the solution-phase concentration of the nuclide varied from about 10^{-2} to less than 10^{-7} M, respectively. For later convenience in discussing the diffusion experiments, equilibrium data for sorption of selected alkali and alkaline earth metals have been included as Figs. 1 and 2, respectively, and for selected lanthanides and actinides as Fig. 3.

Much of the above-discussed equilibrium data can be reasonably well described by semi-empirical Langmuir-type sorption isotherms, the development of which was previously illustrated [4]. These isotherms have been incorporated into mathematical models which are being used for preliminary radionuclide transport analyses [6,7]. Additionally, predictions of the smectite-rich clay's relative sorption selectivity for certain nuclides and of the manner in which variations in the solution-phase ionic strength

should affect the distribution coefficients for selected nuclides were made based on the proposed mechanisms for sorption and on equilibrium constants inferred from the sorption isotherms. These predictions are being evaluated experimentally. Thus far, the available results concerning sorption selectivity [5] and ionic strength effects [8] appear in agreement with predicted behavior.

During the current reporting period, additional experiments concerning sorption equilibria were limited to some specific experiments required for the analysis of data from the one-dimensional diffusion experiments. The results of these experiments are discussed later in conjunction with the diffusion experiments.

During the forthcoming reporting period, investigations of sorption equilibria will be concerned with examining possible hysteresis effects during sorption-desorption processes and with comparing radionuclide sorption equilibria obtained using artificial seawater with equilibria obtained using 0.68 N NaCl solutions. As appropriate additional experiments will also be done in support of the diffusion experiments.

Experimental Acquisition and Mathematical Analysis of One-Dimensional Radionuclide Diffusion Data

These studies have two primary purposes. One is to obtain the data necessary to identify and analyze the important mechanisms affecting radionuclide diffusion rates. In particular, it is important to determine if any mechanisms, such as surface diffusion along the fluid-particle interfaces, exist which can produce higher migration rates than those calculated assuming local equilibrium between solution and solid phases and molecular diffusion through only the interstitial solution. The other primary purpose of the diffusion experiments is to provide initial data for evaluating mathematical models. A secondary purpose of these experiments is to provide a limited amount of data regarding ionic diffusion coefficients in the sediment.

The essential features of the diffusion experiments are shown on Fig. 4 and are as follows. (1) A clay column is artificially compacted into a cylindrical plastic housing having removable seals at each end. (2) One end of the clay column is exposed to a nuclide containing solution of uniform composition. (3) The nuclide diffuses along the axis of the column, and the time-dependent nuclide concentration profiles in the sediment column are then periodically determined using a collimated scanning NaI(Tl) detector system. (4) At the conclusion of each experiment, the clay column is sectioned, so that the results of the final γ -ray scan can be independently evaluated, and cross-sectional uniformity of diffusion can be examined using autoradiography. (5) The data from the diffusion experiments are then compared with analogous data calculated from the appropriate mathematical model.

Diffusion experiments have been conducted using ^{22}Na , ^{137}Cs , ^{133}Ba , ^{144}Ce , and ^{152}Eu . ^{22}Na is only very slightly sorbed, due to isotopic redistribution of exchangeable sodium. However, ^{137}Cs , ^{133}Ba , ^{144}Ce , and ^{152}Eu are all relatively strongly sorbed. For the simple, one-dimensional situation under study, the following assumptions were considered: (1) the effects of competing chemical reactions and nuclear decay are negligible; (2) local equilibrium exists between solid and solution phases; (3) molecular diffusion occurs only through the interstitial solution; (4) radionuclide concentrations are sufficiently dilute that Fick's law is a reasonable approximation; (5) sorption is reversible, and (6) parameter values are approximately constant. The basic equation describing diffusion of radionuclides through the interstitial solution is then

$$\frac{\partial C}{\partial t} = \frac{D/\alpha^2}{1 + \frac{\rho}{\epsilon} K_D} \frac{\partial^2 C}{\partial x^2} = D_e \frac{\partial^2 C}{\partial x^2}$$

where

C = solution-phase radionuclide concentration

D = solution-phase ionic diffusion coefficient

K_D = sorption equilibrium distribution coefficient

t = time

x = distance measured along axis of sample

α = tortuosity

ϵ = void fraction

ρ = mass of solid/unit volume

The initial and boundary ~~equations~~ ^{conditions} for the above equations depend on the details of a given experiment.

The data from the conditions for the above equations depend analogous data calculated from the appropriate mathematical model in order to determine the effective solution-phase diffusion coefficients which produced the best agreement between calculated and experimental results. The effective diffusion coefficients so determined were then compared with the values which would be calculated using the experimentally obtained sorption equilibrium data for the given nuclide and assuming local equilibrium and diffusion only through the interstitial solution. The results of such analyses are summarized below.

The experiments with ^{22}Na indicated that when the small effects due to sorption were accounted for, the diffusion coefficient for sodium in the sediment samples (D/α^2) was on the order of $3 \times 10^{-6} \text{ cm}^2/\text{sec}$ (at about 23°C). Such results appear consistent with similar data reported by Li and Gregory [9].

For the more strongly sorbing nuclides ^{137}Cs , ^{133}Ba , ^{144}Ce , and ^{152}Eu , the depth of penetration of the nuclides into the sediment samples which occurred over periods of 10 to 300 days was on the order of 0.7 centimeters or less and in some cases was not sufficient to permit accurate analyses. Some typical concentration profiles obtained for cesium, barium, and europium are shown on Fig. 5, where M is the total amount of nuclide (per unit cross-sectional area) introduced into the sediment sample and $C(x,t)$ is the total nuclide concentration (solid plus solution phases) as a function of axial distance x and time t . The cesium profile is reasonably well developed. However, the much sharper barium profile is near the limits of the scanning detector system's resolution, and the even sharper europium profile was conservatively estimated by sectioning and subsequent radioassaying because the profile could not be resolved using the scanning detector system. The profile for sodium after 4 days has been included on Fig. 5 in order to illustrate the contrast between the behavior of strongly sorbing and slightly sorbing species. The profiles for cesium and barium correspond to effective diffusion coefficients of 7×10^{-10} and $8 \times 10^{-11} \text{ cm}^2/\text{sec}$, respectively. The profile for europium corresponds to a diffusion coefficient of $7 \times 10^{-11} \text{ cm}^2/\text{sec}$ which is actually an upper bound. These coefficients essentially represent average values because the amount of radioactivity required to use the scanning detector system resulted in solution-phase concentrations in the nonlinear region of the sorption isotherms. However, from the data shown on Figs. 1, 2, and 3, the predicted range of such average values is between 10^{-8} and $10^{-11} \text{ cm}^2/\text{sec}$, which is in agreement with the experimentally determined data.

Although most of the experimentally obtained diffusion data, such as those discussed above, appear consistent with results predicted using the appropriate solution to the diffusion equation and the independently determined sorption equilibrium data, some deviations from expected behavior have been observed and are currently under investigation to determine if such deviations represent significant phenomena or are artifacts of the experimental technique. Anomalies have been observed in experiments with cesium, barium, cerium, and europium. It appears that the anomalies observed with cesium can be dependent on the method of sample preparation, whereas the anomalies observed with barium and europium have shown no such tendencies. Furthermore, sorption equilibrium data obtained from batch experiments using small solution-to-solid ratios (about 5 to 7.5 ml/gm) indicated that for cesium at solution-phase concentrations of about $4 \times 10^{-9} \text{ M}$, a large decrease (between one and two orders of magnitude) occurs in the distribution coefficients;

however, for silver and cerium, no such effects were observed. It appears, therefore, that the anomalies in the cesium diffusion experiments may have resulted from a mechanism which is different from that responsible for the anomalies in the diffusion experiments with barium, cerium, or europium. Current experiments are directed toward identifying possible mechanisms which could produce the observed anomalies. In this regard, initial work has been concerned with: (1) examining the development of anomalous concentration profiles as a function of time, (2) examining the effects of using different techniques for initially contacting the radionuclides with the sediment, and (3) determining if such anomalous profiles occur in similar experiments with different sorbents.

Physical and Chemical Characterization of the Selected Clay Samples

The purpose of this work is to establish a standard set of material characterizations which is applicable to similar sediments and to which the sorption and migration properties of each sediment can possibly be related. It is then hoped that by characterizing the current clay samples, the experimental data obtained using those materials can be applied to other similar materials after performing only a minimum number of additional experiments.

The following types of characterizations or analyses have been or will be done on the current clay samples:

- (1) differential thermal analysis (partially done)
- (2) thermal gravimetric analysis (partially done)
- (3) mineralogical identifications (in progress)
- (4) bulk chemical composition (done)
- (5) ion exchange capacity measurements (partially done)
- (6) zeta potential measurements (initial experiments have been unsatisfactory)
- (7) potentiometric titrations (preliminary titrations done)
- (8) pH dependence of distribution coefficients for selected nuclides (partially done)
- (9) temperature dependence of distribution coefficients for selected nuclides at ambient pressure (preliminary experiments completed)
- (10) particle size distribution (done)
- (11) electron micrographs (preliminary work completed)

As appropriate, additional types of analyses will also be made. However, during the current reporting period, this task has been given low priority.

Evaluation of Other Mass Transport Parameters Such as Ionic Diffusion Coefficients

Though generally not as important as the sorption distribution coefficients, the diffusion coefficients for the nuclides are engineering parameters which must also be evaluated. Fortunately, literature is available from which reasonable estimates for many of the diffusion coefficients can be made. The purposes for experimentally evaluating nuclide diffusion coefficients are to verify or correct estimates made from the literature and to evaluate the diffusion coefficients for nuclides for which the available literature is insufficient to provide acceptable estimates.

Some nuclide diffusion coefficients will be determined during the course of the one-dimensional diffusion experiments. Other nuclide diffusion coefficients will be determined as appropriate. No specific experiments for this purpose have yet been planned; however, the available techniques for evaluating these parameters on a routine basis are periodically being reviewed and evaluated. Equipment will be obtained for use as required.

Identification and Evaluation of Mechanisms and Scenarios Which Could Lead to Increased Migration Rates

As discussed in last year's annual report, some possible increased-migration-rate mechanisms have been identified and the potential hazards associated with these mechanisms will be evaluated as time permits. During the current reporting period, this work has essentially been a part of the analyses being done regarding the previously mentioned deviations from expected behavior which were observed in the diffusion experiments. In particular, investigations are being directed to determining if colloidal particles are involved with those observed anomalies.

Coordination of Plans for and Results from Sorption and Diffusion Experiments

As previously discussed, the plans for and results from the sorption and diffusion work described herein are coordinated with investigators involved with convective nuclide transport and possible enhanced-migration-rate mechanisms. This work is also coordinated with investigators who are developing and evaluating mathematical models, with investigators who are studying the sorption properties of the major types of sediment and the sorption properties of the red clay as a function of vertical position, and with investigators who are studying near-field effects. In particular, the experimental techniques used to study sorption and diffusion of radionuclides, obtained as stock reagents, are currently being adapted, in cooperation with B. T. Kenna of Sandia National Laboratories, for studying sorption and diffusion of radionuclides obtained in solutions from waste form leaching experiments.

CONCLUSIONS

Although some anomalies have been observed during the one-dimensional diffusion experiments, most of the data from those experiments appears in agreement with results predicted using mathematical models and independently measured sorption equilibrium data. Such agreement provides some verification of current radionuclide transport models, which are generally based on reversible sorption equilibria. The sorption equilibrium data which have been previously published [2,3,4,5] such as that shown on Figs. 1-3 were obtained by sorption from solution. If the reverse process, desorption from the solid, were to be relatively more irreversible, then diffusion calculations based on such models and the above mentioned equilibrium data would be conservative estimates. Further research is required to examine possible hysteresis effects during sorption-desorption processes. Additional research is also needed with regard to analyzing some deviations from expected radionuclide diffusion behavior and comparing radionuclide sorption equilibria obtained using seawater with equilibria obtained using 0.68 N NaCl solutions.

REFERENCES

1. J. Crank, The Mathematics of Diffusion, Clarendon Press, London, pp. 28-103 (1975).
2. K. L. Erickson, "Radionuclide Sorption Studies on Abyssal Red Clays," in Radioactive Waste in Geologic Storage, ed. by S. Fried, American Chemical Society, Washington, D.C. (1979).
3. K. L. Erickson, "Nuclide Sorption and Migration," in Seabed Disposal Program Annual Report for January through December 1978, SAND79-1618/1.2, ed. by D. M. Talbert, Sandia Laboratories, Albuquerque, New Mexico, October 1979.
4. K. L. Erickson, "Nuclide Sorption and Migration," in Seabed Disposal Program Annual Report for January Through December 1977, SAND78-1359, ed. by D. M. Talbert, Sandia Laboratories, Albuquerque, New Mexico, January 1979.
5. K. L. Erickson, "Radionuclide Sorption Studies on Abyssal Red Clays," in Scientific Basis for Nuclear Waste Management, Vol. II, ed. by C. J. Northrup, Plenum Press, New York (1980).
6. D. F. McVey, K. L. Erickson, W. Seyfried, "Thermal, Chemical and Mass-Transport Processes Induced in Abyssal Sediments by the Emplacement of Nuclear Waste: Experimental and Modeling Results," to be published in the Proceedings of the Second International Ocean Dumping Symposium, sponsored by the U. S. National Oceanic and Atmospheric Administration, April 15-18, 1980.

7. A. J. Russo, Prediction of the Migration of Several Radionuclides in Ocean Sediment with the Computer Code IONMIG: A Preliminary Report, SAND79-1666, Sandia National Laboratories, Albuquerque, New Mexico, May 1980.
8. K. L. Erickson, unpublished work.
9. Y. Li and S. Gregory, "Diffusion of Ions in Sea Water and in Deep-Sea Sediments," Geochimica et Cosmochimica Acta, Vol. 38, pp. 703-714 (1974).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Appendix J
Heat Transfer Studies
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date: April 6, 1981

to: Ken Hinga - 4536

CZ Hickox

from: C. E. Hickox - 5511

subject: Subseabed Disposal Program Annual Report for 1980

Activities which have been pursued in Department 5510 in support of the subseabed Disposal Program (SDP) during 1980 are summarized in this memorandum. A bibliography of published reports, papers, and in-house memoranda relating to the SDP is attached. Copies of items which you may wish to include as addenda to the final version of the annual report, are attached. My personal feeling is that it is not necessary to include these items in the final report since they are readily available from the respective authors. The activities described herein represent a collaborative effort among several members of Department 5510. Although no concerted attempt will be made to associate any particular individual with a specific topic, those within Department 5510 responsible for the various efforts were: D. F. McVey, J. W. Nunziato, D. K. Gartling, R. R. Eaton, A. J. Russo, C. E. Hickox, M. J. Martinez, and C. M. Korbin. Individuals from other departments and institutions whose efforts are also documented include, S. L. Passman (5531), A. Kraynik (5813), P. B. Bailey (5641), W. E. Williamson (5635), P. R. Dawson (Cornell University), and P. F. Chavez (Cornell University). I will be happy to provide additional details or references for any specific activity if required for the final report.

In Situ Heat Transfer Experiment (ISHTE)

Modeling

Analytical modeling support for the ISHTE was pursued throughout the year. Much of the modeling effort was directed toward identifying appropriate locations for the approximately seventy-seven thermal sensors which will be inserted into the sediment. The placement of these sensors is important since the measurements obtained will be used to

- (1) Verify the thermal energy transport model developed for the analysis of subseabed waste emplacement.

- (2) Provide detailed temperature histories to support post test analyses of cores, geochemical samples, pore pressure data, and the ion migration experiment.
- (3) Provide evidence of unanticipated phenomena which might occur, e.g., sediment fluidation or rupture, significant pore water motion.

Parameter Estimation

The application of parameter estimation techniques to the ISHTE was studied in association with Division 5635. The minimization technique utilized has been implemented in the computer program SRVM (Square-root variable metric). Assuming that an adequate mathematical model exists for the ISHTE, it should then be possible, through use of the SRVM method, to estimate values for the model parameters which cause predicted temperatures to agree with measured temperatures in some best sense. If model parameters are known with reasonable accuracy before the ISHTE, then it should be possible to determine if there is an optimum placement of thermal sensors which will allow improved estimates of model parameters. It is also possible to relate the accuracy with which model parameters can be determined to the accuracy of temperature measurements. The SRVM method was applied to a simplified model problem and results were obtained which confirmed the capabilities described above.

The capability for performing nonlinear parameter estimation studies was also developed within Department 5510. The method has been successfully applied to the interpretation of data obtained with in situ thermal conductivity probes in bedded salt. It is anticipated that this method will be used for the analysis of data from the line source thermal conductivity probe developed for the ISHTE.

Thermal Conductivity Probe

The design and construction of a line source thermal conductivity probe was initiated in association with the Applied Physics Laboratory (APL) at the University of Washington. This instrument will be used to measure the in situ thermal conductivity of the sediment as an ancilliary experiment to the ISHTE. The design theory is based on the well known previous studies of Jaeger and von Herzen. Construction of a prototype probe is in the final stages of completion.

Temperature History for Cores

In order to investigate the thermal and thermochemical response of seabed sediment to long term heating, sediment

samples will be recovered at the termination of the ISHTE. An overcore device will be used to obtain a sample core around the isotope heat source. In addition, five other sediment core samples will be taken prior to the ISHTE platform recovery. Temperature histories of the over-core sample and of a core to be used for biological samples are necessary to predict conditions that could damage the samples.

Transient modeling was performed with a finite difference formulation for the sediment biological core sample and with the COYOTE finite element code for the eccentrically cored heat source. The film coefficient for convection was provided through a subroutine that calculated the local Nusselt number as a function of temperature, pressure and the ocean temperature profile. The results indicate that the heater over-core will stay below the boiling temperature as long as it is in the sea water but that boiling begins in about 5-10 minutes once the core is removed from the ocean. Thus a cooler must be designed to prevent sediment boiling. The biological core cools to nearly ambient ocean temperatures (1.5°C) on the way up and then slowly reheats in the surface water. It appears that on the order of 0.25 hour is available to recover and begin recooling of the biological core before it heats to a temperature sufficient to damage the sample.

Simulation of the In Situ Heat Transfer Experiment (ISIMU)

In support of the ISHTE, a small scale experimental study of the thermal and fluid flow fields induced by a localized source of heat will be conducted to provide preliminary information for the design of the larger experiment. Based on scaling considerations, it has been concluded that a one-third scale model of the ISHTE can provide the necessary information. Testing will be performed in an environmental chamber at temperatures (1°C) and pressures ($3-4 \times 10^7 \text{ Pa}$) typical of those expected for the ISHTE. Reconsolidated seabed sediment will be used in the experiments. Details of the experiment are being worked out in association with personnel at the University of Rhode Island and the Applied Physics Laboratory of the University of Washington. The experiment will be conducted at the Naval Ship Research and Development Center (NSRDC), Annapolis, Maryland, in the fall of 1981.

Ion Transport Experiment

Preliminary discussions were held with Dr. F.L. Sayles of the Woods Hole Oceanographic Institution concerning his proposed design for an ion transport experiment for ISHTE. The experiment is designed to provide basic quantitative information on the diffusion of ions in sediments. In addition, the

presence of a vertical fluid flow within the sediment can be detected. Numerical modeling of the experiment will be performed in Department 5510.

Modeling of Transport Processes

Ion Migration

Support was provided for ion transport calculations. Several improvements were incorporated in the ion transport computer program IONMIG. The program was modified to permit a zero concentration flux boundary condition at the lower (basement rock) boundary instead of a zero gradient condition. This modification will result in more accurate results when there is fluid flow through the lower boundary. An improved numerical solution option was also incorporated in the program. A parameter study in which contaminant release rate to the ocean water was calculated as a function of canister burial depth was also performed. It was found that, down to depths of 45 m, an increase in burial depth caused a larger percentage decrease in peak release rate. First arrival times at the sediment-water interface also decreased rapidly with burial depth. This suggested that deeper burial of hard to contain, isolatable isotopes might be justifiable.

The factors which impose the most severe limits on the accuracy of transport calculations are lack of sorption and diffusion data for many radionuclides of interest. Efforts to obtain better data are underway.

Previous calculations of transport of the actinides indicated that ^{239}Pu would almost totally decay before any reached the surface. A closer look at the error bounds on the sorption coefficient K_d for Pu indicated that values an order of magnitude lower than other actinides might be possible. The transport calculations for Pu were repeated with the lower K_d . Although the Pu moved further from the canister, as expected, there was still no release for one million years at which time virtually all the ^{239}Pu had decayed to ^{235}U .

Analytical results were obtained for simple point source models for radionuclide transport. It was shown that results taken directly from the theory of thermal conduction were also applicable to the simple cases considered for radionuclide transport. In certain instances, results were obtained by a more straightforward process than that employed in previous studies.

Thermal Transport

The computer program MARIAH was completed and released for production use. Several improvements were made to the

original version of the code in terms of graphical output, selective output, and energy balance computations. A user's manual for the code was published. The code is based on the finite element method and provides solutions for non-isothermal flow in porous media. MARIAH is used in concert with IONMIG to analyze the ion migration process.

Numerous studies have been performed with MARIAH in an effort to verify the accuracy of the numerical method employed. Computations were performed for buoyancy driven flows in plane layers heated from below and compared with the results of previous investigators. Several studies involving insulation systems were also performed.

Laboratory experiments have been planned which will provide experimental data for the "benchmarking" of MARIAH. As presently conceived, the experiments will be directed toward the detailed measurement of temperature distributions in well defined geometries with controlled boundary conditions. Two experimental facilities are planned. In the larger and more elaborate of the two, a hollow, cylindrical container filled with a well-characterized porous medium will have a temperature difference maintained across the vertical boundaries and the horizontal boundaries will be insulated. The second experiment will use the analogy between viscous flow between closely spaced parallel plates and flow in a porous medium to simulate the effects of natural convection in a porous medium. This particular device is generally referred to as a Hele-Shaw cell. Construction of the experimental facilities is underway.

As part of the continuing interaction with the Lamont-Doherty Geological Observatory on the fluid flow in ocean sediments, several studies were performed using the MARIAH code. Three specific problems considered were: (1) the effect of basement (basaltic) rock outcropping on heat and mass transfer in the sediment, (2) the effect of basement topography on convection in the sediment, and (3) the effect of sediment thickness on heat and mass transfer through the sediment. Results to date indicate that fluid motion through a basalt outcrop may cause local heat fluxes to be a factor of 20 higher than heat flow through the sediment. Topography of the basalt/sediment interface has also been observed to modify the spatial distribution of heat and mass transfer through the sediment/ocean interface. The results were furnished by Dr. R. N. Anderson of Lamont-Doherty. Good agreement was obtained between calculated results and those observed in ocean sediments by Dr. Anderson.

As is typical of most natural convection codes, the Boussinesq approximation was employed in the development of the equations solved by MARIAH. In practice, the Boussinesq assumption may severely limit the maximum acceptable temperature difference

encountered in a convection problem. In an effort to understand the precise limits of applicability of the Boussinesq approximation, a brief computational and analytical study was undertaken. Natural convection in a simple geometry was considered as a test problem with three different formulations of the equations being analyzed. The accuracy of a strict Boussinesq approximation was compared to a relaxed form of the Boussinesq approximation and a completely compressible formulation. Analytic work has supported the computational effort in an attempt to predict a priori the range of validity of each formulation. Initial results have indicated that the Boussinesq approximation is reasonably accurate for steady-state flows in porous media.

Analytical solutions were obtained for simple point source models of thermal transport in porous media. These results are useful primarily in scoping studies. However, the far field behavior can be represented with reasonable accuracy using these models, even when the thermal and velocity fields are produced by a finite size, heat generating container of radioactive waste. A use is thus foreseen for point source models in the mathematical description of arrays of containers.

The effects of burrows on the thermal transport processes in sediments was studied using simple analytical models. Two idealized situations were treated: (1) a vertical burrow in uniformly heated sediment and (2) a re-entrant burrow in the presence of a sediment temperature which increases linearly with depth. The latter case can produce a "thermosyphoning" effect which can pump water through the burrow. The analysis demonstrated that, under the proper conditions, natural convective motion can occur in burrows. However, for burrows of the size anticipated in the sediments, it was concluded that the water in the burrows would remain stagnant. The effect on the thermal field is thus negligible.

Modeling of Seabed Sediments

Linear theories for flow through rigid porous media are well-established. Generalization to the case where the medium is not rigid and to domains where linear theory is inappropriate, however, must be done with considerable care. The mechanisms for realizing these generalizations have been understood for many years. However, they are not generally dispersed in the literature of soil mechanics. This can, and quite often does, lead to incorrect generalizations of correct linear theories.

A complete thermodynamic theory has been constructed for flow of a linearly viscous fluid through a deformable granular material. The emphasis is on saturated flow and incompressible materials, though these assumptions are not required. The

model is in accord with all principles of nonlinear mechanics. In order to test the model, boundary-value problems have been solved which are directly accessible to experiment. In particular, the motion between two parallel plates, one stationary, the other moving parallel to itself has been considered. The motion in this case is not uniform, but rather exhibits high rates of shearing near the boundaries, with near rigid motion near the central region. The solid constituent tends to migrate toward the region of low shearing. In order to maintain the plates a constant distance apart, a normal stress is required. Such normal stresses are inevitable in nonlinear theories of materials but seldom appear in soil mechanics models. Preliminary experimental tests (Kraynik and Baird) also indicate the existence of normal stresses, in agreement with the present theory, and in contradiction with models generalized from conventional soil mechanics.

The boundary value problem associated with the vane shear experiment has also been set up and tested in a computation, but detailed parameter studies have not yet been carried out.

In the case of hole-closure, migration of the fluid with respect to the solid may not be significant, so a simpler constitutive model may serve. Exact analytical solutions have been found for linear, power-law, and grade two material behavior. In all cases, the radius decreases as e^{-t} . Typical closure times, assuming material parameters of the order of magnitude measured by Kraynik and by Baird, are a few hours to a few days.

Sediment Creep Modeling

Creep modeling efforts included further development of numerical analysis capabilities and creep behavior constitutive equations. The development of numerical modeling tools include efforts for improving the efficiency and ease of use of finite element codes, as well as expanding their applicability to a wider range of problems. The creep constitutive modeling effort initiated this year with studies of possible formulations for representing creep behavior. Application of the numerical tools to long term creep behavior was also continued. Both one-constituent (COUPLEFLO) and two-constituent (NEPTUNE) computations showed minimal motion for heat producing canisters as a result of the density gradients resulting from the heating.

The major portion of the creep modeling effort was performed by P. R. Dawson and P. F. Chavez (Cornell University). A summary of their work is included as Addendum I. We have elected to include this effort as part of our report since the creep modeling program at Cornell University has been coordinated through Department 5510.

Miscellaneous Activities

Transient Pressure Rise in Heated Sediment

Two methods have been used to predict the maximum pore pressure rise adjacent to a nuclear waste canister with an initial power output of 1.5 kW. The first prediction involved the use of an approximate method. In this method, the temperature distribution is assumed to be that which is given by Carslaw and Jaeger for a semi-infinite plate. This is used in conjunction with the continuity equation, Darcy's law, and a linear equation-of-state. The resulting ordinary differential equation is solved numerically. This solution predicts a maximum pressure rise of less than one bar using a sediment permeability of $5 \times 10^{-16} \text{ m}^2$.

The second method involved the use of the SHAFT 79 multi-phase porous flow code. Because of the large background pressure and the small pressure range of interest, water property lookup tables were tailored for the specific application. The results indicate that the maximum sediment pore pressure rise is less than 0.25 bars and occurs within three days after initial burial. This maximum pressure rise is less than the local lithostatic pressure of 1.7 bars based on a 30 m burial depth and 80% sediment porosity.

A slightly revised version of SHAFT 79 is currently being brought on line at Sandia. This version has the capability of obtaining better initial flow conditions. The maximum pressure calculations will be redone when code checkout is completed. It is anticipated that the resulting pressures will be essentially unchanged.

SHAFT 79 has been used to predict the increase in pore pressure which results from the emplacement of the ISHTE. The assumed sediment-water interface temperature and pressure was 2°C and 600 bars respectively. The permeability was $5 \times 10^{-16} \text{ m}^2$ and the porosity was 80%. The results show that the calculated pore pressure increase within 10 cm of the 400 watt heater midplane is in excess of 0.5 bars. The overburden pressure due to the weight of the sediment at this location is approximately 0.1 bars. Therefore, some local deformation of the sediment is anticipated.

Benthic Boundary Layer

Some initial effort was devoted to the planning of experiments directed toward the acquisition of data which would quantify the role of the benthic boundary layer in the transport of radionuclides from the sediment into the water column. This activity resulted in the acquisition of a computer program from Dr. G. L. Weatherly of Florida State University, which can be used for the simulation of flow processes in the benthic boundary layer. The experimental effort was

not continued, but the computer program acquired will ultimately be incorporated in the physical oceanography model.

Participation in Meetings

Personnel from Department 5510 participated in several meetings during the year which were either directly related to the activities of the Subseabed Disposal Program (SDP) or provided a forum for the presentation of results obtained in support of the SDP. A list of these meetings is provided below.

1. ISHTE Project Planning Meetings; Seattle, Salt Lake City
2. SDP Annual Meeting; Denver, CO
3. Marine Technology Society Annual Meeting; Washington, DC
4. Physical Oceanography Workshop; Big Sky, Montana
5. Biological Oceanography Workshop; Jackson Hole, Wyoming
6. Winter Annual Meeting of ASME; Chicago, IL
7. Third International Symposium on Finite Element Methods, U. of Calgary, Banff, Alberta, Canada
8. Second International Dumping Symposium, Woods Hole Oceanographic Institution, Woods Hole, MA
9. Third International Conference on Finite Elements in Water Resources, Oxford, MS

Distribution:

4536 D. R. Anderson
4536 C. M. Percival
5500 O. E. Jones
5510 D. B. Hayes
5511 J. W. Nunziato
5511 D. C. Reda
5511 D. K. Gartling
5511 R. R. Eaton
5512 D. F. McVey
5512 A. J. Russo

Sandia Reports

Gartling, D. K. and Hickox, C. E., "MARIAH - A Finite Element Computer Program for Incompressible Porous Flow Problems," Sandia National Laboratories Report, SAND79-1623, Albuquerque, NM, Aug. 1980.

Russo, A. J., "Prediction of the Migration of Several Radionuclides in Ocean Sediment with the Computer Code IONMIG: A Preliminary Report", SAND79-1666, Apr. 1980.

Percival, C. M., McVey, D. F., Olson, L. O. and Silva, A. J., "The Subseabed Disposal Program In Situ Heat Transfer Experiment (ISHTe)", SAND80-0202, in preparation.

Gartling, K. D. and Hickox, C. E., "MARIAH - A Finite Element Computer Program for Incompressible Porous Flow Problems: Theoretical Background", SAND79-1622, in preparation.

Papers/Presentations

- Hickox, C. E., and Watts, H. A., "Steady Thermal Convection from a Concentrated Source in a Porous Medium", *Journal of Heat Transfer*, Vol. 102, May 1980, pp. 248-253.
- Hickox, C. E., Gartling, D. K. McVey, D. R., Russo, A. J., and Nuttall, H. E., "Analysis of Heat and Mass Transfer in Sub-Seabed Disposal of Nuclear Waste", *Marine Technology*, Oct. 1980.
- Hickox, C. E., "Thermal Convection at Low Rayleigh Number from Concentrated Sources in Porous Media", in *Heat Transfer in Nuclear Waste Disposal*, HTD - Vol. 11, Presented at ASME Winter Annual Mtg., Chicago, Ill., Nov. 1980. (Accepted for publication, *Journal of Heat Transfer*).
- Hadley, G. R., McVey, D. F., and Morin, R., "Thermophysical Properties of Deep Ocean Sediments", *Marine Technology*, Oct. 1980.
- Gartling, D. K., "Finite Element Analysis of Convective Heat Transfer in a Porous Medium", Third International Symposium in Finite Element Methods, U. of Calgary, Banff, Alberta, Canada, June, 1980.
- Percival, C. M. and McVey, D. F., "In Situ Heat Transfer Experiment (ISHTe)", *Marine Technology*, Oct. 1980.
- McVey, D. F., Erickson, K. L., and Seyfried, W., "Thermal Chemical and Mass Transport Processes Induced in Abyssal Sediments by the Emplacement of Nuclear Waste: Experimental and Modeling Results", Second International Dumping Symposium, Woods Hole Oceanographic Institution, Woods Hole Oceanographic Institution, Woods Hole, MA, Apr. 1980. To appear: *Wastes in the Ocean*, Vol. III: Radioactive Material, John Wiley & Sons.
- Gartling, D. K., "Finite Element Analysis of Thermal Convection in Deep Ocean Sediments", Third International Conference on Finite Elements in Water Resources, Oxford, MS, May 1980 (Invited Paper).

Memoranda

- C. E. Hickox to C. M. Percival, "Thermal Effects of Burrows in Seabed Sediment", dtd. Feb. 11, 1981.
- D. F. McVey to C. M. Percival, "ISHTe Thermal Instrumentation", dtd. Feb. 20, 1980.
- C. E. Hickox, D. F. McVey, and W. E. Williamson to Distribution, "Application of Parameter Estimation Techniques to the In Situ Heat Transfer Experiment", dtd. Apr. 1, 1980.
- C. E. Hickox to D. R. Anderson, "Development of Transport Models for Sub-Seabed Waste Disposal Program", dtd. Apr. 22, 1980.
- C. E. Hickox and R. R. Eaton to C. M. Percival, "Prediction of Induced Pore Pressure for the ISHTe Using SHAFT 79", dtd. May 12, 1980.
- C. E. Hickox to Distribution, "Modeling Requirements for the Scaled In Situ Heat Transfer Experiment", dtd. May 13, 1980.
- D. F. McVey to C. M. Percival, "Design of Thermal Conductivity Probe for ISHTe", dtd. June 13, 1980.
- C. E. Hickox to Distribution, "Thermal Analysis of Scaled In Situ Heat Transfer Experiment", dtd. Sept. 9, 1980.
- A. J. Russo to L. H. Brush, "Anion Release Rate Calculations", dtd. Oct. 14, 1980.
- C. E. Hickox to C. M. Percival, "Action Items for Eleventh ISHTe Project Planning Group Meeting", dtd. Dec. 18, 1980.
- C. E. Hickox to R. D. Klett, "Diffusion Models for Ion Transport", dtd. Dec. 23, 1980.

Addendum I

Sediment Creep Modeling

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I. Introduction

During 1980 progress was made in several areas related to the modeling of creep of ocean sediments that are subjected to the effects of the emplacement and pressure of heat producing nuclear wastes. Computer code capabilities were extended for both single and multi-constituent representations of the saturated sediment system, and documentation of the capabilities was prepared. Constitutive equations for the creep of sediments also proceeded with several models being proposed and subjected to reviews and discussions. From these efforts, candidate models with the features necessary to describe the consolidation, shear, and dilation behavior during both creep and quasi-static deformations are being examined in the light of data generated by the Subseabed Disposal Program for this purpose as well as data reported in the open literature. Modifications have been made to the finite element formulations to incorporate these models. Further examinations of subseabed disposal scenarios were conducted using the developed capabilities in order to bound the magnitude of sediment, canister, and pore water motion expected as a result of heating from the wastes.

The following sections summarize the progress and results achieved in each of the areas mentioned above. In most cases, reports have been issued that provide more detailed description. These reports are referenced and their findings summarized rather than being repeated in this report.

II. Numerical Modeling Developments

Two computational tools have been developed and used by the Subseabed Disposal Program for analyzing the creep deformations of saturated sediments. The first is the COUPLEFLO code that simulates the response of a locally homogeneous (single constituent) material as it deforms by creeping viscous flow. The finite element program couples the momentum and energy equations so that conductive-convective heat transfer can be considered with nonlinear viscous flow. The coupling permits temperature dependent material properties, temperature dependent body forces, viscous heating, and changing geometry to be simulated directly. The second code is NEPTUNE. NEPTUNE has been developed solely from Subseabed Disposal Program funds and has been directed from its beginning at the creep of saturated, cohesive, deep-ocean sediments. In the governing equations for NEPTUNE, creeping flow of a porous cohesive matrix results from effective stresses applied to the skeleton. Pore water migration concurrent to the matrix deformations is included with a momentum equation for the fluid motion. Coupling between the momentum and energy equations is also included in NEPTUNE to accommodate modeling of heated systems. Developmental work was performed on both COUPLEFLO and NEPTUNE during 1980.

A. COUPLEFLO Improvements

An effort initiated in 1979 to improve pre- and post-processing capabilities for COUPLEFLO was continued in 1980. Enhancement of the plotting capabilities associated with mesh generation was added to the MESH9 subprogram. These improvements provided automated labeling of element and nodal point numbers on the plotted mesh in a manner that facilitates more expedient preparation of the input files for mechanical and thermal analyses. Post-processing for COUPLEFLO was expanded with the implementation of the EDIT9 subprogram. This program reads restart tapes written by COUPLEFLO and produces history or profile plots. Specifically, if the velocity, temperature, stress or strain is desired as a function of time for particular points within the region of analysis, EDIT9 will extract the needed information from the restart tape corresponding to specified times and generate files required for plotting. Similarly, if any of these same quantities are desired as a function of spatial position for particular times, the program will perform the required editing and create the plot files. These additional capabilities were documented in an addendum to the existing COUPLEFLO reports [5]. The pre- and post-processing modifications are compatible with the NEPTUNE input and output files.

The additional capabilities added to the creeping flow formulation were also documented in 1980 in the COUPLEFLO addendum. These changes included addition of a primary creep model, capability to integrate the velocity gradient to obtain the deformation gradient for Lagrangian analyses, and ability to specify more general boundary conditions.

B. NEPTUNE Improvements

The NEPTUNE code was first implemented during 1979. Efforts in 1980 centered around additional testing and verification of its capabilities, development of a more thorough understanding of the solutions it provides, and improvement of its operating efficiency. A draft of the program documentation was also prepared. The documentation will provide users with a description of the governing differential equations, and associated finite element formulation utilized in NEPTUNE to model fully saturated marine sediments. It also describes in detail the preparation of input files for the mesh generation pre-frontal, mechanical and thermal, and post-processing subprograms.

The major changes occurring in the program occurred as a result of redefining the skeleton effective stress in terms of the solid matrix area. Most frequently in geotechnical analyses, the porous matrix stress is defined in terms of the total cross-sectional area of an infinitesimal cube rather than the proportion of the total area that the matrix actually occupies. This was the initial approach taken in the NEPTUNE formulation. However, by formulating the equations with stresses defined over the actual area of each constituent

(mineral platelet solid and pore water fluid), the boundary conditions result more naturally and the constitutive model is not required to be porosity specific. The equations modeled in NEPTUNE in this manner are summarized in a chapter of a book under preparation [6].

The creep behavior models first implemented in NEPTUNE were simple in nature (temperature-dependent bulk and shear viscosities). More elaborate creep models were incorporated in NEPTUNE during 1980 that better describe the nonlinear consolidation, shear, and dilatation behavior that can occur in real sediments. Details of the model are described in the next section. In terms of the numerical implementation, however, the nonlinearity of the consolidation and shear behavior has been incorporated by a modified Newton-Raphson technique. The dilation term, however, is handled only through a pseudo-force method because the quadratic form of the second invariant of the effective deviator stress is more easily handled in this manner. Full verification of the nonlinear creep modeling capability will continue in 1981.

The large arrays generated by NEPTUNE as a result of its implicit formulation are stored in peripheral devices rather than in the computer's central memory. During the program execution it is necessary to transfer large portions of these arrays between the peripheral devices and the central memory where they are used. This is accomplished on the CDC 7600 using the large core memory (LCM) as a buffer between the small core memory (SCM) and the disc space. Over the past year the information transferred in this manner was streamlined and combined to speed execution of the program. Substantial savings were obtained in the costs associated with unoverlapped input-output (IO) time as well as achieving lower central processing times. Wall clock times were also significantly reduced.

Several one-dimensional problems were analyzed in 1979 to verify the ability of NEPTUNE to simulate saturated porous material behavior. Additional analyses were performed in 1980 to test NEPTUNE over a wider range of the material parameters that appear in these problems. Excellent agreement was obtained between the exact solutions and the NEPTUNE analyses for these cases, as summarized in [6].

III. Saturated Sediment Creep Behavior

The creep behavior of saturated, cohesive porous sediments is critical to the longterm response of a subseabed repository. Following emplacement of a canister, the disturbed sediments may flow, either to close any residual hole left along the emplacement path or as a result of differential body forces induced by density gradients from the spatially varying temperature field. Other aspects of the Subseabed Disposal Program

also may be influenced by creep deformations, including the behavior of bottom vehicles or platforms that must provide adequate support for equipment on the ocean floor.

The prediction of the sediment response during situations such as mentioned above requires accurate mathematical description of the sediment creep behavior. Considerable work has appeared in the literature regarding the creep of saturated porous geotechnical materials. Both terrestrial and marine clays have been subjected to creep tests of varying lengths. However, mineral compositions and deposition histories vary significantly, necessitating tests by the Subseabed Disposal Program of materials characteristic of program study sites. Examination of the test results and formulation of a mathematical description of the observed behavior provide equations needed in the modeling effort. In 1980, test results from the Subseabed Disposal Program and behavior reported in the literature were studied and constitutive models were proposed.

The behavior of saturated, cohesive sediments are known to include:

- (a) thermal dependency
- (b) nonlinear stress, strain-rate dependency
- (c) strain hardening and/or softening behavior
- (d) consolidation, shear, and dilation deformations
- (e) strength dependency on consolidation history

(It is recognized that both the consolidation and dilatative behavior change the specimen volume. Here, we use consolidation to describe volume changes occurring from the skeleton pressure and dilation to refer to volume changes arising from shears.) It was felt that all these effects need to be modeled in order to describe the sediment behavior in sufficient detail to have confidence that near field effects could be understood.

Formulating a model that included both quasi-static and creep behavior was also felt to be advantageous. The model could then be used to describe behavior ranging from short-term loadings but limited to applications with negligible inertia to longterm creep applications. Discussions with personnel from Sandia National Laboratories, Cornell University, University of Rhode Island, University of California at Berkeley, and Colorado State University have helped focus on a model with the features described above that is consistent with the participant's experiences.

The creep model consists of:

- (a) nonlinear equations relating the invariants of the stress, deformation rate, and strain
- and
- (b) an associated flow rule for relating the magnitude of individual components of the stress and deformation rate

In the model we assume that the elastic and plastic components of the deformation rate are additive:

$$d_{ij} = d_{ij}^e + d_{ij}^p$$

where

d_{ij} = deformation rate

d_{ij}^e = elastic component of the deformation rate

d_{ij}^p = plastic component of the deformation rate

Further, it is assumed that the above relationship can be divided into spherical and deviatoric components as

$$d'_{ij} = d'^e_{ij} + d'^p_{ij}$$

$$\text{and } d_{ii} = d_{ii}^e + d_{ii}^p$$

The viscoelastic model proposed is of the form

$$d'_{ij} = \frac{\bar{\sigma}'_{ij}}{2\mu} + \frac{\dot{\bar{\sigma}}'_{ij}}{2G}$$

$$\text{and } d_{ii} = \frac{\bar{\sigma}_{ii}}{3K^p} + \frac{\bar{\sigma}_{II}'}{3\Omega} + \frac{\dot{\bar{\sigma}}_{ii}}{3k^e}$$

where μ , G , K^p , Ω , k^e are material parameters which themselves can be functions of the invariants of the effective stress σ_{ij} and the deformation rate, d_{ij} , as well as the strain, porosity and temperature. Here $\bar{\sigma}'_{ij}$ is the effective stress and $\bar{\sigma}'_{ij}$ is an objective form of the stress rate. Written as a single equation the model is

$$\sigma_{ij} = \left(2\mu d_{ij} - \frac{\mu}{G} \dot{\bar{\sigma}}'_{ij} \right) + \delta_{ij} \left(\lambda^p d_{kk} - \frac{\lambda^p}{\lambda^e} \dot{\bar{\sigma}}_{kk} \right) - \frac{\bar{\sigma}_{II}'}{3\Omega} \delta_{ij}$$

where $\bar{\sigma}_{II}'$ is the second invariant of the effective deviatoric stress.

The consolidation behavior is described by an equation that relates the first invariants of the effective stress and deformation rate. The dilatation behavior has been added to this, with a tentative form shown below. For the examination of the consolidation and creep data, the stresses are nearly constant and the elastic deformation term, which is based on the stress rate, is not important. Thus, for the plastic contribution we propose

$$d_{II}^P = A_0 e^{-Q_0/R\theta} \bar{\sigma}_I^{-n} \alpha_s^m + \frac{\bar{\sigma}_{II}'}{3\Omega}$$

where $\bar{\sigma}_I$ is the first invariant of the effective stress

α_s is the solid volume fraction

θ is the temperature

R is the universal gas constant

and A_0 , Q_0 , n , and m are empirically determined constants. This equation provides a function description of the K^P parameter appearing earlier. Here the sediment structure softens with elevated temperature and, hardens with higher mineral fraction (volumetric strain). The deformation rate is nonlinearly dependent on the mean effective stress. Note that due to the definition of effective stress, σ_I physically represents a difference in pore fluid and sediment matrix pressure. The dilatation term relates the second invariant of the effective deviatoric stress tensor to the first invariant of the deformation rate. Data reduction performed to date has not given sufficient insight to specify this aspect of the behavior in any more detail than is shown.

The shear behavior is described by an equation relating the second invariants of stress, deformation rate and strain. The form of the equation was motivated by several factors. First, the creep data demonstrated a nonlinear relationship between the stress and deformation rate. Further, the deformation rate diminishes rapidly with strain in the creep tests, demonstrating what is typically referred to as primary creep response.

Another factor that contributed to the overall form was the nature of the quasi-static behavior. In these cases the sediment demonstrated strain-hardening characteristics up to its peak strength and strain-softening following the peak. Such a change in the behavior appears analagous to the transitions from primary to secondary or tertiary creep frequently observed. The form of the equation is intended to include both creep and quasi-static behavior in a unified treatment.

The equation relating the second invariants of stress and deformation-rate, then, is given by (for the inelastic component)

$$d_{II}^{'P} = A_1 e^{-Q_1/R\theta} f \left[\frac{\bar{\sigma}_{II}'}{\sigma_f} \cdot \frac{1}{g(\epsilon_{II}')}\right]$$

where d_{II}' is the second invariant of the deviatoric deformation stress

σ'_{II} is the second invariant of the deviatoric effective stress

$g(\epsilon)$ a function of strain second invariant

σ_f the peak strength

A_1 , Q_1 , and n are empirical constants.

Exponential and power law forms are being evaluated for the function f . As with the volumetric deformations, the stiffness decreases with temperature. The function of strain is chosen to be consistent with the quasi-static tests and the creep tests. Different forms for this function are being investigated relative to experimental data. The peak strength is usually taken to be the quasi-static strength. However, this value is not rate independent. A relationship between the strength and matrix structure is felt to have better potential for accurately describing the normalizing strength.

The creep model discussed represents the initial form chosen to begin study relative to the data generated for creep characteristics of deep-ocean clay sediments. During 1981 implementation of data reduction and empirical fitting programs will assist in evaluating the applicability of various options within the framework of this model for modeling sediment behavior.

IV. Subseabed Disposal Application of Modeling

The movement of nuclear waste canisters emplaced in ocean sediments due to long term sediment creep deformations have been postulated as a possible mechanism for breaching the isolation of the waste. Density differences resulting from heating of the sediment as the waste decays, produce differential body forces within the heated sediment. It is thus possible that a convective cell capable of transporting the canister upward could be formed. Preliminary thermomechanical analyses that include both creep deformations of the sediment and heat transfer within the canister-sediment system were performed as reported in the 1978 annual report. These analyses were used to evaluate the possible magnitude of canister movement and to assess the stress levels the buoyant forces produce.

COUPLEFLO was used to expand on the previous calculations using thermal loads within the metallurgical and geochemical constraints proposed since the previous calculations were performed. Thermal properties of the sediment and canister were modified from the earlier work based on recent data generated by investigators concentrating on the thermal aspects of the Subseabed Disposal Program (Table 1). A range of viscosity values for the marine sediments was also considered in these analyses (Table 2). These values span several orders of magnitude over the range of temperatures achieved in the sediments near the canister. Details of the modeling are reported in a Sandia National Laboratories document devoted to this topic [4].

TABLE I
Thermal Properties

Property	Sediment	Canister
k (conductivity)	.885 $\frac{W}{m \text{ K}}$	1.25 $\frac{W}{m \text{ K}}$
C _p (heat capacity)	3780 $\frac{J}{kg \text{ K}}$	864 $\frac{J}{kg \text{ K}}$
ρ (density)	1390 $\frac{kg}{m^3}$	2275 $\frac{kg}{m^3}$ *
α (expansivity)	.255 x 10 ⁻³ $\frac{1}{K}$	0

*One of the parameters varied in the study.

TABLE II
Variation of Parameters
for Buoyant Motion Calculations

Case	C ₁ (Eq. 12)	C ₂ (Eq. 12)	Q (kw)	Canister Density (kg/m ³)
Reference	0.17x10 ⁻⁷	14700	1.5	2275
A	0.17x10 ⁻⁷	14700	.75	2275
B	0.17x10 ⁻⁷	14700	1.5	1500
C	0.17x10 ⁻⁷	14700	1.5	4000
D	0.17x10 ⁻⁶	14700	1.5	2275
E	0.188x10 ⁸	5000	1.5	2275
F	0.17x10 ⁻⁸	14700	1.5	2275

The purpose of the parameter study, then, was to assess the sensitivity of heat load, effective viscosity and canister density on the motion of a waste canister and the sediment in which it was buried. The calculations consisted of a reference case from which one variation in the thermal output power, two variations in the canister density, and three variations in the effective viscosity were considered. The resulting canister and sediment motions tended to vary significantly in each of the cases considered. The thermal response of the sediment only differed appreciably in the analysis where the canister thermal output power was modified. Changes in the velocity of the sediment had little bearing on the thermal portion of the analysis which supports the observation that it is a conduction dominated process.

In particular, the peak velocity of the canister was always directed downwards and occurred at about 7 years. The magnitude of the velocity of the canister varied from a low of less than 4 pm/s (4×10^{-12} m/s) in Case E to a maximum of almost 1800 pm/s (1800×10^{-12} m/s) for Case F. The corresponding displacements of the canister for these extremes were slightly more than 0.2 cm to about 115 cm. The peak temperature of the canister for 1.5 kW case was approximately 500K, or 220 K above ambient while for the .75 kW case (Case A) was approximately 385 K, or 110 K above ambient. The peak temperature in the canister and in the sediment, where significant heating is evident, occurs usually within the first few years.

Significant decreases in both velocity and temperature of the sediment were apparent away from the canister. In general, the vertical velocity of the sediment at the outside boundary was at least 2 orders of magnitude smaller than velocities of the canister at any given instant. Also, at the far outside boundary no temperature increases were observable. The formation of the convective cell that contributes to retarding the downward canister motion in the sediment, and may even reverse the direction of motion, is evident in all cases considered. The relative strength of this convective cell is dependent on the thermal output power of the canister. The effect of the convective cell on the canister motion is dependent on the velocity of the canister. The velocity of the canister is determined from the density differences between the canister and sediment and the viscosity of the sediment. The low predicted deformation rates in the sediment contribute to an effective deviatoric stress on the order of several hundred Pa, which is well below the estimated in situ yield strength of 20 kPa for the sediment.

Thus, it was observed that all the parameters considered for variation in the study had significant impact on the behavior of the canister-sediment system. Although none of the simulations predicted any upward displacement of the canister for the times analyzed, such motion is a distinct possibility, as has been observed in a previous calculation. Thus, it is

imperative that the behavior of marine sediments typical of those being considered for nuclear waste disposal be characterized experimentally. Included in this characterization should be an appropriate description of the nonlinear relationship between the effective deformation rate and the effective deviatoric stress. Care should also be taken to determine the value of the thermal activation energy in the sediment material model. With this additional and more precise information it will be possible to verify that the integrity of the sediment barrier will be maintained for time periods over which the waste is producing significant heat.

V. Summary and Future Work

Over the past year emphasis was placed on improving the ability of modeling capabilities to simulate the creep response of marine sediments. Of principal concern has been the improvement of the finite element code NEPTUNE, which models the creeping flow of a fully saturated cohesive porous matrix in conjunction with migration of an incompressible pore fluid under pressure gradients and heat transfer by conduction and convection. NEPTUNE was modified to incorporate stresses defined in terms of constituent areas, to include more elaborate creep models, and to process information more effectively.

Formulation of accurate constitutive equations and determination of the empirically obtained parameters within the equations was also given high priority. Candidate models were proposed and examined closely. The constitutive model described herein represents a hypothesis for sediment behavior which serves as a guide for the reduction of the data generated by the creep testing program. The form of the model will be refined as examination of the data provides insight into the actual material behavior.

Using estimates of the effective viscosity of sediment, computations were performed using COUPLEFLO and NEPTUNE to assess the potential for canister movement arising from thermally induced density gradients. COUPLEFLO analyses indicate that even under extreme conditions of canister density, heat load, and sediment viscosity, significant motion does not result.

Further computation using NEPTUNE were initiated and will be continuing. These computations tend to show that the effects of dissipation of momentum by migration of pore fluid retards motion relative to computations made without consideration of the pore fluid motion.

Several of these efforts will be continued in 1981. In particular, investigations of creep constitutive equations are given a high priority. Application of NEPTUNE to hole closure, sediment buoyancy, and experimental support using better creep models is anticipated.

VI. Publications, Reports and Publications

Publications and Reports

- (1) "Thermomechanically Coupled Creeping Flow of Saturated Cohesive Porous Media", P. R. Dawson and P. F. Chavez, Third International Symposium on Finite Element Methods in Fluid Mechanics, June 10-14, 1980, Banff, Canada.
- (2) "Creep of Ocean Sediments Resulting From the Isolation of Radioactive Wastes", P. R. Dawson, P. F. Chavez, J. Lipkin, and A. J. Silva, Second International Conference on Ocean Dumping, April 1980, Woods Hole Oceanographic Institute.
- (3) "Sediment Mechanical Response Due to Emplacement of a Waste Canister", C. H. Karnes, P. R. Dawson, A. J. Silva, and W. T. Brown, Marine Geotechnology Conference, (Also submitted to Marine Geotechnology) Oct. 1980, Washington, D.C.
- (4) "Thermally Induced Motion of Marine Sediments Resulting From Disposal of Radioactive Wastes", P. F. Chavez and P. R. Dawson, SAND80-1476, Jan. 1981.
- (5) "COUPLEFLO - A Computer Program for Coupled Creeping Viscous Flow and Conductive-Convective Heat Transfer Addendum", P. F. Chavez and P. R. Dawson, SAND80-2566, Nov. 1980.
- (6) "Thermomechanically Coupled Creeping Flow of Saturated Cohesive Porous Media", P. R. Dawson and P. F. Chavez, To appear in Finite Element in Fluids Volume IV, R. H. Gallegher, Editor, John Wiley & Sons.

Presentations and Meetings

- (1) Subseabed Program Briefing for ONWI, Washington, D.C., Jan. 30, 1980, given by P. R. Dawson covering mechanical behavior.
- (2) Subseabed Program Briefing For USGS, Washington, D.C., Jan. 30, 1980, given by P. R. Dawson covering mechanical behavior.
- (3) Creep Modeling Workshop for Subseabed Program, Albuquerque, N. M., July 1980, Participation by P. R. Dawson and P. F. Chavez.
- (4) Subseabed Annual Meeting. Progress report given by P. R. Dawson, October 1980.

Addendum II

Supporting Documents

ANALYSIS OF HEAT AND MASS TRANSFER IN SUB-SEABED DISPOSAL OF NUCLEAR WASTE

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ABSTRACT

A mathematical basis is developed for the prediction of thermal and radionuclide transport in marine sediments. The theory is applied to the study of radioactive waste disposal by emplacement, in specially designed containers, well below the sediment/water interface. Numerical results are obtained for a specified model problem through use of two computer programs designed primarily for the analysis of waste disposal problems. One program (MARIAH) provides descriptions of the temperature and velocity fields induced by the presence of a container of thermally active nuclear waste. A second program (IONMIG), which utilizes the results of the thermal analysis, is used to provide predictions for the migration of four representative radionuclides: ^{239}Pu , ^{137}Cs , ^{129}I , and ^{99}Tc .

INTRODUCTION

It has been suggested by Bishop and Hollister¹ that the mid-plate, mid-gyre regions of the major oceanic basins be investigated as possible repositories for high level radioactive waste. It was proposed that solidified nuclear waste be encapsulated in suitably designed containers and implanted in the seabed below the surface of the sedimentary layer. This scheme would provide a series of barriers to the release of radionuclides into the environment. One potential barrier is the marine sediment itself which is composed of very fine, porous, consolidated clay of low permeability.

The fundamental problem addressed in this paper is that of describing, mathematically, the transport of radionuclides which may inadvertently be released in marine sediments. We assume that the sediment can be adequately represented as a rigid, fluid-saturated porous medium. In general, the transport of radionuclides in such a medium involves the four fundamental processes: convection, diffusion-dispersion, sorption, and radioactive decay. Mathematical models are proposed for the description of the processes involved. Subject to

rather stringent simplifying assumptions, it is possible to obtain approximate analytical solutions of the basic models, and this approach is outlined briefly. Solutions of the complete mathematical system can, however, be obtained only through the use of numerical techniques. The major portion of the paper is then devoted to the description and application of two computer programs which have been developed for the analysis of the radionuclide migration process.

One program (MARIAH^{2,3}) is used to provide descriptions of the temperature and velocity fields. The analysis is conducted under the assumption that only weak concentrations of radionuclides exist in the pore water. Hence, thermal processes are not influenced by the radionuclide migration processes and can thus be analyzed separately. A second program (IONMIG⁴) then utilizes the results of the thermal analysis to complete the description of the migration of radionuclides.

Preliminary results are presented for a proposed emplacement geometry. For the particular arrangement considered, it is shown that thermally induced fluid motion is relatively weak and, consequently, has little influence on the transport of radionuclides. The migration of representative radionuclides is analyzed and the associated breakthrough times computed.

Many aspects of the analyses which will subsequently be considered have been reported previously by McVey, Gartling, and Russo.⁵ We have made extensive use of this earlier work in the preparation of the present paper.

REFERENCE EMPLACEMENT CONFIGURATION

In order to facilitate comparative studies, a reference emplacement configuration has been specified. The particular configuration was chosen to represent what is, at this time, believed to be a practically attainable scheme for the emplacement of nuclear waste in the seabed, and is the basis for all subsequent calculations.

A cylindrical container of solidified nuclear waste 3 m in length and 0.3 m in diameter is emplaced vertically in undisturbed sediment with the center of the container 30 m below the sediment/water interface. The sediment layer is 60 m thick and is bounded from below by a relatively impermeable layer. Temperature and pressure at the sediment/water interface are assumed constant at 1.5°C and 6×10^7 Pa (600 bar), respectively, corresponding to a water depth of approximately 6000 m. The initial temperature distribution in the sediment is established by the steady geothermal heat flux ($0.015 \text{ cal/m}^2 \cdot \text{s}$) and the constant interfacial temperature. A generic study site, with the described characteristics, has been selected in a region of the Central North Pacific.

The thermal power output of the container decays with time in response to the radioactive decay processes associated with the nuclear waste. In this paper, we assume the nuclear waste is typical reprocessed high level waste (HLW) resulting from a uranium only reprocessing cycle. The HLW is emplaced 10 years after reprocessing with reprocessing occurring 160 days after removal from the core. A normalized power history for the HLW is depicted in Fig. 1. Isotope inventories for the decay calculations were determined through use of the computer program ORIGEN.⁶

Fig. 1. Normalized Power History for HLW.

Krumhansl and Hadley⁷ have reported studies dealing with thermally induced changes in the physical properties of saturated marine sediments, while Braithwaite and Molecke⁸ have studied the effects of saturated sediment on corrosion of candidate container materials. Based on these studies, recommendations were made to limit the maximum temperature of the container to the range 200-250°C. Thermal analyses were then used to predict an associated maximum allowable thermal power output of 1.5 kW per container.

THERMALLY INDUCED CONVECTION

Basic Theory

In this section, we identify a mathematical model which is appropriate for the description of two-dimensional, free convection in a fluid-saturated porous medium and which forms the basis for the analytical and numerical studies to be described subsequently. The porous matrix is assumed to be rigid and the fluid incompressible, with density changes occurring only as a result of changes in the temperature according to

$$\rho = \rho_0 [1 - \beta(T - T_0)] \quad (1)$$

where ρ is the fluid density, T is the temperature, β is the coefficient of thermal expansion, and the subscripts refer to reference conditions. In accordance with the Boussinesq approximation, the effects of density changes are accounted for in the buoyancy term of the equations of motion and are neglected in the continuity relation. It is also assumed that the fluid and matrix are in thermal equilibrium and that the fluid motion can be adequately described by Darcy's law. The equations of continuity, motion, and thermal transport can then be expressed, respectively, as

$$\frac{\partial v_i}{\partial x_i} = 0 \quad (2)$$

$$v_i = - \frac{k_{ij}}{\mu} \left(\frac{\partial P}{\partial x_j} + \rho g \frac{\partial z}{\partial x_j} \right) \quad (3)$$

$$(\rho C_p)_e \frac{\partial T}{\partial t} + \rho_0 C_p v_i \frac{\partial T}{\partial x_i} =$$

$$\frac{\partial}{\partial x_i} \left[\left(\kappa_{eij} - \phi E_{ij} \right) \frac{\partial T}{\partial x_j} \right] + Q \quad (4)$$

where the indices i and j take on the values (1,2) and summation is implied by repeated indices. The bulk volume average Darcy velocity component associated with the x_i coordinate direction is denoted by v_i , P is the pore volume average pressure, and t is the time. The permeability, effective thermal conductivity, and thermal dispersion tensors are denoted, respectively, by k_{ij} , κ_{eij} , and E_{ij} . Also, C_p , μ , ϕ , Q , and g are, respectively, the specific heat, viscosity, porosity, volumetric heat source, and acceleration of gravity. The elevation z is measured vertically upward. Effective properties are identified by the subscript e and are related to the fluid and solid matrix properties by the assumed relations

$$(\rho C_p)_e = \phi \rho_0 C_p + (1 - \phi)(\rho C_p)_s, \quad (5)$$

$$\kappa_{eij} = \phi \kappa + (1 - \phi) \kappa_{sij}, \quad (6)$$

where the subscript s refers to solid matrix properties and properties with a zero subscript or without a subscript are those of the fluid. It should be noted that we have used an extended form of the Boussinesq approximation in the development leading to Eqs. (2)-(4), in that we have not demanded that all thermophysical properties remain constant.

The mathematical system described thus far can be further simplified by combining Eqs. (2) and (3) to yield the scalar equation for pressure

$$\frac{\partial}{\partial x_i} \left(- \frac{k_{ij}}{\mu} \frac{\partial p}{\partial x_j} \right) = \frac{\partial}{\partial x_i} \left\{ \frac{k_{ij}}{\mu} \rho_0 [1 - \beta(T - T_0)] g \frac{\partial z}{\partial x_j} \right\} \quad (7)$$

It is usually convenient when implementing this equation to add the hydrostatic term $\rho_0 g z$ to the pressure, and to define this sum as a new pressure. The numerical method to be considered subsequently utilizes Eqs. (4) and (7) for the description of the pressure and temperature fields. Darcy's law, Eq. (3), is then used to obtain the velocity field from the pressure and temperature fields.

In order to complete the mathematical description, appropriate initial and boundary conditions must be specified for the dependent variables. Initial conditions are obtained by simply specifying initial values of pressure and temperature throughout the domain of interest. Over that portion of the boundary which encloses the hydrodynamic part of the problem, either the pressure or the velocity normal to the boundary must be specified. The specification of normal velocity is equivalent to the specification of the pressure gradient normal to the boundary. Over that portion of the boundary associated with the heat transfer portion of the problem, temperature or heat flux normal to the boundary must be specified. The latter condition is equivalent to the specification of the temperature gradient normal to the boundary. All boundary conditions can, in general, be functions of time as well as position.

Analytical Solutions

Here we wish to briefly review some previous attempts to describe, analytically, the thermal convection induced by a concen-

trated source in a fluid-saturated porous medium. If all physical properties are assumed constant, Eqs. (1)-(4) can be rendered non-dimensional in such a way that the only parameter involved is the Rayleigh number

$$Ra = \frac{k \rho_0^2 C_p g B Q'}{\kappa^2 \mu}, \quad (8)$$

which is physically representative of the relative importance of buoyancy forces, viscous forces, momentum diffusion, and thermal diffusion. In Eq. (8), Q' is the energy released per unit time by the concentrated source, and all other parameters have been defined previously. Using the physical parameters for marine sediment summarized in Table I, the anticipated value for Ra is approximately 10^{-3} .

TABLE I
PHYSICAL PROPERTIES (20°C)

Property	Pore Fluid	Mineral	Waste Solid
ρ (kg/m ³)	1000.0	2950.0	2275.0
C_p (W·day/kg·°C)	0.052	0.010	0.010
κ^* (W/m·°C)	0.646	1.896	1.286
μ^* (kg/m·day)	93.590	---	---
β^* (1/°C)	3.380×10^{-4}	---	---
ϕ ---	---	0.8	---
k_{11} (m ²)	---	5×10^{-16}	---
k_{22} (m ²)	---	5×10^{-17}	---

For the steady-state, Hickox and Watts⁹ obtained a numerical solution for the case of a point source in an infinite region. Results of this analysis show that when $Ra \ll 1$, the temperature distribution is virtually unaffected by the fluid motion and is essentially identical with that established by thermal conduction. Hence, the straightforward application of conduction theory is expected to provide an accurate description for the temperature distribution associated with the proposed emplacement scheme.

Bejan¹⁰ obtained transient and steady-state solutions, for the problem described above, in terms of power series in Ra which are valid for $Ra \ll 1$. For the limiting case $Ra \rightarrow 0$, Hickox¹¹ extended Bejan's results to the case of a concentrated source in a semi-infinite region below a permeable boundary on which the pressure and temperature are maintained constant. This latter case provides a reasonably accurate description of the far-field behavior for the reference emplacement.

Numerical Solutions

Computational Approach. Numerical solutions to Eqs. (3), (4), and (7) are obtained through use of the finite element computer program MARIAH which is based on the Galerkin form of the finite element method. The program structure parallels those of previous finite element computer programs developed by Gartling^{12,13} and thus shares many of the conventions and capabilities of these programs. The application of the Galerkin form of the finite element method has received comprehensive treatment in previous publications^{14,15} and will not be considered in detail here. Rather, the discussion will be limited to a brief description of the basic numerical procedure and some of the more important features of the computer program. Complete details concerning the construction and capabilities of the program are available in Refs. 2 and 3. In general, MARIAH can be used to analyze a rather broad class of transient or steady-state problems in arbitrarily shaped, two-dimensional (planar or axisymmetric) porous regions.

Application of the finite element approximation to Eqs. (7), (4), and (3), respectively, results in a system of discrete algebraic equations which can be written in matrix form as

$$\underline{K} \underline{P} = \underline{F}(\underline{T}) \quad , \quad (9)$$

$$\underline{N} \underline{\dot{T}} + \underline{D}(\underline{v}) \underline{T} + \underline{L} \underline{T} = \underline{G} \quad , \quad (10)$$

$$\underline{v} = \underline{Q}^T \underline{P} + \underline{R}^T \underline{T} \quad . \quad (11)$$

Eqs. (9)-(11) represent a system of coupled, non-linear equations for the unknown vectors $\underline{P}$, $\underline{T}$, and $\underline{v}$ which are the nodal values of pressure, temperature, and velocity. Within each element, the pressure and temperature are approximated using quadratic basis functions. The velocity components are linear within the element and discontinuous between elements.

The solution algorithms used for Eqs. (9)-(11) depend on the type of flow problem under consideration (i.e., isothermal, forced convection, free convection) and its dependence on time. For the solution of steady-state problems ($\dot{T} = 0$), one of several methods based on Picard iteration can be selected. Transient flow problems are solved with a modified Crank-Nicholson procedure. In general, the solution methods employed in the computer program closely parallel the methods described in Ref. 12 for non-isothermal Navier-Stokes problems. In all cases, the actual solution of the matrix equations is accomplished by a frontal elimination procedure which is a special

variant of Gaussian elimination.

Results for Reference Emplacement Configuration. The computational domain and boundary conditions for the numerical study of the natural convective flow induced by a thermally active container of nuclear waste are shown in Fig. 2. The container geometry, initial power, decay history, and burial configuration were described in a previous section. For computational purposes, we consider an axisymmetric region 120 m in diameter and 60 m thick, where the latter dimension corresponds to the thickness of the sedimentary layer. The diameter of the region was chosen to be sufficiently large so that the thermal field associated with the container is unaffected by the presence of the lateral boundary. This is not an unrealistic situation since, in an actual repository, waste containers would be emplaced sufficiently far apart to preclude thermal interaction. On the upper, horizontal, permeable boundary, pressure and temperature are held constant. Both the lower horizontal and vertical lateral boundaries are impermeable. The vertical boundary is insulated and the steady geothermal heat flux is applied to the lower boundary. Additional boundary conditions, required for the radionuclide migration study, are also included on Fig. 2.

Fig. 2. Reference Emplacement Configuration.

In Table I, the material properties used in the thermal analysis are tabulated for a temperature of 20°C. Those properties indicated with an asterisk were actually allowed to vary with temperature in the analysis, in accordance with the relations given in Ref. 5.

Typical results of the numerical study are given in Figs. 3-5. In Fig. 3, selected isotherms are plotted for one and ten years after emplacement. As indicated in a previous section, a Rayleigh number of approximately 10^{-3} is appropriate for this

situation. We thus expect the thermal field to be relatively unaffected by convection, as confirmed by Fig. 3. The symmetry of the isotherms indicates that the temperature distribution is established by thermal conduction. A typical computed axisymmetric streamline pattern is illustrated in Fig. 4 for an elapsed time of 10 years after emplacement. Finally, in Fig. 5, we present plots of temperature and vertical velocity versus time as calculated for a point adjacent to the container on the horizontal mid-plane. It is observed from this last figure that essentially all thermal activity has ceased as a result of thermal decay during the first 100 years of emplacement.

Fig. 3. Isotherm Patterns Near Container for Two Times.

Fig. 4. Streamline Pattern at 10 Years After Emplacement.

Fig. 5. Velocity and Temperature Histories on Container at a Depth of 30 m.

RADIONUCLIDE MIGRATION

Basic Theory

The development of the basic theory as well as the numerical solution of the resulting equations have been described in detail by Russo.⁴ In what follows, we make extensive use of this previous work. For purposes of modeling the transport of radionuclides, it is assumed that the presence of radionuclides does not alter the fluid properties or the behavior of other nuclides and that sorption processes are reversible and describable in terms of an equilibrium distribution coefficient. Consequently, the transport of radionuclides in a porous medium by the combined effects of convection, diffusion-dispersion, sorption, and radioactive decay is described by the partial differential equation

$$\frac{\partial}{\partial t}(C^n \phi K^n) + \frac{\partial}{\partial x_i} \left(C^n v_i - D_i^n \frac{\partial C^n}{\partial x_i} \right) = - \sum_{k=1}^N \lambda^{nk} K^n \phi C^n + \sum_{k=1}^N \lambda^{kn} K^k \phi C^k + S^n, \quad (12)$$

where C^n is the concentration for the ionic species n . In Eq. (12), K^n is the species equilibrium coefficient

$$K^n = \left(1 + \frac{1 - \phi}{\phi} \right) \rho_s K_d^n, \quad (13)$$

where K_d^n is the equilibrium distribution coefficient which is, in general, a function of species concentration and temperature. For the numerical results to be described subsequently, we have neglected the temperature dependence and assumed

$$K_d^n = \frac{a_2}{1 + a_1 C^n} + \frac{a_4}{1 + a_3 C^n}, \quad (14)$$

where the a 's are constants. The quantity D_1^n is the diffusion-dispersion coefficient

$$D_1^n = \alpha_{ij}^n |v_j| + D_0^n, \quad (15)$$

where α_{ij}^n are dispersion coefficients, D_0^n is the molecular diffusion coefficient, and the velocity v_i is the Darcy velocity as defined by Eq. (3). In our analysis, we have assumed $\alpha_{11}^n = \alpha_{22}^n = 6.1$ m and $\alpha_{12}^n = \alpha_{21}^n = 0.61$ m. Finally, λ_{nk} is the radioactive decay rate from species n to species k and S^n is a source term. All other parameters in Eq. (12) have been defined previously. The fluid velocity v_i is obtained directly from the thermal analysis.

Analytical Solutions

Numerous prior publications have dealt with the solution of various special forms of Eq. (12) for the transport of radionuclides in a one-dimensional system. We shall not attempt to review this rather large body of work, but will instead focus attention on a single analytical solution which has a more direct bearing on the problem at hand. Nuttall, Ray, and Davis¹⁶ developed an analytical solution for the isothermal migration of a single radionuclide from a point source embedded in a semi-infinite region below a boundary on which the concentration was maintained at a constant value of zero. The processes of diffusion, sorption, and radioactive decay were included in the analysis. Convective transport was assumed negligible. In view of the rather weak convection predicted for the reference emplacement configuration, this last assumption appears reasonable. Concentration profiles and breakthrough times were predicted for the cases of instantaneous dissolution of the container and constant leakage rate from the container. The analysis is viewed as a reasonable first approximation to the far-field behavior of the migration process.

Numerical Solutions

Computational Approach. Numerical solutions to Eq. (12) were obtained with the computer program IONMIG. In IONMIG, Eq. (12) is solved in finite difference form through use of an explicit, predictor-corrector technique originated by McCormack.¹⁷ Stable integration of the

finite difference form of the equation can, in general, require a different time step for each species. This is accomplished by selecting a global time step based on decay rate and output data considerations and an integration time step for each species which is an integer subdivision of the global time step and satisfies an appropriate stability criterion.

Decay chain species which are short-lived compared to the other chain members may be omitted by merely bypassing them in the definition of the decay chain matrix λ_{nk} . If such elements are included in the chain, the code will artificially reduce their decay constant (increase their half life) to a level for which they will disappear in several global time steps. This permits the inclusion of transition species in the chain without going to excessively small time steps. However, the instantaneous concentrations of such short-lived species will be greatly overestimated and should not be considered as part of the usable results.

In order to retain the flexibility of use provided by the options of axisymmetric geometry and variable mesh calculations, conservation differencing, which becomes rather unwieldy for these options, was not used. It is possible, therefore, that discretization and truncation errors may introduce some source error into the calculations. To partially correct for this possibility, a separate and more accurate time integration of the global quantities is performed and compared with the mesh point summations. An option to correct the mesh point values at each time step is available.

Results for Reference Emplacement Configuration. The computational domain utilized for the analysis of the radionuclide migration process is the same as that used for the thermal analysis and is depicted in Fig. 2. It is assumed that the entire contents of the waste container are initially uniformly distributed within a cylindrical region 5 m in height and 4 m in diameter centered about the location of the original container. The computer program IONMIG is then used to predict the subsequent migration of the radionuclides present in the initial inventory. Referring to Fig. 2, we note that the concentration is maintained at a value of zero at the sediment/water interface. Both the vertical and lower boundaries of the domain are considered impermeable to the transport of radionuclides.

For comparative purposes, we have considered the migration of four representative nuclides: the cationic species ^{239}Pu and ^{137}Cs , and the anionic species ^{129}I and ^{99}Tc . Plutonium is considered representa-

tive of transuranic elements with long half life and large equilibrium distribution coefficients K_d . Cesium is typical of fission products with short half life and moderate K_d . Both iodine and technetium have long half life and low K_d . Based on limited laboratory results obtained by Erickson,¹⁸ we have assumed values for molecular diffusion and equilibrium distribution coefficients. These values can be obtained from the information contained in Table III. In order to study the migration of the four representative radionuclides, it was necessary to simultaneously consider the associated parent and daughter nuclides. Decay chains for each of the representative elements are listed in Table II along with the mass of each element present in the initial inventory for the waste container. The initial inventory is the same as that used for the thermal source calculations.

TABLE II
INITIAL INVENTORIES OF RADIONUCLIDES
USED IN THE CALCULATIONS

Radionuclide	Mass in Container (kg)
²⁴³ Am	0.121
²³⁹ Np	1.0 E-7
²⁴³ Cm	6.92 E-5
²³⁹ Pu	3.58 E-2
²³⁵ U	1.0 E-5
¹²⁹ I	0.305
¹²⁹ Xe	1.178 E-4
⁹⁹ Tc	1.13
⁹⁹ Ru	4.32 E-5
¹³⁷ Cs	1.33
¹³⁷ Ba	2.01 E-7

Calculations for ¹³⁷Cs were carried out to 3500 years to verify that little motion took place prior to decay. Since the half life of ¹³⁷Cs is only 30 years, in a few hundred years virtually all the ¹³⁷Cs decays to ¹³⁷Ba, in place, and none reaches the surface. The same behavior is expected of other short-lived species with moderate values of K_d such as ⁹⁰Sr.

For long-lived isotopes having a high K_d , such as many forms of ²³⁹Pu, the situation is similar except over much longer time scales. Fig. 6 shows the concentration of ²³⁹Pu over a vertical plane containing the buried canister after 10⁵ years.

TABLE III
DIFFUSION COEFFICIENTS AND PARAMETERS
FOR EQUILIBRIUM DISTRIBUTION COEFFICIENTS

Radio-nuclide	D_0 (m ² /yr)	a_1	a_2 (m ³ /kg)	a_3	a_4
Pu	0.010	3x10 ⁸	1x10 ²	0.0	0.010
Cs	0.010	2x10 ⁵	1x10 ¹	0.0	0.100
I	0.018	1x10 ⁴	1x10 ⁻⁴	0.0	0.0
Tc	0.010	1x10 ⁴	1x10 ⁻⁴	0.0	0.0

Fig. 6. Plutonium Concentration in the Sediment at 10⁵ Years.

Although 4.1 half lives of ²³⁹Pu have elapsed, the remaining plutonium is a little less than 1/3 of the original inventory because of the decay of ²⁴³Am to ²³⁹Pu. In this calculation, the Am and Np were assumed to have the same K_d as the plutonium. Data currently available indicate this is a reasonable assumption for Am but may yield too large a value for K_d for the short-lived Np. The migration rate of plutonium is so slow (a few metres per 10⁵ years) that even after 10⁶ years, less than 10⁻²⁰ percent of the depleted inventory has crossed the surface. At that time, less than 10⁻¹⁰ grams of ²³⁹Pu remain.

For anionic nuclides having a long half life and a very small K_d , such as ¹²⁹I and ⁹⁹Tc, the behavior is quite different. Without the retarding action of sorption, these substances diffuse through the sediment in a relatively short time (5000 years or less). Fig. 7 shows the release rate of radioactivity, at the sediment/water interface, associated with the decay of ¹²⁹I as a function of time. The release rate reaches a peak of 0.52 μ Ci/yr at about 8,000 years and then declines to approximately 1/3 of that value in 10⁵ years. The specific activity of ¹²⁹I is low, decaying to ¹²⁹Xe by beta decay with a half life of 15.9 million years. Fig. 8 shows a similar release rate profile for ⁹⁹Tc. The peak value of 180 μ Ci/yr is much higher than that for ¹²⁹I because both the initial container inventory and the specific activity of ⁹⁹Tc, which beta decays to

^{99}Ru with a half life of 213,000 years, are higher.

Fig. 7. Release Rate of ^{129}I from the Sediment Surface Covering a Single Container.

Fig. 8. Release Rate of ^{99}Tc from the Sediment Surface Covering a Single Container.

As a final observation, we note from Fig. 5 that after approximately 30 years, the maximum fluid velocity induced by thermal convection has decayed to a value typical of that due to diffusion (5-10 mm/yr). Consequently, we anticipate that convection has little effect on the migration of radionuclides in marine sediment; a conclusion which has been verified computationally.

DISCUSSION

We have developed a mathematical basis for the prediction of thermal and radionuclide transport in marine sediments. The theory was applied to the study of problems associated with the disposal of radioactive waste by emplacement in oceanic sedimentary layers well below the sediment/water interface. A reference emplacement configuration was defined and used for all analyses

reported. Aside from some analytical approaches which were only briefly described, the studies reported in this paper were performed, numerically, using two computer programs which were designed especially for the analysis of the problem at hand.

Numerical results indicated that, for the proposed disposal scheme, the Rayleigh number associated with the thermally induced convective motion is expected to be quite small (10^{-3}). Hence, the convective velocity is small and has only a negligible effect on the temperature distribution. Thermal conduction theory can thus be used effectively for the prediction of the temperature distribution. For the reference container, it was shown that all thermal effects decay to a negligible level in approximately 100 years.

The migration of the four representative nuclides ^{239}Pu , ^{137}Cs , ^{129}I , and ^{99}Tc was computed. For the reference problem, it was predicted that no plutonium or cesium would breach the sediment/water interface. It was, however, predicted that iodine and technetium would migrate to the interface and the associated release rates were computed.

The significance of the computed release rates in terms of human or ecological hazards can be determined only by a comprehensive analysis of the water column transport mechanisms and marine bio-system concentration mechanisms. Some perspective on the predicted release rates can be obtained, however, by a comparison with other oceanic radioactive sources. For the axisymmetric case for which the calculations were made, the area per container is based on a spacing of 120 m. This results in an average release per container of $4.5 \times 10^{-5} \mu\text{Ci/yr-m}^2$ for ^{129}I and $1.6 \times 10^{-2} \mu\text{Ci/yr-m}^2$ for ^{99}Tc . These fluxes compare to natural radium and radon fluxes of $3.5-8.8 \times 10^{-4} \mu\text{Ci/yr-m}^2$ for ^{226}Ra and $0.26-0.88 \mu\text{Ci/yr-m}^2$ for ^{222}Rn .⁴ Based on this comparison, it may be hypothesized that the immediate exposure effects of the released ^{129}I and ^{99}Tc on benthic organisms would be negligible since they evolved in a much more intense field. Confirmation of this hypothesis awaits completion of ongoing research and experimentation on biological concentration, water column transport mechanisms, and development of pathways-to-man models.

At this point, a few final comments are offered concerning possible sources of error in our analyses. At the present, only rudimentary information is available for the thermophysical properties required in the thermal analysis. Lack of property information aside, the assumptions most likely to introduce errors into the thermal analysis are those associated with the Boussinesq approximation and the assumed

rigidity of the porous matrix. The rapid heating of a liquid confined in a rigid porous matrix of low permeability can actually produce a rather high transient pore pressure. As a result of the assumptions invoked, this behavior is not evidenced by our solutions. If the porous matrix is composed of clay particles, as is the case for marine sediments, then it is likely that some local deformation of the matrix will occur in regions of high heating rates. Questions regarding the deformational behavior of marine sediments cannot be answered conclusively until rheological properties have been accurately determined.

Accurate predictions of migration processes are also severely hampered by lack of experimental confirmation of various assumed properties. For example, insufficient information exists concerning equilibrium distribution coefficients. Recent laboratory studies¹⁸ suggest that the mathematical form we assumed for the equilibrium distribution coefficient may be inadequate to describe the sorption of certain radionuclides, particularly iodine. Future predictive capability will depend crucially on the outcome of planned experimental research.

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REFERENCES

1. Bishop, W. P. and Hollister, C. D., "Seabed Disposal--Where to Look," Nuclear Technology, Vol. 24, 1974, pp. 425-443.
2. Gartling, D. K. and Hickox, C. E., "MARIAH--A Finite Element Computer Program for Incompressible Porous Flow Problems, Part I--Theoretical Background," SAND79-1622, Sandia Laboratories, Albuquerque, NM, to be published.
3. Gartling, D. K. and Hickox, C. E., "MARIAH--A Finite Element Computer Program for Incompressible Porous Flow Problems, Part II--User's Manual," SAND79-1623, Sandia Laboratories, Albuquerque, NM, to be published.
4. Russo, A. J., "Prediction of the Migration of Several Radionuclides in Ocean Sediment with the Computer Code IONMIG, A Preliminary Report," SAND79-1666, Sandia Laboratories, Albuquerque, NM, May 1980.
5. McVey, D. F., Gartling, D. K., and Russo, A. J., "Thermal/Fluid Modeling of the Response of Saturated Marine Red Clays to Emplacement of Nuclear Waste," in: Proc. Workshop on the Use of Argillaceous Materials for the Isolation of Radioactive Waste, Nuclear Energy Agency, Paris, 1979, pp. 179-201.
6. Bell, M. J., "ORIGEN--The ORNL Isotope Generation and Depletion Code," ORNL-4628, Oak Ridge National Laboratory, May 1973.
7. Krumhansl, J. L. and Hadley, G. R., "Thermal and Chemical Properties of Saturated Marine Clays in a Near Field Environment," in: Proc. Workshop on the Use of Argillaceous Materials for the Isolation of Radioactive Waste, Nuclear Energy Agency, Paris, 1979.
8. Braithwaite, J. W. and Molecke, M. A., "High-Level Waste Canister Corrosion Studies Pertinent to Geologic Isolation," Nuclear Waste Management and Technology, Vol. 1, No. 1, Pergamon Press, 1979.
9. Hickox, C. E. and Watts, H. A., "Steady Thermal Convection from a Concentrated Source in a Porous Medium," J. Heat Transfer, Vol. 102, No. 2, May 1980, pp. 248-253.
10. Bejan, A., "Natural Convection in an Infinite Porous Medium with a Concentrated Heat Source," J. Fluid Mech., Vol. 89, Part 1, 1978, pp. 97-107.
11. Hickox, C. E., "Thermal Convection at Low Rayleigh Number from Concentrated Sources in Porous Media," to be presented at ASME Winter Annual Meeting, Chicago, IL, November 1980.
12. Gartling, D. K., "NACHOS--A Finite Element Computer Program for Incompressible Flow Problems, Part I--Theoretical Background," SAND77-1333, Sandia Laboratories, Albuquerque, NM, 1978.
13. Gartling, D. K., "COYOTE--A Finite Element Computer Program for Nonlinear Heat Conduction Problems," SAND77-1332, Sandia Laboratories, Albuquerque, NM, June 1978.
14. Gartling, D. K., "Convective Heat Transfer Analysis by the Finite Element Method," Comp. Meths. Appl. Mech. Eng., Vol. 12, No. 3, 1977, pp. 365-382.
15. Zienkiewicz, O. C., The Finite Element Method in Engineering Science, McGraw-Hill, London, 1971.

16. Nuttall, H. E., Ray, A. K., and Davis, E. J., "Ion Migration in Ocean Sediments: Subseafloor Radioactive Waste Disposal," Proc. Mat. Res. Soc. Annual Mtg., Boston, MA, November 1979.
17. MacCormack, R. W., "The Effect of Viscosity in Hypervelocity Impact Cratering," AIAA Paper No. 69-354, 1969, also "Numerical Solution of the Interaction of a Shock Wave with a Laminar Boundary Layer," Proc. of the Second Intl. Conf. on Numerical Methods in Fluid Dynamics, University of Calif. at Berkeley, September 15-19, 1970.
18. Erickson, K. L., Personal Communication, Sandia Laboratories, Albuquerque, NM.

THERMOPHYSICAL PROPERTIES OF DEEP OCEAN SEDIMENTS*

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Abstract

Here we report measurements of the thermal conductivity and diffusivity of reconsolidated illite and smectite ocean sediments at a pore pressure of 600 bars and temperatures ranging from 25-420°C. The conductivity and diffusivity were found to be in the range of 0.8-1.0 W/m-K and $2.2 - 2.8 \times 10^{-7} \text{ m}^2/\text{s}$, respectively. These data are consistent with a mixture model which predicts sediment thermal properties as a function of constituent properties and porosity. Comparison of pre- and post-test physical properties indicated a decrease in pore water content and an order of magnitude increase in shear strength and permeability.

I. Introduction

The deep seabed is one of the geological formations presently under consideration as a repository for the long-term disposal of nuclear waste. Its remoteness and relative geological stability are some of the attractive features which have led to an intensive study of the response of seabed sediments to the emplacement of waste canisters. Of primary interest is the thermal response, since sediment temperature in the immediate vicinity of a typical canister might conceivably rise several hundred degrees Celsius above ambient (depending on the waste form) for periods of a few tens of years. A predictive capability is being sought which would allow calculation of the temperature field and general response to that field for given disposal scenarios. The responses might include changes in mechanical properties such as shear strength or permeability, chemical reactions, or ion adsorption properties. The present work discusses measurement of thermal properties of the sediment at temperatures to 420°C and pore pressures of 600 bars. The experiments provided valuable preliminary information on sediment thermal response.

Previous work in this area has been motivated primarily by studies of heat flow through the ocean floor. Various in situ

and shipboard conductivity measurements using the line source probe technique have been made in the temperature range 0-25°C. Von Herzen and Maxwell,¹ Lister,² and Anderson et al.³ are a few of the many authors who have reported such measurements at various locations on the ocean floor. Ratcliffe⁴ and Horai⁵ have made laboratory measurements on sediment cores obtained from various sites using both steady state and transient methods. They have reported values at room temperature and atmospheric pressure, with Ratcliffe giving correction factors for conversion to lower seabed temperatures. To the authors' knowledge, the present work reports the first attempt to measure sediment thermal properties at elevated temperatures.

II. Experimental Apparatus

In order to approximate the subseabed environment, the test apparatus was required to impose a lithostatic pressure of 30-100 k Pa on the sediment while maintaining a pore pressure of 60 MPa over a temperature range of 25-450°C for the duration of the required property measurements.

The apparatus consisted of a high pressure autoclave (located at the Hot Isotatic Processing Facility of the Battelle Columbus Laboratories), a thermal shield to protect the autoclave wall, a heater assembly, and a water tight experiment chamber.

The ocean sediment and the sea water used as a saturating fluid were completely contained in the experiment chamber shown in Figure 1. Since the pH of the heated sediment can decrease drastically, almost all assembly components were fabricated from corrosion resistant Inconel 600. The autoclave pressure was transmitted from the argon gas to the seawater through a deformable bellows which could also accommodate the water expansion during heating. A weight inside the bellows provided the desired lithostatic load which was transmitted to the sediment by a movable piston. Water was allowed to escape from the top of the sediment through a porous alumina filter and a central hole in the piston and through a filter and water path at the bottom of the sample.

The sediment sample was consolidated in an Inconel Tube 0.1 m inside diameter by 0.35 m high. The base plate contained water tight fittings to allow insertion of the line source thermal conductivity probe and sheathed

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thermocouples. The thermocouples (all K-type) were arranged near the sample midpoint at various radii from the line source probe. A so-called "vernier" heater was wrapped directly onto the experiment chamber wall both to aid in stabilizing the sediment thermally and also to allow the measurement of diffusivity. A heater cover or can surrounding the winding acted to reduce convection of the high pressure argon gas.

III. Sediment Preparation and Characterization

The thermal properties measurements reported herein were conducted on three different samples of reconsolidated ocean sediment. The sediments tested were surficial, fine-grained, illitic and smectite clays obtained from a dredging operation conducted in the MPG-1 study area of the Pacific Ocean (30° 19.9'N, 157° 49.4'W). After screening to remove nodules, the clays were each thoroughly mixed, homogenized, and then reconsolidated to different effective stresses and water contents.

In the first test, the illite sample was consolidated to an effective stress similar to its in-situ overburden stress of about 34 kPa (5psi). Because of the remolded nature of the sample, the water content at this stress was less than that evidenced by an undisturbed (in-situ) sample at the same stress ($w = 120\%$ for undisturbed vs. 97% for remolded). For the second test, the illite was consolidated to a smaller overburden stress of 14 kPa (2 psi). This test attempted to simulate overburden stresses which might be encountered in future near-surface field studies. Because of the smaller loadings, less water was forced out of the sediment and the clay had a higher pre-test water content of 109%. In the third test, remolded smectite was consolidated to an overburden stress of 103 kPa (15 psi) to simulate conditions at a sediment depth of approximately 30 m. Due to the nature of this sediment type, the pre-test water content of the smectite was much higher than that of the illite samples previously tested (130% for smectite vs. 109% for illite).

For each of the three tests the consolidation load was kept on the sediment for a few days after consolidation had essentially ceased, to allow the pore water pressure to dissipate and the water content profile through the column to approach equilibrium. Pre-test specimens were then obtained from the top few inches of the sediment and measurements of permeability, consolidation, water content, and shear strength were made.^{6,7} For tests 1 and 2 only, these measurements were repeated after completion of the thermal properties tests at high temperature and pressure.

IV. Measurement Methods

The thermal conductivity of the sediment sample was determined by applying constant power per unit length to a small diameter cylindrical heater (line source probe) containing

thermocouples to monitor temperature rise. The technique is developed by Jaeger^{8,9} and the use in seabed sediments discussed by several other authors.^{1,2,3} Using the line source probe with a constant power input Q (W/m) the conductivity k (2/m-K) is given by

$$k = \frac{Q}{4\pi \frac{\partial \Delta T}{\partial \ln t}}$$

where $\partial \Delta T / \partial \ln t$ is the slope of the temperature vs $\ln t$ curve. For sufficiently long times, a plot of ΔT vs. $\ln t$ is a straight line; therefore the slope, together with a measurement of Q yields k . For the present experiment, the initial transient phase was about 3 min long. It was found that after 30-40 minutes, the chamber wall began affecting the results, leaving about a 30 min. window for data taking.

The method used for determining thermal diffusivity was a cylindrical variation of the well known "flash" technique.¹⁰ With this method, a fast rise heat pulse is applied at one point in the medium while monitoring the subsequent temperature rise somewhere else. In the present case, the heat pulse was applied at the circumference of the sample and the temperature monitored on axis (at the line source probe). Under certain conditions, the governing equations may be solved analytically and a direct expression obtained for diffusivity. In the present case, it was not always possible to maintain the required condition and so a more general solution method was used:

- 1) An initial guess was made for diffusivity and the boundary conditions computed from experimental data
- 2) The governing equation was solved numerically and the result compared with the data on axis.
- 3) Based on the mismatch in 2), a better guess for diffusivity was made and steps 1) and 2) repeated.

This method was found to work very well in practice since the numerical effort involved was minimal.

A special line source probe design was used for these experiments. The probe outer diameter (3 mm) was determined from the sample chamber size, estimated sediment conductivity and the requirement that the data taking be completed before the thermal pulse from the probe interacted with the chamber wall. The aspect ratio (~ 50) was large enough to reduce axial conduction errors below 1%. The probe radius was kept small enough to insure that large Fourier numbers (~ 240) and consequently good linearity in the data would be obtained before wall effects from the chamber would be felt.

A power supply circuit was designed to deliver a constant power to the probe regardless of heater resistance. The power supply was able to maintain both a short and long-term stability of 0.1% or better over a change in heater resistance of 15%. The supply typically delivered about 2 watts to the probe during a measurement.

The probes were checked by casting them into a block of naphthalene which has a conductivity in the range of that of sediment (0.336 W/m-K vs. 0.8 - 1.0 W/m-K). Results from the calibration tests showed an experimental variation from test to test of $\pm 5\%$.

V. Results

It is of importance to determine correlations which give good predictions of sediment thermal properties in terms of the constituent properties and the porosity. In the case of heat capacity per unit volume the formula is well known and is

$$(\rho C)_m = (\rho C)_w \phi + (\rho C)_s (1 - \phi)$$

where the subscripts m, s, w refer to mixture, sediment matrix, and water, respectively. This equation follows from the fact that, for an incompressible substance, the total change in internal energy upon increasing the temperature is an extensive quantity and hence is additive.

For thermal conductivity, there is no unique formula and in fact different substances seem to have different mixture formulas.^{11,12,13}

Looking at conductivity as a sort of "inverse thermal resistance," the mixture conductivity may be dominated by either the high conductivity phase or the low conductivity phase depending on whether the material is more closely approximated as a series or parallel arrangement. In general, a given mixture may fall in between the two pictures. For consolidated sediment, the platelets that form the matrix are evidently forced into good thermal contact and so form a "short" with respect to the lower conductivity water phase. As will be shown, the parallel circuit seems to fit sediment data quite well. The resulting equation for thermal conductivity is then

$$k_m = k_w \phi + k_s (1 - \phi)$$

Thermal Conductivity

Measured values for the thermal conductivity of the two types of ocean sediment for tests 2 and 3 along with the mixture theory prediction is shown in Figure 2. Test 1 illite data is omitted but follows closely the results for Test 2. The measurements of Birch and Clark¹⁴ for the conductivity of slate were used in the mixture formula for the sediment component. Slate was chosen because of its mineralogical similarity to sediment material and also because of its low porosity. Thermal properties of water were obtained from Burnham et al.¹⁵

The results show that, below 200°C, the illite conductivity is nearly constant. This is explained by the model in that below 200°C the conductivity of water is increasing while that of slate is decreasing. At higher temperatures both are decreasing, leading to the falloff

shown. The smectite data appears to rise immediately, although no data was obtained above 100°C due to equipment failure. The mixture model prediction is less accurate for this case. Some indication of the validity of the present measurements as well as the usefulness of the mixture model may be obtained through a comparison of thermal conductivity measurements made on a variety of sediment samples. Such a comparison is provided in Figure 3 for room temperature data measured by Horai on samples obtained in connection with the Deep Sea Drilling Project.⁵ The measurements were made on a large number of samples obtained from several different cores and ranging in hardness and porosity from crustal material to soft sediments similar to those used in the present work. The lines shown represent a fit to Horai's data and the linear model prediction for the present data at room temperature. It is evident that the two differ only slightly for porosities typically encountered in sediments (≥ 0.6). For lower porosities, a considerable range of matrix conductivities must be allowed for. It appears that a higher value of matrix conductivity than that of slate would provide a better universal fit for the proposed mixture model.

Thermal Diffusivity

The thermal diffusivity results are shown in Figure 4. The same basic trend is exhibited as was found for conductivity except that the smectite shows a less dramatic increase with temperature than before. Specific heat values for the sediment material were obtained from measurements of six rock types,¹⁶ since values for slate could not be found. This procedure is justifiable because the specific heat in the temperature range below 500°C only varied by $\pm 5\%$ for the six common rock types surveyed. It is assumed that values for slate would fall within the range of values for granite, basalt, limestone and marble. Note that for both conductivity and diffusivity modeling, the porosity used in the mixture formula was taken from pre-test measurements.

Sediment Physical Properties

Physical properties changes are typified by the data presented in Table 1 and Figures 5, 6, and 7. The post-test sediment was quite brittle and displayed an order of magnitude increase in shear strength over the pre-test specimens. The increase in overconsolidation ratio (OCR) determined during consolidation tests was another indicator of strength increase.

In order to better understand physical property differences, scanning electron micrographs were obtained from a few illite specimens. These were examined to determine whether any high temperature/high pressure effects on the sediment fabric could be detected visually. Micrographs showed the pre-test sample to have a flaky texture, composed primarily of clay platelets. The post-test photos, however, indicated that this structure

had been covered with a precipitate, the product of chemical reactions occurring during test conditions. This coating presumably promoted some cementing among plates, thereby accounting, in part, for the sample's significant increase in shear strength.

The sediment column underwent a considerable amount of contraction during the testing, and this movement produced a clay with a lower water content, Figure 5. This condition also contributed, to some extent, to the higher post-test shear strength as seen in Figure 6. The shear strength of the pre-test sample was quite similar to that found for undisturbed illite samples taken from the top two meters of sediment cores in the same areas where the test samples were acquired.

The permeability of the pre-test samples compared very closely to values obtained from other permeability tests performed on remolded illite. The post-test samples, however, showed a sizeable increase in permeability over the pre-test specimens at equivalent void ratios, Figure 7. It is not evident, from observation of the electron micrographs, why this condition exists.

VI. Discussion and Conclusions

This paper reports the results of tests conducted to characterize the properties and behavior of ocean sediment at elevated temperatures and pore pressures typical of the deep ocean. Both thermal conductivity and diffusivity have been measured at temperatures ranging from room temperature to 420°C. In addition, pre- and post-test characterization studies have been conducted to examine the effects of heating upon shear strength, permeability, and consolidation state. The samples were two different kinds of ocean sediment, illite and smectite, obtained by dredging from the MPG-1 study area north of Hawaii. Prior to testing, the samples were homogenized and reconsolidated to preset overburden stresses.

These tests indicate that thermal properties of consolidated sediment may be described by a simple mixture model. The latter implies that for consolidated sediment the platelets make sufficiently good contact with each other to effectively provide a "thermal short" with respect to the water. However, the high porosity of most sediments causes the thermal properties to remain closer to water values than rock values.

Analysis of physical sediment properties both before and after heating indicate that sediment changes occurred during heating. A partial result of these changes was the order of magnitude increase in both sediment shear strength and permeability. An S.E.M. examination suggested that a chemical "cementing" of the sediment platelets to each other may have taken place. No exact chemical analysis of this process was attempted.

VII. Acknowledgements

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References

1. R. Von Herzen, A. E. Maxwell, "The Measurement of Thermal Conductivity of Deep-Sea Sediments by a Needle-Probe Method," JGR, vol. 64, no 10, 1557 (1959).
2. C. R. B. Lister, "Measurement of In-Situ Sediment Conductivity by Means of a Bullard-Type Probe," Geophys. Journal Roy Astr. Soc. 19, 521 (1970).
3. R. N. Anderson, M. A. Hobart, M. G. Langseth, "Geothermal Convection Through Oceanic Crust and Sediments in the Indian Ocean," Science 204, no. 4395, 828 (1979).
4. E. H. Ratcliffe, "The Thermal Conductivity of Ocean Sediments," JGR, 65, no. 5, 1535 (1960).
5. Ki-Iti Horai, "Thermal Conductivity of DSDP LEG 60 Oceanic Crustal Samples," to appear in Initial Report of the Deep Sea Drilling Project, Vol. LX, U. S. Govt. Printing Office.
6. A. J. Silva, J. R. Hetherman, D. I. Calnan, "Low Gradient Permeability Testing of Fine-Grained Marine Sediment," Amer. Soc. Testing Mats, 1980, in press.
7. T. W. Lambe and R. V. Whitman, Soil Mechanics, J. Wiley & Son, 1969, pp. 76, 77.
8. J. C. Jaeger, "The Measurement of Thermal Conductivity and Diffusivity with Cylindrical Probes," Transactions, American Geophysical Union 13, No. 4, 1958, pp. 708-710.
9. J. C. Jaeger, "Conduction of Heat in an Infinite Region Bounded Internally by a Circular Cylinder of a Perfect Conductor," Australian Journal of Physics 9, 1956, pp. 167-179.
10. W. J. Parker, R. J. Jenkins, C. P. Butler, and G. L. Abbott, "Flash Method of Determining Thermal Diffusivity, Heat Capacity, and Thermal Conductivity," J. App. Phys. 32, no. 9, 1679 (1969).
11. W. Woodside and J. H. Messmer, "Thermal Conductivity of Porous Media II. Consolidated Rocks," J. App. Phys. 32, no. 9, 1699 (1961).
12. M. R. J. Wyllie and P. F. Southwick, J. Petro. Tech 6 TP3750 (1954).

13. Ki-iti Horai, "Thermal Conductivity of Rock-Forming Minerals," JGR 76, no. 5, 1278 (1971).
14. F. Birch and H. Clark, "The Thermal Conductivity of Rocks and Its Dependence upon Temperature and Composition," Am. Journ Sci., 238, no. 8, 37 (1940).
15. C. W. Burnham, J. R. Holloway, N. F. Davis, "Thermodynamic Properties of Water to 1000°C and 10000 bars," Geol. Soc. of Am. Special Paper no. 132 (1969).
16. D. P. Lindroth, W. G. Krawza, "Heat Content and Specific Heat of Six Rock Types at Temperatures to 1000°C," Rept. 7503, U. S. Dept. of Interior.

Table I

Comparison of Illite Sediment Properties Before and After Exposure to Test Conditions

	Pre-Test	Post Test
Shear Strength - g/cm ² (Test 1)	26.4	264
Shear Strength - g/cm ² (Test 2)	16.2	100
Overconsolidation Ratio (Test 1)	1.5	2.6
Permeability - cm/sec (Test 1 at a void ratio of 1.85)	6.8×10^{-8}	9.0×10^{-7}

Figure 2 - Sediment Thermal Conductivity

Figure 1 - Experiment Chamber

Figure 3 - Comparison of Present Data at 25°C with Data From DSDP⁵. Curved Line Best Fit for DSDP Data, Straight Line, Present Correlation.

Figure 4 - Thermal Diffusivity Data

Figure 5 - Water Content, Illite Test 2.

Figure 6 - Shear Strength, Illite Test 2.

Figure 7 - Coefficient of Permeability (K), Illite Test 1.

THERMAL CONVECTION AT LOW RAYLEIGH NUMBER FROM CONCENTRATED SOURCES IN POROUS MEDIA

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ABSTRACT

A simple mathematical theory is proposed for the analysis of natural convective motion, at low Rayleigh number, from a concentrated source of heat in a fluid-saturated porous medium. The theory, which consists of retaining only the leading terms of series expansions of the dependent variables in terms of the Rayleigh number, is thus linear, and is valid only in the limit of small Rayleigh number. Based on fundamental results for a variety of isolated sources, superposition is used to provide solutions for situations of practical interest. Special emphasis is given to the analysis of sub-seabed disposal of nuclear waste.

NOMENCLATURE

a	Radius of sphere	t	Time
C_p	Specific heat	$\underline{v}$	Velocity vector
D	Burial depth for heat source	v_R, v_ϕ	Velocity components in spherical coordinates
g	Acceleration of gravity	v_R, v_ϕ	Non-dimensional velocity components in spherical coordinates
H	Length of line source	v_r, v_θ	Velocity components in cylindrical coordinates
k	Permeability	v_r, v_θ	Non-dimensional velocity components in cylindrical coordinates
L	Reference length	z	Vertical coordinate
P	Pressure	<u>Greek</u>	
Q	Strength of heat source	β	Coefficient of thermal expansion
R	Radial distance, spherical coordinates	η	Non-dimensional parameter ($r/2\tau^{1/2}$)
r	Normalized spherical radial coordinate	θ	Non-dimensional temperature difference
r	Radial distance, cylindrical coordinates	κ	Thermal conductivity
Ra	Rayleigh number	μ	Viscosity
s	Integration variable for line source	ρ	Density
T	Temperature	τ	Non-dimensional time
		ϕ	Spherical coordinate
		ψ	Stream function
		Ψ	Non-dimensional stream function

Subscripts

- a Refers to sphere radius
e Effective value
0,1,2,... Indicate terms in power series
∞ Reference condition

Superscript

- ' Denotes quantity normalized by division by L

INTRODUCTION

It has been suggested by Bishop and Hollister¹ that the mid-plate, mid-gyre regions of the major oceanic basins be investigated as possible repositories for high level radioactive waste. It was proposed that solidified nuclear waste be encapsulated in suitably designed containers and implanted in the seabed below the surface of the sedimentary layer. This scheme would provide a series of barriers to the release of radionuclides into the environment.

One such potential barrier is the seabed material itself which, although composed primarily of very fine, compacted clay, is still sufficiently permeable to permit interstitial pore water migration. An implanted container of waste material, which is generating heat, can cause an upward migration of pore water due to thermally induced convective motion. Interstitial water motion is a key parameter in studies of radionuclide transport which can ultimately determine the effectiveness of the seabed as a barrier to the release of radionuclides into the water column.

In this paper, a simple mathematical model is proposed for the analysis of thermal convection from a concentrated source of heat in a fluid-saturated porous medium of low permeability. It is assumed that the Rayleigh number (Ra) associated with the natural convection process is small enough so that the temperature distribution is unaffected by the fluid motion and is established by thermal conduction. This assumption is shown to be reasonable for parameters typical of the seabed. The temperature field is then used to predict the associated velocity distribution through use of Darcy's law and the Boussinesq approximation. In essence, the theory is developed by retaining only the leading terms of series expansions of the dependent variables in terms of the Rayleigh number. This general approach has been utilized previously by several authors. Yamamoto² used a Rayleigh number expansion to obtain a solution for the steady natural convection induced by a constant temperature sphere embedded in an infinite porous medium. Steady thermal convection induced by a variety of concentrated sources was studied by Hickox³ for the limiting case of small Rayleigh number, $Ra \rightarrow 0$. Bejan⁴ presented solutions, in terms of power

series in Ra, for transient and steady natural convection induced by a concentrated heat source in an infinite porous medium. Most recently, Hodgkinson⁵ obtained solutions for thermal convection associated with an idealized spherical nuclear waste repository in a permeable rock mass, also for the limiting case of small Rayleigh number.

Simple, algebraic solutions are obtained for the steady-state thermal and flow fields induced by point and line sources as well as those resulting from a constant temperature sphere embedded in a semi-infinite, fluid-saturated, porous region below a horizontal, permeable boundary on which the temperature and pressure are constant. Based on the work of Bejan, the transient response to an embedded point source is also analyzed for the same geometry. Application of these results to the sub-seabed disposal of nuclear waste is considered. A solution which describes the steady natural convection due to a point source situated at the base of a semi-infinite region is also presented. All solutions are valid only for the limiting case of small Rayleigh number.

BASIC THEORY

In this section, a mathematical model is developed for the description of axisymmetric free convection produced by a concentrated source in a fluid-saturated porous medium. The porous medium is assumed to be rigid, homogeneous, and isotropic and the fluid incompressible, with density changes occurring only as a result of changes in the temperature according to

$$\rho = \rho_{\infty} [1 - \beta(T - T_{\infty})] \quad (1)$$

where ρ is the density, T is the temperature, β is the coefficient of thermal expansion, and the subscripts refer to reference conditions. In accordance with the usual Boussinesq approximation, density changes are accounted for only in the buoyancy term in the equations of motion. It is also assumed that the fluid and porous matrix are in thermal equilibrium and that the fluid motion can be adequately described by Darcy's law. Permeability, viscosity, thermal conductivity, thermal capacity, and the coefficient of thermal expansion are assumed constant and dispersion effects are neglected.

The equation of continuity, Darcy's law, and the energy equation are then

$$\text{div } \mathbf{v} = 0 \quad (2)$$

$$\frac{\mu}{\kappa} \mathbf{v} = -\text{grad}(P) + \rho g \text{grad } z \quad (3)$$

$$\begin{aligned} (\rho C_p)_e \frac{\partial T}{\partial t} + \rho_{\infty} C_p \mathbf{v} \cdot \text{grad } T \\ = \kappa_e \text{div}(\text{grad } T) \end{aligned} \quad (4)$$

where $\mathbf{v}$, k , μ , κ_e , P , g , ρ , and C_p are, respectively, the velocity vector, permeability, dynamic viscosity, effective thermal conductivity, pressure, acceleration due to gravity, density, and specific heat. The subscript e refers to effective values. The elevation z is measured vertically upward.

Since only axisymmetric convection is to be considered, it is convenient for purposes of analysis to write Equations (2)-(4) in terms of spherical polar coordinates (R, ϕ) with associated velocity components (v_R, v_ϕ) . In subsequent developments, it will be helpful to also make use of the cylindrical polar coordinates (r, θ) with associated velocity components (v_r, v_θ) . The relationship between the two coordinate systems is illustrated in Figure 1. The continuity relation given by Equation (2) is identically satisfied through the introduction of an appropriately defined stream function ψ , and the pressure is eliminated by taking the curl of Equation (3) after substituting for the density from Equation (1).

Figure 1. Axisymmetric Coordinate Systems

After implementation of the procedure described above, it is also convenient to write the resulting equations in non-dimensional form through the introduction of the non-dimensional parameters

$$r = R/L, \quad \theta = \phi/L, \quad \tau = \tau \kappa_e / (\rho C_p) L^2, \quad (5)$$

$$(v_R, v_\phi) = \frac{\rho_\infty C_p L}{\kappa_e} (v_R, v_\phi), \quad \psi = \frac{\rho_\infty C_p}{\kappa_e L} \psi,$$

$$\theta = \frac{\kappa_e L}{Q} (T - T_\infty),$$

where Q is the rate of energy release from the concentrated source and L is an appropriately chosen length scale. For those situations in which there is no obvious physical length scale (e.g., point source in an infinite region), it is usually convenient to set $L = k^2$. Equations (1)-(4) can now be written in final, non-dimensional form, as

$$\frac{1}{r^2} \frac{\partial}{\partial \phi} \left(\frac{1}{\sin \phi} \frac{\partial \psi}{\partial \phi} \right) + \frac{1}{\sin \phi} \frac{\partial^2 \psi}{\partial r^2} =$$

$$Ra \left(\cos \phi \frac{\partial \theta}{\partial \phi} + r \sin \phi \frac{\partial \theta}{\partial r} \right), \quad (6)$$

$$\frac{\partial \theta}{\partial \tau} + \frac{1}{r^2 \sin \phi} \left(\frac{\partial \psi}{\partial \phi} \frac{\partial \theta}{\partial r} - \frac{\partial \psi}{\partial r} \frac{\partial \theta}{\partial \phi} \right) =$$

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial \theta}{\partial r} \right) + \frac{1}{r^2 \sin \phi} \frac{\partial}{\partial \phi} \left(\sin \phi \frac{\partial \theta}{\partial \phi} \right), \quad (7)$$

where Ra is the Rayleigh number

$$Ra = \frac{k \rho_\infty^2 C_p g \beta Q}{\kappa_e^2 \mu}, \quad (8)$$

and the velocities are related to the stream function by

$$v_R = \frac{1}{r^2 \sin \phi} \frac{\partial \psi}{\partial \phi}, \quad v_\phi = - \frac{1}{r \sin \phi} \frac{\partial \psi}{\partial r}. \quad (9)$$

In the limit of small Rayleigh number, solutions to Equations (6) and (7) can be sought through expansion of the dependent variables in power series in Ra , viz

$$\psi = \psi_0 + Ra \psi_1 + Ra^2 \psi_2 + \dots,$$

$$\theta = \theta_0 + Ra \theta_1 + Ra^2 \theta_2 + \dots \quad (10)$$

The zeroth-order functions correspond to a state of pure conduction, hence there is no fluid motion and $\psi_0 = 0$. The zeroth-order temperature distribution is obtained from the solution of

$$\frac{\partial \theta_0}{\partial \tau} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial \theta_0}{\partial r} \right) +$$

$$\frac{1}{r^2 \sin \phi} \frac{\partial}{\partial \phi} \left(\sin \phi \frac{\partial \theta_0}{\partial \phi} \right). \quad (11)$$

The first non-zero contribution to the stream function is then found from the solution of

$$\frac{1}{r^2} \frac{\partial}{\partial \phi} \left(\frac{1}{\sin \phi} \frac{\partial \psi_1}{\partial \phi} \right) + \frac{1}{\sin \phi} \frac{\partial^2 \psi_1}{\partial r^2} =$$

$$\cos \phi \frac{\partial \theta_0}{\partial \phi} + r \sin \phi \frac{\partial \theta_0}{\partial r}. \quad (12)$$

In the examples which follow, only solutions to the linear system comprised of

Equations (11) and (12) will be considered. The linearity of this system can be used to advantage in that superposition of certain basic solutions is thus allowed. However, all solutions are then, of necessity, limited to cases for which the Rayleigh number is small ($Ra \rightarrow 0$).

Also, in the cases to be considered subsequently, thermal energy is released continuously at a finite rate from a concentrated source. Hence, in the absence of any bounding surfaces which can inhibit motion, any deviation from an isothermal state will result in fluid motion. Therefore, no lower limit for the occurrence of natural convective motion is expected.

FUNDAMENTAL SOLUTIONS

In this section, certain fundamental solutions to Equations (11) and (12) are identified for concentrated sources in an unbounded region. These results then form the basis for superposition models involving more complex boundary geometries. Since it is a straightforward exercise to verify that the quoted results satisfy the appropriate differential equations, details of the solution procedure are omitted.

Steady-State Point Source

When a point source of strength Q is located at the origin of the coordinate system, the appropriate steady-state solutions for the temperature and stream function are

$$\theta_0 = \frac{1}{4\pi r}, \quad \psi_1 = \frac{1}{8\pi} r \sin^2 \phi. \quad (13a,b)$$

From this result, it is apparent that there is a singularity at the origin, and $(T - T_\infty)$ as well as the velocity components approach zero for large r . Additional terms in the series expansion are available in the paper by Bejan. Also, a numerical solution for this situation based on the use of similarity transformations, and valid for any Rayleigh number, is presented by Hickox and Watts⁶.

Transient Point Source

If a point source of strength Q is placed at the origin at time $\tau = 0$, Bejan has shown that the transient response is expressed by

$$\theta_0 = \frac{1}{4\pi r} \operatorname{erfc} \eta, \quad (14a)$$

$$\psi_1 = \frac{1}{8\pi} \tau^{1/2} \sin^2 \phi \left[2\operatorname{nerfc} \eta + \frac{1}{\eta} \operatorname{erfn} - \frac{2}{\pi^{1/2}} \exp(-\eta^2) \right], \quad (14b)$$

where $\eta = r/2\tau^{1/2}$, erf is the error function, and erfc is the complementary error function. This solution is also singular at the origin and the far-field behavior is the same as

that described for the steady-state case.

Steady-State Line Source

The steady-state solution for a vertical line source of length H , coincident with the vertical axis, symmetrically located about the origin, and with strength per unit length Q/H can be obtained from superposition of the fundamental results for a point source as given in Equation (13). Converting to cylindrical polar coordinates and assuming all lengths have been normalized with respect to the length scale L , allows the temperature and stream function to be expressed by the integrals

$$\theta_0 = \frac{1}{4\pi H'} \int_{-H'/2}^{H'/2} \left[r'^2 + (y' - s')^2 \right]^{-1/2} ds', \quad (15a)$$

$$\psi_1 = \frac{1}{8\pi H'} \int_{-H'/2}^{H'/2} r'^2 \left[r'^2 + (y' - s')^2 \right]^{-1/2} ds', \quad (15b)$$

where primes denote that the indicated quantities have been normalized by division by the length scale L (i.e., $H' = H/L$, $r' = r/L$, $y' = y/L$, $s' = s/L$), and s' is an integration variable.

Integration then provides the results

$$\theta_0 = \frac{1}{4\pi H'} \ln \left\{ \frac{[y' + H'/2 + [(y' + H'/2)^2 + r'^2]^{1/2}][y' - H'/2 + [(y' - H'/2)^2 + r'^2]^{1/2}]}{r'^2} \right\}, \quad (16a)$$

$$\psi_1 = \frac{1}{8\pi H'} r'^2 \ln \left\{ \frac{[y' + H'/2 + [(y' + H'/2)^2 + r'^2]^{1/2}][y' - H'/2 + [(y' - H'/2)^2 + r'^2]^{1/2}]}{r'^2} \right\}. \quad (16b)$$

These results exhibit a singularity along the portion of the $-y$ -axis occupied by the line source and have the same far-field behavior previously discussed in conjunction with the point source solution. For solutions expressed in terms of cylindrical polar coordinates, the velocity components are obtained from the nondimensional relations

$$v_r = \frac{1}{r'} \frac{\partial \psi}{\partial y'}, \quad v_y = -\frac{1}{r'} \frac{\partial \psi}{\partial r'}. \quad (17a,b)$$

Steady-State, Constant-Temperature Sphere

Yamamoto has analyzed the natural convection process associated with an isothermal sphere of radius a and surface temperature T_a embedded in an infinite porous medium. Retaining only the leading terms of his solution provides

$$\theta_0 = \frac{1}{4\pi r} \quad (18a)$$

$$\psi_1 = \frac{1}{8\pi} \left[\frac{Lr}{a} - \left(\frac{Lr}{a} \right)^{-1} \right] \sin^2 \phi \quad (18b)$$

where the center of the sphere is coincident with the origin, and the energy release rate from the sphere is $4\pi a k_e (T_a - T_m)$. Hence, it is readily deduced that Equations (18) yield a temperature of T_a on the surface of the sphere. The stream function takes on the value zero on the surface of the sphere and velocities approach zero for large r .

Steady-State Point Source at the Base of a Semi-Infinite Region

For a point source situated on the lower, insulated, boundary below a semi-infinite region, the temperature and stream function are given by

$$\theta_0 = \frac{1}{2\pi r} \quad (19a)$$

$$\psi_1 = \frac{r}{4\pi} \cos \phi \left[(\tan \phi + 1)^{-1/2} - 1 \right] \quad (19b)$$

where the source is, as usual, located at the origin and the behavior for large r is as previously described for a point source. A numerical solution for this case is also presented in the paper by Hickox and Watts.

Although this case is not used in the superposition models described subsequently, it is included for completeness. In order to illustrate the solution for this configuration, isotherms and streamlines obtained from Equations (19) are plotted in Figure 2.

Figure 2. Steady-State Streamlines and Isotherms for a Point Source at the Base of a Semi-Infinite Region ($L = k_e$)

CONCENTRATED SOURCES BELOW A PERMEABLE BOUNDARY

Thermal and Flow Fields

If a thermally active container of nuclear waste material is emplaced in the sediment below the seabed, the situation resembles that depicted in Figure 3 where a concentrated source is located in the sediment a distance D below the sediment-water interface. The interface is represented as a horizontal, permeable boundary on which the pressure and temperature are both constant.

Figure 3. Concentrated Source Below a Permeable Boundary

For small Rayleigh number, the thermal and flow fields associated with the concentrated source can be determined approximately through superposition of the solutions to the linear system described by Equations (11) and (12), in the previous section. The boundary conditions at the interface are satisfied by locating an appropriate image of the concentrated source at the mirror image point above the boundary. The image is thus a source of negative strength (sink) located a distance D above the interface. The direction of gravity is also reversed in the image plane.

In Figures 4-7, non-dimensional representations are presented for solutions obtained by the superposition principle described above. In all cases, a permeable boundary on which pressure and temperature are constant has been assumed. Figure 4 depicts isotherms and streamlines for steady flow induced by a point source located a distance D below the interface. As an example of the transient behavior associated with a point source, isotherms and streamlines are plotted in Figure 5 for a Rayleigh number of 0.5 and a non-dimensional time of 0.1. For large time, the isotherm and streamline patterns approach those of Figure 4. In Figure 6, results for a line source of length H are presented. In this figure, the top of the line source is located a distance D below the interface. Finally, in Figure 7, results for a constant temperature sphere buried a distance D below the interface are presented.

Figure 4. Steady-State Streamlines and Isotherms for a Point Source Located Below a Permeable Boundary ($L=D$)

Figure 5b. Transient Isotherms for a Point Source Located Below a Permeable Boundary ($Ra=0.5$, $\tau=0.1$, $L=D$; $\theta_0 \times 10^2 = 1, 2, 3, 4, 5, 10, 20, 30, 40$)

Figure 5a. Transient Streamlines for a Point Source Located Below a Permeable Boundary. ($Ra=0.5$, $\tau=0.1$, $L=D$; $\Psi_1 \times 10^3 = 0.25, 0.5, 1, 2, 3, 4, 4.5$)

Figure 6. Steady-State Streamlines and Isotherms for a Line Source Located Below a Permeable Boundary ($L=H$, $D/H=2$)

Figure 7. Steady-State Streamlines and Isotherms for a Constant Temperature Sphere Located Below a Permeable Boundary ($L = a$, $D/a = 6$)

Note on Velocities

Explicit relations for the velocity components associated with a concentrated source can be obtained by differentiation of the formulas for the stream functions given in the previous section. The relations between velocity components and stream function in spherical and cylindrical polar coordinates are given by Equations (9) and (17), respectively. Once formulas for the velocities are derived for individual sources, superposition can be used to predict velocities for the geometries treated in this section. These results can then be used to predict the fluid particle paths produced by a particular concentrated source, thus providing an estimate of the maximum distance traversed by a fluid particle in a given time interval. This latter result is of some importance in evaluating the potential for convective transport of radionuclides, a topic considered briefly in the following section.

APPLICATION TO SUB-SEABED DISPOSAL OF NUCLEAR WASTE

As an example of the application of the ideas developed in the previous section, brief consideration will be given to the prediction of the flow field associated with the sub-seabed disposal of nuclear waste. Currently, it is conjectured that such a disposal scheme would consist of emplacing a cylindrical canister of nuclear waste material at a depth of approximately 30 m below the sediment-water interface. Suggested canister dimensions are 3 m in length and 0.3 m in diameter. Thermal considerations

for the canister design require the initial thermal output to be no greater than 1.5 kW. A generic disposal site, located in the Central North Pacific is currently under study. The water depth and bottom temperature in this region are approximately 6000 m and 1.5°C, respectively.

Referring to Figure 3, it is assumed that the situation described above can be represented by the transient solution for a point source located a given distance below the sediment-water interface. Using current estimates for the thermophysical properties of the sediment, an initial Rayleigh number of approximately 10^{-3} is predicted. The condition of small Rayleigh number, required by the theory, is thus easily satisfied. For a burial time of one year, the corresponding non-dimensional time τ is approximately 4.8×10^{15} . Assuming that the power output remains constant over the time period of interest, the associated streamline pattern at the end of one year is illustrated in Figure 8. Thermal properties are such that, at a distance of 3 m from the source, the temperature rise is only approximately 5°C. Hence the thermal field is relatively uninteresting and is not reproduced.

Figure 8. Transient Streamlines at One Year for Sub-Seabed Disposal of Nuclear Waste. ($Ra = 10^{-3}$, $\tau = 4.8 \times 10^{15}$, $L = D$; $\psi_1 \times 10^{-4} = 1, 2, 3, 4, 5, 6, 8, 10, 12, 14$)

Analyses using models such as the one just described can provide useful information for studies of the transport of radionuclides inadvertently released from emplaced canisters. In general, the transport of radionuclides in a fluid-saturated porous medium involves the four fundamental processes: convection, diffusion-dispersion, sorption, and radioactive decay. Assuming only weak concentrations of radionuclides in the pore water, the analysis of this section can provide estimates of the fluid velocity necessary to evaluate the convective transport. If the sorption process is temperature dependent, then predictions of the thermal field based on simple models will also prove useful.

The analyses discussed apply only to regions sufficiently far removed from the thermal source so that the physical processes are relatively unaffected by the geometry of the canister. Indications are that this distance need be no greater than a few canister lengths.

DISCUSSION

Subject to the small Rayleigh number limit, $Ra \rightarrow 0$, solutions have been presented which describe the thermal and flow fields produced by an isolated, concentrated, thermal source in a fluid-saturated porous medium. A variety of concentrated sources were considered. All solutions presented were obtained by retaining only the leading terms in expansions of the dependent variables in power series in the Rayleigh number, resulting in a system of linear partial differential equations for the description of the processes involved.

The linearity of the basic system allowed the use of superposition to obtain solutions for concentrated sources embedded in a semi-infinite region below a permeable boundary on which the pressure and temperature were held constant. This particular geometry was used as a model for the sub-seabed disposal of nuclear waste. Although attention was focused on a particular geometry in this paper, the principle of superposition can be used in conjunction with the various fundamental solutions to provide descriptions for a variety of geometries.

Aside from the assumption of small Rayleigh number, the assumptions most likely to introduce errors into the analysis are those associated with the Boussinesq approximation and the assumed rigidity of the porous matrix. The rapid heating of a liquid confined in a rigid porous matrix of low permeability can actually produce a rather high transient pore pressure⁷. As a result of the assumptions invoked, this behavior is not evidenced by the solutions presented in this paper. If the porous matrix is composed of clay particles, as is the case for marine sediments, then it is likely that some local deformation of the matrix will occur in regions of high heating rates. The resulting deformation need not necessarily be large since only a small deformation is required to relieve the pressure in a liquid-saturated

porous medium. Some investigators (e.g., Chavez and Dawson⁸) have suggested that it is possible for certain deformable porous media to deform continuously in response to local heating, thereby providing a mechanism for the movement of an emplaced container of thermally active nuclear waste. However, questions regarding the deformational behavior of marine sediments cannot be answered conclusively until the rheological properties of marine sediments have been accurately determined. A calculational procedure must then be developed which properly accounts for the anticipated behavior.

Additional comments are perhaps in order regarding the applicability of the results, for small but finite values of the Rayleigh number. For a point source embedded in an infinite porous medium, Hickox and Watts have shown that the thermal field is relatively unaffected by convection for Rayleigh numbers less than unity. Hence, the results of this paper are expected to provide accurate descriptions for natural convective flows so long as the Rayleigh number remains less than unity. For the sub-seabed disposal of radioactive waste, a Rayleigh number of only 10^{-3} is anticipated.

Hodgkinson has indicated that Rayleigh numbers on the order of 10^{-2} are expected for disposal of radioactive wastes in a hard rock depository. Hence, it is expected that the current results may find application in the analysis of proposed nuclear waste disposal schemes other than the one treated in this paper. Also, the possibility of applications in the analysis of geothermal systems should not be overlooked.

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REFERENCES

1. Bishop, W. P. and Hollister, C. D., "Seabed Disposal--Where to Look," Nuclear Technology, Vol. 24, 1974, pp. 425-443.
2. Yamamoto, K., "Natural Convection About a Heated Sphere in a Porous Medium," J. Phy. Soc. Japan, Vol. 37, No. 4, 1974, pp. 1164-1166.
3. Hickox, C. E., "Steady Thermal Convection at Low Rayleigh Number from Concentrated Sources in Porous Media," Report SAND77-1529, Sandia National Laboratories, Albuquerque, NM, 1977.
4. Bejan, A., "Natural Convection in an Infinite Porous Medium with a Concentrated Heat Source," J. Fluid Mech., Vol. 89, Part 1, 1978, pp. 97-107.
5. Hodgkinson, D. P., "A Mathematical Model for Hydrothermal Convection Around a Radioactive Waste Depository in Hard Rock,"

Report AERE-R9149, AERE Harwell, Oxfordshire, July, 1979.

6. Hickox, C. E. and Watts, H. A., "Steady Thermal Convection from a Concentrated Source in a Porous Medium," J. Heat Trans., V. 102, N. 2, May 1980, p. 248.
7. Eaton, R. R., et al., "Calculated Hydrogeologic Pressure and Temperatures Resulting from Radioactive Waste in the Eleana Argillite," Proc. International Sym. on the Scientific Basis for Nuclear Waste Management, Materials Res. Soc., Plenum Press, March, 1980.
8. Chavez, P. F., and Dawson, P. R., "Thermally Induced Motion of Marine Sediments Resulting from Disposal of Radioactive Wastes," Sandia National Laboratories Report (in press), Albuquerque, NM, 1980.

THERMAL, CHEMICAL, AND MASS-TRANSPORT PROCESSES INDUCED IN
ABYSSAL SEDIMENTS BY THE EMPLACEMENT OF NUCLEAR WASTE:
EXPERIMENTAL AND MODELING RESULTS

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ABSTRACT

In this paper, we discuss the current status of heat and mass transport studies in marine red clay sediments being considered as a nuclear waste isolation medium. Both analytical and experimental studies are reviewed. Calculations based on numerical models indicate that for a maximum allowable sediment/canister interface temperature of 200°C to 250°C, the sediment can absorb about 1.5 kW initial power from waste in a 3 m long by 0.3 m diameter canister buried 30 m in the sediment. The resulting fluid displacement due to convection is found to be small, less than 1 m. Laboratory studies of the geochemical effects induced by heating sediment/seawater mixtures indicate that the canister and waste form must be designed to resist a hot, acid (pH 3 to 4) oxidizing environment. Since the thermally altered sediment volume of about 5.5 m³ is small relative to the sediment volume overlying the canister, the acid and oxidizing conditions are not anticipated to effect the properties of the far field. Using sorption coefficient correlations from experiments discussed in the paper,

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the migration of four nuclides (^{239}Pu , ^{137}Cs , ^{129}I , and ^{99}Tc) were computed for a canister buried 30 m deep in a 60 m thick red clay sediment layer. It was found that the ^{239}Pu and ^{137}Cs , which migrate as cations and have high distribution coefficients, are essentially completely contained in the sediments. The anionic species, ^{129}I and ^{99}Tc , which have relatively low distribution coefficients broke through the 30 m of sediment in about 5000 years. The resultant peak injection rates of $4.6 \times 10^{-5} \text{ } \mu\text{Ci/year-m}^2$ for ^{129}I and $1.6 \times 10^{-2} \text{ } \mu\text{Ci/year-m}^2$ for ^{99}Tc were found to be less than the natural radioactive flux of ^{226}Ra (3.5 to $8.8 \times 10^{-4} \text{ } \mu\text{Ci/year-m}^2$) and ^{222}Rn (0.26 to $0.88 \text{ } \mu\text{Ci/year-m}^2$).

INTRODUCTION

Participants in the United States Sub-Seabed Disposal Program are investigating the technical and environmental feasibility of emplacement of nuclear waste in the deep ocean sediments as a possible disposal option [Macleish, 1977; and Anderson, 1979]. Of particular interest are illite-rich and smectite-rich red clays located in oceanic mid-plate, low current regions between 4000 and 6000 m depth. The clays in the regions of interest are attractive [Talbert, 1979A; and Talbert, 1979B] in that they have good cation retention characteristics, low permeability, are vertically and laterally uniform over large areas, and are relatively plastic, promoting self-healing. Dating studies of a 24 m core from the Pacific study area show a continuous depositional record for about 76 million years, demonstrating extremely good geologic stability.

There is nothing at this time to indicate that these clays, in a properly selected oceanic location, do not have the properties necessary for effective isolation of nuclear waste.

For the design of a disposal system, it is necessary to understand and be able to model and predict the thermal, chemical, and mass transport processes induced in the sediment by emplacement of a canister containing radioactive waste. Specifically, predictions of waste, canister, and sediment temperatures, sediment pore pressures, pore water motion, chemical interactions between the pore water/sediment/canister/waste form, radionuclide migration, sediment structural response, and nuclide biological concentration are necessary to define problem areas and propose solutions, develop an optimum design, and assure that the system is safe. To this end, a set of computer models are being developed. At present, model development efforts embody: thermal energy transport and pore fluid motion, sediment thermochemistry, radionuclide migration, canister corrosion and waste form leaching, canister and sediment motion, and ocean/biological transport of nuclides.

The model development efforts are being supplied with basic data and guidance by active laboratory and field experimental programs. These experimental programs cover aspects of the program ranging from sediment chemical, thermal, and structural properties [Seyfried, 1979; Fried, 1980; Krumhansl, 1979; and Silva, 1979] to canister corrosion [Braithwaite, 1979], ocean biology [Gomez, 1980], and an in situ thermal,

fluid, and mass transport test [McVey, 1980]. The program philosophy is to develop a theory and model, obtain required input data from laboratory or field experiments, and evaluate the model predictions with field experiment data. If required, the theory, model, or input data will be refined or modified until an accurate prediction is obtained.

The purpose of this paper is to summarize the results and conclusions, to date, of the thermal and fluid analysis, the geochemical studies, the radionuclide sorption and chemical stability experiments, and the radionuclide migration calculations. It must be emphasized that these studies are ongoing and development programs that have not yet reached final conclusions. It is appropriate, however, to discuss progress since the results are being used to guide decisions made by the Sub-Seabed Disposal Program management.

Thermal and Fluid Transport Analysis

A transient, non-linear, two-dimensional (planar or axisymmetric) finite element computer code (MARIAH), incorporating the Darcy equation and Boussinesq* approximation, has been developed to compute the heat and incompressible fluid transport through a rigid, anisotropic porous matrix. The governing continuity, momentum, and energy equations, along with appropriate initial/boundary conditions for pressure and temperature were converted by a method of weighted residuals into a form suitable for finite element application. The details of the

*The fluid is incompressible except insofar as the thermal expansion produces a buoyancy force. This assumption is standard in natural convection problems and has been used by many authors in addressing problems of natural convection in porous media.

code development and users instructions are provided by Gartling and Hickox [1980A, 1980B].

The MARIAH code has been used to study the heat transfer from waste canisters emplaced in seabed sediment. As a reference problem, the waste was assumed to be emplaced in undisturbed sediment such that the center of the canister was 30 m deep in a 60 m thick layer of sediment (Figure 1). A 1.5 HFU*, geothermal heat flux was applied to the impermeable lower boundary. The outer boundary at 60 m radius was also impermeable and assumed insulated. This distance is greater than the thermal penetration in the 100 years for which the problem was run. The top boundary was at a constant pressure of 600 bars corresponding to a depth of about 6000 m. A constant temperature of 1.5°C, equal to the water temperature, was imposed on the upper boundary. The initial temperature distribution in the sediment was determined by the steady state geothermal heat flux and the 1.5°C surface temperature.

The canister power output is a function of time and waste type. In this study, calculations were made for a reprocessed high level waste (HLW) and spent fuel (SF). The HLW was assumed to result from a uranium only reprocessing cycle in order to leave the plutonium in the waste for the long term heating and nuclide migration problem. The HLW was assumed to be emplaced in the sediment 10 years after reprocessing, with reprocessing occurring 160 days out of core. The SF was assumed

*Heat Flux Unit: $1 \text{ HFU} = 1 \times 10^{-6} \text{ cal/cm}^2\text{s}$.

to be a single pressurized water reactor spent fuel assembly emplaced 10 years and 160 days out of core. The initial thermal half lives are about 30 and 40 years, respectively, for the HLW and SF. Isotope inventories for the decay calculation were determined by use of the ORIGEN [Bell, 1973] code.

Material properties used in the analysis are given in Table 1. For sediment, the thermal properties are input for the solid and fluid components and the effective properties computed from mixture laws confirmed by comparison with the data of Krumhansl and Hadley [1979]. Pore fluid properties are for pure water. Appropriate ranges of sediment porosity and permeability were obtained from the data reported by Silva [Talbert, 1979A; Talbert, 1979B; Silva, 1979].

The MARIAH code was used with the foregoing input to compute the maximum sediment/canister interface temperature as a function of initial waste thermal power with the reference geometry in Figure 1. The results are summarized by the curve in Figure 2. The curve is applicable to both HLW and SF.

One of the program goals is to develop a canister that will contain the waste for several thermal half-lives. The environment controlling canister life develops through the physical and chemical changes induced by heating of the sediment/seawater mixture. As will be discussed in more detail in the next section, heating of the seawater/sediment mixture produces a decrease in pH resulting in a distinctly acid condition. The solution becomes more strongly acid and oxidizing as temperature increases. Based on this consideration, Krumhansl [1979] and Braithwaite [1979] recommend limiting the

maximum canister temperature to "significantly below 300°C." Although the final studies are not complete, it presently appears that 200°C to 250°C may be reasonable. For this temperature range, Figure 2 gives a maximum desirable canister power at emplacement of 1.3 to 1.5 kW.

Temperature histories at seven locations radially outward from the canister are given in Figure 3 for 1.5 kW, HLW. Comparable SF temperature curves are shown in Figure 4 for a canistered reactor fuel assembly with 0.58 kW initial power. The surface temperatures peak quite rapidly (in about 1 to 2 years) and then fall off with a half-maximum equal to the initial waste thermal half-life of about 30 years for HLW and 40 years for SF. The peak temperatures are about 220°C for HLW and a relatively benign 48°C for the canistered SF assembly.

The convective velocity histories for four locations corresponding to temperature locations in Figure 3 are shown in Figure 5 for the HLW calculations. Since the convection is thermally driven, the velocity curves have essentially the same character as the temperature curves, peak at about 1 to 2 years and decay with a half-maximum about equal to the waste half-life. For HLW, the convective velocity decreased from a maximum of 0.02 m/yr to about the same magnitude as the velocity due to molecular diffusion after about 25 years. In the case of SF, of 0.58 kW initial power, the maximum convective velocity is about the same as the velocity due to molecular diffusion. It may be inferred from the velocity history that the total convective contribution to the displacement of the water molecules is small, less than 1 metre. The low velocity is,

of course, due to the low permeability of the seabed sediment. Because of the low velocity, the contribution of convection to both energy and nuclide transport is expected to be quite small. The relatively small effect of convection on the energy transport was demonstrated by Hickox [1979] who showed analytically that for Rayleigh numbers* less than about 0.1, the temperature field is dominated by conduction. In the present case, the Rayleigh number is in the range 10^{-3} to 10^{-4} , depending on temperature.

Isotherm patterns for the 1.5 kW, HLW at 1 and 10 years are shown in Figure 6. It is noted that the maximum extent of the 100°C isotherm, the temperature below which it now appears that significant hydrothermal alteration of the sediment will not occur, is less than about 0.8 metre from the canister. The region within the 100°C isotherm, termed the near field, is a small volume (about 5.5 m³) relative to the 30 m of sediment above the canister. Thus, although the chemical environment within the 100°C isotherm may be significantly altered, the effects are limited in extent. Krumhansl [1979] points out that less than about 2 cubic metres of unheated sediment will neutralize the acid produced during the thermal period. As a result, the ongoing geochemical alteration studies are primarily concentrating on defining the environment for which the canister and waste form must be designed. It is also apparent from Figures 3 and 4 that thermally driven effects last for a relatively short time, e.g., the canister surface temperature is less than 100°C in 40 years for the HLW case and never exceeds 100°C for the SF case.

*Ratio of buoyancy induced effect to thermal diffusion.

With these considerations in mind, it is appropriate to review the studies of the thermally induced geochemical environment.

Sediment/Seawater Interaction Experiments

In an attempt to make a realistic appraisal of the geochemical environment in the vicinity of the buried waste canister (i.e., near field), sediments retrieved from a Central North Pacific study site (MPG I, about 31°N - 158°W) have been reacted with seawater at 300°C, 500 bars and a sediment/seawater ratio of 0.2. Additional studies are in progress at a temperature of 200°C. Characterization of the near field chemical environment is particularly important to understanding of canister and waste form stability.

Sediment/seawater interaction experiments were performed using "Dickson" hydrothermal apparatus with modifications described by Seyfried, et al., [1979]. An advantage to this type of equipment is that the aqueous phase can be sampled during the experiment. Thus, by monitoring the change in solution chemistry, reaction progress can be assessed allowing one to qualitatively, and at times quantitatively, infer mechanisms of sediment alteration.

Although many experiments have been performed heretofore, only two of these will be discussed at this time: (1) illite, quartz, Fe-chlorite-seawater interreaction, and (2) smectite-seawater interaction. In this report, we refer to illite-quartz-Fe chlorite sediment as sediment-A and the smectite-rich sediment as sediment-B. These sediments reflect a mineralogy analogous to that constituting near surface

(sediment-A) and relatively deep (sediment-B) sediments of cores taken from MPG I [Hollister, 1979]. Thus, determining their reactivity in seawater at elevated temperatures is crucial to an accurate understanding of the near field chemical environment.

The change in concentration of the major, minor, and trace element chemistry of seawater after reaction with the illite and smectite-rich sediments discussed above is revealed in Tables 2 and 3. For brevity, only the chemistry of the solutions from the final high temperature sample is reproduced here.

In general, the major element chemistry of seawater (Ca, Mg, K, Sr, SO_4 , Cl, and Na) was similarly modified during both experiments (Table 2). The concentration of Mg, Ca, Sr, and SO_4 decreased, that of K and Na increased, while the concentration of Cl remained constant or increased slightly. Concomitantly, $\text{SiO}_2(\text{aq})$ increased sharply, then decreased slowly, and pH decreased to values between 2.8 and approximately 4.0. In response to the low pH, heavy metals (e.g., Fe, Mn, Zn, Ni, Co, Cr) enter solution (Table 3). The greater concentration of Fe and Mn in solution during sediment-A/seawater interaction than during sediment-B/seawater interaction is conspicuous, while the reverse is true for Ni, Co, Cr, and Au. We will return to this point later since it is of particular importance to the near field chemical environment.

Alteration products formed during these experiments are in excellent agreement with the observed changes in the aqueous

phase. For example, the Fe-chlorite component of sediment-A has been replaced, in part, by Mg-chlorite, while the abundance of quartz and illite decreased slightly. Sediment-B/ seawater interaction resulted in a more profound modification, and was characterized by the formation of a well defined trioctahedral smectite. A significant portion of this smectite may have been derived from amorphous material, which constituted a significant portion of sediment-B. Anhydrite was a minor alteration product of both experiments.

The generation of a relatively acid-rich fluid during these experiments is conspicuous and fundamentally attributable to two processes: (1) Mg-hydroxysulfate formation, and (2) hydrous Mg-silicate formation. Mg-hydroxysulfate formation occurs whenever seawater is heated above 250°C at 500 bars [Bischoff, 1978], an event which can be illustrated by the following reaction:

where $3 \leq n \leq 5$. In contrast, hydrous Mg-silicate formation, in the form of talc, talc layers in chlorite or smectite, requires significant concentrations of $\text{SiO}_2(\text{aq})$ in solution. A generalized reaction describing H^+ generation owing to Mg-silicate formation is as follows:

That smectite and Mg-chlorite were identified as alteration products of these experiments is consistent with reaction (2) and the observed influx of H^+ .

Whether or not acidity is maintained critically depends on the bulk mineralogy of the sediment. Sediment containing appreciable quantities of anhydrous components such as feldspar minerals and volcanic glass or carbonate minerals can effectively "titrate" the acidity and raise the pH to near or above neutrality (at the temperature of the experiment). In contrast, sediments containing clay minerals (especially smectite) and quartz are relatively stable in the distinctly acid seawater composition at 300°C. For example, using the consistent set of thermodynamic data for minerals, ions, and gases, which has been calculated and tabulated recently by Helgeson, et al., [1979], a mineral activity diagram has been constructed for the $\text{MgO-SiO}_2\text{-Al}_2\text{O}_3\text{-H}_2\text{O}$ system (Figure 7). On this diagram, we have plotted relative positions of solutions sampled from the present experiments. Activities (a_i) of aqueous species at 300°C were calculated using the computer program SOLVEQ [Reed, 1977].

$a_{\text{Mg}^{++}}/a_{\text{H}^+}^2$ ratios versus $a_{\text{SiO}_2(\text{aq})}$ of solutions derived from interaction with sediment-A and sediment-B plot in the Mg-saponite and Mg-beidellite stability fields, respectively (Figure 7). The higher $a_{\text{SiO}_2(\text{aq})}$ values of solutions from sediment-B/seawater interaction possibly reflect the presence of more readily soluble amorphous material. That these solutions and those from sediment-A/seawater interaction are characterized by $a_{\text{SiO}_2(\text{aq})}$ values significantly greater than that in equilibrium with quartz implies dissolution of unstable SiO_2 -rich components in the sediments exceed precipitation of

phases such as quartz. Nevertheless, that solutions from both experiments consistently plot in the smectite (saponite, beidellite) stability field provides evidence supporting the stability of smectite phases in distinctly acid fluids. Thus, a smectite component in sediments reacted with seawater at elevated temperatures and pressures is by itself incapable of neutralizing significant amounts of acidity and, in fact, the formation or recrystallization of this phase may contribute acidity owing to Mg removal from solution.

In addition to reactions which remove Mg from seawater, and create hydrogen ions (H^+), the redox potential of the sediments may prove to be of profound importance to the near field chemical environment and radionuclide mobility. The sediments used for the present experiments contain abundant iron and manganese. However, the relative amounts and valence states of these species are a function of sediment mineralogy. For example, chemical analyses of sediments-A and B show that the quartz-illite-Fe-chlorite assemblage (A) contains less Fe and Mn than the smectite-rich sediment-B (Table 4). Furthermore, Fe^{3+}/Fe^{2+} and Mn^{4+}/Mn^{2+} ratios of sediments-A and B (unpublished data) reveal that sediment-B contains significantly greater amounts of the higher valence forms of iron and manganese than does sediment-A. Preliminary estimates indicate that virtually all of the iron and approximately 90% of the manganese in sediment-B is Fe^{3+} and Mn^{4+} , respectively. In contrast, sediment-A contains significant Fe^{2+} and only 30% of the manganese is Mn^{4+} . Thus, sediment-B is distinctly more

oxidized than the dominantly detrital sediment-A. What are the implications of sediment redox potential to radionuclide mobility?

Table 3 reveals that seawater reacted with the smectite-rich sediment is characterized by significant concentrations of gold (Au) in solution; the Au being dissolved from the reaction cell. It is important to note, however, that no Au dissolved during quartz, illite, Fe-chlorite/seawater interaction. Considering that Au is virtually inert in most chemical environments, even at high temperatures, Au solubility (88.5 ppm) during the former experiment is striking, and defines a particularly severe chemical environment (acidic and extremely oxidizing). We believe the oxidizing agent in this case is a Mn^{4+} -rich component of the sediment which, as mentioned, is abundantly present. Thus, the following reaction can be written:

where the dominant aqueous species of gold in acidic, chlorite-rich solution is AuCl_2^- [Helgeson, 1968]. This reaction predicts high gold concentrations in acidic solutions reacted with Mn^{4+} -rich sediments and conversely low Au concentrations in solutions having a higher pH and access to Mn^{2+} -rich sediments. The influx of Mn^{2+} to solution during sediment-A/seawater interaction, in effect, drives the above reaction to the left and accounts for the lack of Au dissolution. In contrast, sediment-B, containing abundant Mn^{4+} , drives the above reaction to the right. Thus, a substantial portion of the Mn (Mn^{2+}) which enters solution during sediment-B/seawater

interaction is derived from reduction of some of the MnO_2 contained within this sediment.

The similarity between the high temperature solubility of gold and that of various radionuclides is difficult to estimate owing to a lack of thermochemical data. However, from thermochemical data at 25°C and 1 atmosphere pressure, it appears that most transuranic species are particularly soluble in an acidic oxidizing milieu [Brookins, 1978, and reference therein]. Thus, if these relations exist at higher temperatures as well, then sediments having high $\text{Fe}^{3+}/\text{Fe}^{2+}$ and especially $\text{Mn}^{4+}/\text{Mn}^{2+}$ ratios would be expected to be quite corrosive in the near field region. Thus, design of the canister and waste form require careful consideration of the local acidity levels and redox potential. The acidity level and redox potential will depend upon the detailed composition of the sediment at the chosen disposal site.

The reactions described above suggest that sediment pore waters in the immediate vicinity of a buried waste canister will be hot, acidic, and oxidizing. Although chemical reactions which dominate this environment must be understood for development of canister and waste form, they cannot and must not be extended, a priori, to the sediment/seawater system at lower temperatures. The canister and near field sediments will be contained by at least 20-25 m of overlying sediment which never attain temperatures greater than approximately 20°C. All experimental evidence to date indicates that sediments in this environment (far field) act as highly effective "sinks" for radionuclide species and H^+ and provide the major containment barrier against waste migration. It is thus appropriate

to emphasize low temperature experiments when investigating nuclide transport phenomena. This work is summarized in the following sections.

Radionuclide Transport

The transport of radionuclides through a two-phase (liquid-solid) medium such as the oceanic red clay sediments is described by the continuity equations for the bulk phases and for the fluxes across the interfaces between phases. For an incompressible solution-phase, the transport equation for a given nuclide can be reduced to a reasonably convenient form using the following assumptions:

- (1) The physical and chemical properties of the sediment can be considered continuous.
- (2) Local equilibrium exists between bulk phases.
- (3) "Surface diffusion" does not occur.
- (4) The solid matrix does not deform.

An equation for describing transport of dissolved radionuclides is then

$$\frac{\partial c}{\partial t} = -\nabla \cdot vc - \nabla \cdot J - \frac{\rho}{\epsilon} \frac{\partial Q}{\partial t} + R_j ,$$

where c is the interstitial solution-phase concentration of a dissolved nuclide; v is the interstitial mass-average fluid velocity; J is the interstitial nuclide flux relative to the mass average fluid velocity; ρ is the mass of solid matrix per unit volume of sediment; ϵ is the volume of solution per

per unit-volume of sediment; Q is the total nuclide concentration associated with the solid matrix and results from sorption, heterogeneous chemical reaction, and/or nuclear decay; and the R_j are terms representing rates of solution-phase nuclide production and/or depletion resulting from homogeneous chemical reaction and/or nuclear decay.

In order to evaluate and use this equation, values or expressions for v , ρ , ϵ , J , Q , and R_j are required. The fluid velocity field (v) may be computed by use of the MARIAH code [Gartling, 1980A and 1980B] while the material constants may be determined by laboratory evaluation [Talbert, 1979A and 1979B; Fried, 1980; and Silva, 1979]. The experimental and theoretical work underway to develop appropriate expressions for J , Q , and R_j include the following principal programs:

- (1) Analysis and quantitative description of important homogeneous and heterogeneous chemical reactions.
- (2) Analysis and quantitative description of important radionuclide sorption mechanisms.
- (3) The development of analytical models to describe the nuclide transport.

The details and current results from these programs are discussed below.

Analysis of Chemical Reactions

In modeling mass transfer of radionuclides through the abyssal red clays, a transport equation must be written for each of the nuclides' chemical species which will be present

in the sediment. For nuclides having multiple oxidation states, the equilibria and kinetics must be determined for transformation between oxidation states and for homogeneous or heterogeneous chemical reactions such as polymerization, precipitation, and complex formation with constituents of the sediment or interstitial solution. These data are used to define the expressions for the production and depletion terms, other than those resulting from sorption or nuclear decay, for the R_j and Q terms.

Actinide elements exhibit multiple oxidation states. Chemical studies being conducted by Argonne National Laboratory are focused on the relative stabilities of the oxidation states of the elements U, N_p , Pu, and Am under various experimental conditions. Experiments with plutonium were begun first [Fried, 1980]. The procedures and results from these experiments are briefly summarized below.

Artificial seawater samples and artificial seawater and smectite-rich sediment samples were contacted with plutonium solutions under anoxic conditions and the presence of air. Due to experiment configuration, pH and Eh could only be controlled in part of the experiments. The plutonium solutions were about 0.02 M, which permitted the use of spectrophotometric observations to determine and monitor changes in oxidation states. Plutonium (^{242}Pu) was prepared in pure oxidation states as the chloride.

The most important conclusion of these experiments is that the oxidation states of plutonium in solution are affected

by the radiolysis of water. Experiments in which ^{244}Cm , sufficient to increase the alpha activity by 10 to 100 times the ^{242}Pu activity, was added to distilled water, artificial seawater, or saturated brine solutions of Pu(III) found that the rate of oxidation of Pu(III) increased roughly in proportion to the added alpha activity. The initial oxidation of Pu(III) is relatively fast and exhibits pseudo first order kinetics. This rate of oxidation increase was observed under acidic and basic conditions and under anoxic conditions or in the presence of air. It appears that the net effect of the radiolysis of water is to both oxidize and reduce the Pu in a cyclic process of oxidation-reduction.

Pu(V) then disproportionates. The effects due to radiolysis of water may not be confined to plutonium. Neptunium, uranium, technetium, and iodine also could be affected.

The influence of radiolysis induced by the canister will be localized within a few canister diameters. Thus, significant radiolysis and the resultant changes in oxidation states are not expected to extend to the far field which is the major barrier. The change in oxidation states will be important in determining the species available for transport in the far field.

Analysis of Sorption Mechanisms

The purpose of the sorption studies is to provide data on the rate-of-change terms for the solid-phase concentration, Q ,

resulting from sorption of the various chemical species of each nuclide of interest. Although this work primarily addresses smectite-rich sediments, it is probably indicative of the behavior of most deep ocean sediments. Heath, et al., [1977] have summarized the available data on sorption distribution coefficient as a function of sediment type. They found that the sorption coefficients for the ions, ^{137}Cs , ^{90}Sr , ^{54}Mn , ^{59}Fe , ^{60}Co , ^{65}Zn , ^{95}Zr , ^{106}Ru , ^{144}Cs , ^{147}Pm , ^{239}Pu , ^{240}Pu , although different for each ion, varied by less than a factor of 10 from pelagic clay to calcareous oozes.

In addition, Heath [1977] conducted a detailed investigation of the variation of Eu distribution coefficients as a function of concentration, temperature, and depth into the sediment using samples from core LL44-GPC3 taken from the central North Pacific at $30^{\circ} 19.9' \text{N}$, $157^{\circ} 49.4' \text{W}$. The data are shown on Figure 8 taken from Talbert [1979B]. In general, the effects on K_D due to concentration changes are much greater than the changes due either to temperature or depth. Similar trends were reported by Heath for thorium experiments in MacLeish [1977].

Sorption of the actinide elements is generally considered to be of principal concern. However, before pursuing an extensive experimental program involving the actinides, a preliminary investigation was conducted to examine the sorption of several nuclides having much less complicated solution chemistries [Erickson, 1979]. The generalizations developed

to describe sorption of those nuclides were then used to plan the initial actinide experiments [Erickson, 1980].

The initial sorption experiments were done using 0.68 N NaCl solutions, rather than artificial seawater, in order to reduce the competing chemical reactions which might complicate analysis of the experimental results. Sorption equilibrium data were obtained from batch equilibration experiments at 4°C and 11°C in which samples of the clay at atmospheric pressure were contacted with 0.68 N NaCl solutions containing a single nuclide of interest. Samples of the clay were dialyzed, vacuum dried, and then stored in sealed containers prior to use. The pH of the solutions were adjusted by adding small amounts of sodium bicarbonate, boric acid, or hydrochloric acid solutions. In some experiments, the hydrous iron and manganese oxides were removed from the clay.

For purposes of mathematical modeling, the most convenient expression for representing sorption equilibrium data is the distribution coefficient K_D defined by

$$K_D = \frac{\text{solid phase equilibrium concentration}}{\text{solution phase equilibrium concentration}}$$

For a given sorbent, the distribution coefficients for each chemical species is a function of temperature, pressure, the concentration of the species of interest, and the concentrations of all other competing species.

In the preliminary investigation mentioned above, distribution coefficients for the sorption of rubidium, cesium, strontium, barium, silver, cadmium, cerium, promethium,

europium, and gadolinium were evaluated as functions of nuclide concentration. Some of the data indicating typical trends are shown in Figures 9 through 11. The coefficients generally varied from about 10 to 10^4 ml/g or greater as the solution-phase nuclide concentration varied from about 10^{-2} to 10^{-7} M or less, respectively. These results appeared consistent with data for other oceanic sediments and for similar clay minerals found within the continental United States [Erickson, 1979]. It was further found that the distribution coefficients depended little on the solution pH within the range of 6 to 8. At pH values on the order of 2.7, the coefficients for cesium were still relatively unaffected; however, those for barium, silver, and europium were greatly diminished relative to the corresponding coefficients at solution pH values of 6 to 8. Also, some additional experiments involving cesium and barium were conducted using clay which had been leached to remove the hydrous iron and manganese oxides. Again, the cesium coefficients appeared relatively unaffected, but the barium coefficients were greatly diminished relative to the corresponding coefficients obtained with the "natural" clay.

Based on the above results, it appeared that the sorption distribution coefficients for each nuclide studied resulted from at least two separate sorption mechanisms. In all cases, one mechanism appears to be an ion-exchange phenomenon associated with the silicate phases and appears to have a relatively much larger sorption capacity and smaller equilibrium constant than the other mechanism. For cesium, and probably rubidium, the second mechanism is not clear but appears to also be associated with the silicates; however, for the other

elements studied, the second mechanisms appear to be associated with the hydrous metallic oxide phases.

Following the above preliminary investigation, sorption experiments were run with technetium, uranium, plutonium, americium, and curium. For the technetium experiments, ^{99}Tc was used and was initially added as the pertechnetate anion. For the actinide experiments, the oxidation states of the uranium, plutonium, americium, and curium were not determined. However, as supplied by the manufacturer, the oxidation state of the uranium should have been (VI), of the plutonium probably predominately (IV), and of the americium and curium probably (III).

The samples for the technetium experiments were exposed to air during preparation and, therefore, the experiments could be considered to have been done under mildly oxidizing conditions. The distribution coefficients for technetium were essentially zero at solution pH values of 2.6 and 8.2.

At solution-phase nuclide concentrations of about 10^{-9} m and less and pH values of about 6.9, the distribution coefficients for plutonium were on the order of 3×10^3 ml/g and the coefficients for uranium, americium, and curium were on the order of 10^5 or greater (see Figure 10). The actinide sorption data, at pH values of about 7 and 2.7, were obtained using identically prepared samples, except for pH adjustment. Therefore, although the pH and concentration dependence of the actinide distribution coefficients cannot be independently obtained from Figure 10, it appears that the distribution coefficients for uranium, americium, and curium show a

pH dependence similar to the lanthanides and alkaline earths. The distribution coefficients for plutonium also appear dependent on solution pH but not as strongly as the other actinides studied. Also, some additional experiments with uranium were done with clay which had been leached to remove hydrous iron and manganese oxides. The resulting distribution coefficients at solution pH values of 7.6 and 8.2 were essentially zero. Furthermore, the uranium was subsequently removed from the solution by co-precipitation with $\text{Fe}(\text{OH})_3$.

The above results appear to indicate that the same mechanisms which dominate sorption of the lanthanides and alkaline earths also dominate sorption of the actinides, particularly the mechanisms associated with the hydrous metallic oxide phases.

Future sorption work will include evaluation of distribution coefficients in artificial seawater solutions, at elevated temperatures and pressures, and in the presence of competing nuclides. Additional work will also be attempted in order to more clearly define the effects of hydrolysis observed during the initial sorption studies.

Nuclide Migration Calculations

To assess the suitability of the seabed sediment as a nuclear waste containment medium, it is necessary to determine the time required for nuclides that may be released from the canister to reach the sediment surface and to know the quantity and rate of nuclide injection into the seawater. To this end, methods of computing the radionuclide migration are being developed.

A closed form analytical approach was developed by Nuttall, et al., [1980]. The region far from the canister is modeled by an unsteady isothermal diffusion model. Analytical solutions for transient concentration profiles, ion flux, and ion discharge rate are derived. The solutions are presented in non-dimensional form and are useful in sensitivity and systems analysis studies for assessing the influence of parameters such as burial depth, etc.

Details of a computer code, IONMIG, are presented by Russo [to be published]. The two-dimensional planar or axisymmetric code solves a species transport equation including convection, molecular diffusion, axial and transverse dispersion, concentration-dependent sorption, and radioactive decay. In the formulation, it is assumed that the radionuclide concentration remains dilute enough such that fluid properties are not altered and that sorption is non-selective instantaneous, linear, reversible, and thus describable by an empirically determined equilibrium coefficient which may be a function of concentration. The velocity and temperature fields are input from the MARIAH calculations.

For this analysis, the equilibrium distribution coefficient, K_D , was written as a function of species concentration in the form

$$K_D = \frac{k_2}{1 + k_1 C} + \frac{k_4}{1 + k_3 C}$$

Data for the K_D were taken from the experiments discussed in the previous section. The coefficients for the equation are given in Table 6.

The computational domain is a region necessarily of the same configuration as shown in Figure 1 since temperature and velocity from the MARIAH calculations were used in IONMIG. The side and bottom boundaries are impermeable to the nuclides. At the ocean/sediment interface, it is assumed that nuclides are removed as they are introduced. The concentrations and sources are initially specified throughout the field and the code computes the subsequent time variations.

The IONMIG code has been used to make initial breakthrough, concentration distribution and surface injection estimates for the HLW reference study case previously described. For the present, it is assumed that the majority of the radioisotope inventory in nuclear waste will migrate as cations. Pu and Cs were chosen as being typical: ^{239}Pu -- typical of the trans-uranic elements with long half-life and high K_D ; ^{137}Cs -- typical of fission products with a relatively short half-life and moderate K_D . In addition, since concern has been expressed regarding the behavior of anionic species: ^{129}I -- a long half-life element with low K_D , and ^{99}Tc -- a fission product with long half-life and low K_D , were included for reference purposes. ^{129}I is present in SF or liquid waste but usually not in solidified HLW since it volatilizes during processing. In spite of the fact that the specific activity and relative toxicity are low, it is not desirable to release significant amounts of ^{129}I . Hence, the isotope must be isolated and disposed of in some manner; possibly in the same geologic repository that receives the HLW. Thus, it may pose essentially the same containment problem as if included with the HLW.

The nuclides considered in the decay chain with each of the four elements are listed in Table 5. The initial canister inventories were taken from the ORIGEN [Bell, 1973] calculations made for the thermal source terms. Additional data used in the calculations are given in Table 6. Data given by Li and Gregory [1974] were used in estimating the value for the molecular diffusion coefficient. For lack of more complete data, this coefficient was assumed the same for each species. In the absence of complete data, the dispersivity coefficients were estimated. Rough estimates of dispersivity are acceptable since the velocity is very low and decays to zero early in the problem making dispersion a negligible effect.

In defining the source term for the IONMIG calculations, the canister inventory of each element was assumed to be initially uniformly distributed within a 5 m long by 2.0 m radius cylinder about the canister. This is because the near-field hydrothermal and chemical effects are so complex and presently incompletely defined (see preceding two sections) that this set of initial calculations neglects the thermally altered zone and assumes that the migrating species are injected outside of the "near-field." This is reasonable since the region is relatively small and the time for thermal decay and for heat dissipation is small relative to the migration time. Any time delay required for the canister to corrode and for the material to leach out of the waste form was neglected.

Calculations for ^{137}Cs were run out to 3500 years. Little motion took place prior to complete decay of the ^{137}Cs into ^{137}Ba . Since the half-life of ^{137}Cs is only 30 years, virtually all the ^{137}Cs decayed in place, and essentially none reached the surface. The same behavior is expected of other short-lived species with moderate values of K_D such as ^{90}Sr .

For long-lived isotopes having a high K_D , such as ^{239}Pu , the situation is similar except the time scales are large. Figure 12 shows the distribution at 100,000 years of ^{239}Pu over a vertical symmetry plane containing the buried canister. Although 4.1 half-lives of ^{239}Pu have elapsed almost one-third of the original inventory of plutonium remains because of the decay of ^{243}Am to ^{239}Np and then to ^{239}Pu . In this calculation, the Am and Np were assumed to have the same K_D as the plutonium. Data currently available indicate this is a reasonable assumption for Am but may be non-conservative for Np. The migration rate of plutonium is so slow (a few metres per 100,000 years) that even after 10^6 years when the concentration had decayed to 10^{-10} g per canister, breakthrough (when 1% of the remaining concentration crosses the surface) does not occur.

For nuclides having long half-life and very small K_D , such as ^{129}I and ^{99}Tc , the behavior is quite different. Without the retarding action of sorption, these substances diffuse through the sediment and begin to enter the benthic boundary layer in about 5000 years. Figure 13 shows the per canister release rate of radioactivity associated with ^{129}I as a function of time. The release rate reaches a peak of 0.52 $\mu\text{Ci}/\text{year}$ at

about 15,000 years and then declines to approximately one-fourth of that value in 100,000 years. ^{129}I has a low specific activity, decaying to ^{129}Xe by beta decay with a half-life of 15.9 million years. Figure 14 shows a similar per canister release rate profile for ^{99}Tc . The peak value of 180 $\mu\text{Ci}/\text{year}$ is much higher than that for ^{129}I because both the initial canister inventory and the specific activity of ^{99}Tc , which beta decays to ^{99}Ru with a half-life of 213,000 years, are higher.

Based on these calculations, it appears that but a miniscule fraction of the radioisotopes migrating as cations will ever cross the ocean/sediment interface. This is not the case for Tc and I, elements which will travel in solution as anions. Additional efforts, perhaps involving the development of an appropriate overpack canister or selection of a site with an appropriate layering of clays that sorb both cations and anions may be required to reduce anionic release rate to values that are comparable to the cationic release rates.

Even for the worst case, however, (which we do not advocate) the predicted release rates of ^{129}I and ^{99}Tc can be put somewhat into perspective by comparing them to the natural flux of radioactive ^{226}Ra and ^{222}Rn from the pelagic clay sediments. For the axisymmetric case for which the IONMIG calculations were made, the per canister area is based on a canister spacing of 120 m. This results in an average per canister release of $4.6 \times 10^{-5} \mu\text{Ci}/\text{year}\cdot\text{m}^2$ for ^{129}I and

$1.6 \times 10^{-2} \text{ } \mu\text{Ci/year-m}^2$ for ^{99}Tc . These fluxes compare to natural radioactive fluxes of $3.5\text{-}8.8 \times 10^{-4} \text{ } \mu\text{Ci/year-m}^2$ for ^{226}Ra and $0.26\text{-}0.88 \text{ } \mu\text{Ci/year-m}^2$ for ^{222}Rn [Cochran, 1979; Heath, personal communication]. Recall that both ^{226}Ra and ^{222}Rn decay by alpha emission (4.78 meV and 5.49 meV, respectively), while the ^{129}I and ^{99}Tc decay by beta emission (0.15 meV and 0.292 meV). Also recall that the alpha particle released within tissue is about an order of magnitude more damaging than the beta particle. Based on these comparisons of flux level and radiation type, one may infer that the potential exposure effects of the released ^{129}I and ^{99}Tc on benthic organisms would be minimal (or perhaps negligible) since they have evolved in a much more intense radiation field. Confirmation of this hypothesis will require biological modeling (studies of possible concentration mechanisms), physical oceanographic modeling (studies of ocean transport mechanisms), to be followed by development of a detailed pathways-to-man model.

CONCLUSIONS

From the analysis and laboratory studies to date, we conclude that for the seabed sediment:

- (1) When the canister initial power is limited to 1.5 kW in order to keep the maximum sediment temperature between 200°C and 250°C dictated by physical, thermochemical, and corrosion considerations, the

high temperature region ($T > 100^{\circ}\text{C}$) surrounding the waste canister is of limited extent in both space and time (0.8 m radius x 3.6 m long, less than 35 years).

- (2) Total fluid displacement due to the convective velocity induced by the thermal energy is small (3%) relative to the proposed canister burial depths.
- (3) Hydrothermal alteration of the sediment yields a hot, acid, oxidizing environment about the waste canister. The environment produced from the smectite-rich sediment is more strongly oxidizing than that from the illite-rich sediment. This results from a greater percentage of higher valence forms of iron (Fe^{3+}) and manganese (Mn^{4+}) in the smectite sediments than in the illitic sediments which contain more of the lower valence forms Fe^{2+} and Mn^{2+} .
- (4) For nuclides presumed to form cationic species, Cs, Rb, Sr, Ba, Cd, Ce, Eu, Gd, Pm, U, Pu, Am, and Cm, the distribution coefficients generally vary from about 10 ml/g at solution phase concentrations on the order of 10^{-2} M to 10^4 and greater at concentrations on the order of 10^{-7} M and less. These distribution coefficients appear to result from at least two separate mechanisms. One appears to be an ion-exchange phenomenon associated with the

silicate phases and appears to have a relatively much larger sorption capacity but much smaller equilibrium constant than the second mechanism. In the case of cesium, and probably rubidium, this second mechanism also appears to be associated with the silicate phases. However, for the other elements studied, the second mechanism appears to be associated with the hydrous metallic oxide phases.

- (5) Nuclide migration calculations using measured sediment properties for the representative nuclides ^{239}Pu , ^{137}Cs , ^{129}I , and ^{99}Tc indicate that (a) fission products such as ^{137}Cs and ^{90}Sr will decay prior to any release, (b) long-life radionuclides such as ^{239}Pu diffuse so slowly through the sediment that release is delayed for such extremely long times that the release rates are negligible, and (c) nuclides that migrate as anions with a long half-life and a very small sorption coefficient, such as ^{129}I and ^{99}Tc diffuse to the sediment water interface in several thousand years. However, modeled release rates for ^{129}I and ^{99}Tc are below the naturally occurring injection rates of ^{226}Ra and ^{222}Rn .
- (6) Nothing has been found by the studies to date to indicate that the red clay sediments cannot be an effective containment barrier for nuclear waste.

The final results of ongoing work to measure the transport coefficients of nuclides in the sediments, coupled with the results of biological modeling, physical oceanographic studies, and pathways-to-man models will be required for the final technical assessment.

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TABLE I
MATERIAL PROPERTIES FOR SEABED THERMAL ANALYSIS
USED IN MARIAH ANALYSIS

<u>Sediment</u>		
<u>Units</u>	<u>Pore Fluid</u>	<u>Mineral</u>
Density, kg/m ³	1000.0	2950.0
Specific Heat, W-day/kg-°C	0.05208	0.01018
Conductivity, W/m-°C	$0.62071 + 0.0013769T$ $-4.584 \times 10^{-6}T^2$ $+3.8889 \times 10^{-10}T^3$	$1.92 \exp(-6.37 \times 10^{-4}T)$
Viscosity, kg/m-day	$1441.15T^{-0.8987}$ $T \geq 25^\circ\text{C}$ $148.45 - 27.43T$ $T \leq 25^\circ\text{C}$	-----
Bulk Expansion, 1/°C	$0.25 \times 10^{-3} + 4.4 \times 10^{-6}T$	-----
Porosity,	-----	0.8
Permeability, K_{zz} m ²	-----	5.0×10^{-17}
Permeability, K_{rr} m ²	-----	5.0×10^{-16}
<u>Waste Solid</u>		
Density, kg/m ³	2275.0	
Specific Heat, W-day/kg-°C	0.010	
Conductivity, W/m-°C	$1.21 + 0.0038T$	
<u>T = Temperature (°C)</u>		

TABLE II
CONCENTRATION OF SELECTED DISSOLVED SPECIES (ppm)
IN STANDARD SEAWATER BEFORE AND AFTER
INTERACTION WITH SEDIMENTS A AND B
(see text)

<u>Sample</u>	<u>Mg</u>	<u>Ca</u>	<u>K</u>	<u>Na</u>	<u>Sr</u>	<u>SiO₂</u>	<u>SO₄⁼</u>	<u>Cl⁻</u>	<u>pH</u>
Standard seawater 25°C	1296	412	399	10,756	7.0	<0.2	2616	19,375	7.8
Seawater reacted with sediment-A at 300°C, 500 bars, 1243 hours	186	150	796	12,046	2.8	939	329	19,253	3.87
Seawater reacted with sediment-B at 300°C, 500 bars, 1461 hours.	279	113	1344	11,160	(-)*	1959	~150	19,352	3.02

*Not analyzed.

TABLE III
CONCENTRATION OF SELECTED TRACE AND MINOR DISSOLVED
SPECIES (ppm) IN STANDARD SEAWATER BEFORE AND
AFTER INTERACTION WITH SEDIMENTS A AND B
(see text)

<u>Sample</u>	<u>Fe</u>	<u>Mn</u>	<u>Ni</u>	<u>Cr</u>	<u>Co</u>	<u>Zn</u>	<u>Au</u>
Standard seawater 25°C	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Seawater reacted with sediment-A at 300°C, 500 bars, 1243 hours	7.07	669	0.01	0.012	0.079	16.11	<0.01
Seawater reacted with sediment-B at 300°C, 500 bars, 1461 hours	<0.1	104	0.021	0.123	0.097	19.00	88.5

TABLE IV
CHEMICAL COMPOSITION OF SEDIMENTS* FROM MPG REGIONS

<u>Wt. % Component</u>	<u>Sediment A</u>	<u>Sediment B</u>
SiO ₂	53.46	51.72
Al ₂ O ₃	17.35	14.28
Fe ₂ O ₃ **	7.64	9.06
MgO	3.21	3.49
CaO	0.73	1.31
Na ₂ O	1.43	1.47
K ₂ O	4.24	3.79
MnO	0.47	1.26
TiO ₂	0.84	0.61
H ₂ O ⁻	0.86	1.52
H ₂ O ⁺	6.48	8.69
Total	96.71	97.20

*Prior to analysis sediments dried at 40°C.

**Total Fe as Fe₂O₃.

TABLE V
 NUCLIDE DECAY CHAINS AND ZERO-TIME CANISTER INVENTORY
 FOR IONMIG CALCULATIONS: HIGH LEVEL WASTE
 INITIAL THERMAL POWER = 1.5 kW

<u>Radionuclide</u>	<u>Initial Canister Inventory (kg)</u>
^{230}Pu	3.58×10^{-2}
^{243}Am	0.121
^{239}Np	1.0×10^{-7}
^{243}Cm	6.92×10^{-5}
^{235}U	1.0×10^{-5}
^{129}I	0.305
^{129}Xe	1.178×10^{-5}
^{99}Tc	1.13
^{99}Ru	4.32×10^{-5}
^{137}Cs	1.33
^{137}Ba	2.01×10^{-7}

TABLE VI
 PROPERTIES FOR NUCLIDE MIGRATION ANALYSIS
 FOR IONMIG ANALYSIS

D_o	$m^2/year$	0.01
α_L	m	6.1
α_t	m	0.61
K_d	m^3/kg	$\frac{100}{1.0 + 3 \times 10^8 C_{Pu}} + 0.01$
K_d	m^3/kg	$\frac{10}{1.0 + 2 \times 10^5 C_{Cs}} + 0.1$
K_d	m^3/kg	$\frac{0.0001}{1.0 + 1 \times 10^4 C_{I,Tc}}$

C = Concentration in kg/m^3

REFERENCES

- Anderson, D. R., "Nuclear Waste Disposal in Subseabed Geologic Formations: The Seabed Disposal Program," SAND78-2211, Sandia Laboratories, Albuquerque, NM, May 1979.
- Bell, M. J., "ORIGEN--The ORNL Isotope Generation and Depletion Code," ORNL-4628, Oak Ridge National Laboratory, May 1973.
- Bischoff, J. L. and W. E. Seyfried, "Hydrothermal Chemistry of Seawater from 25°C to 350°C," Amer. J. Sci., 278, p. 838, 1978.
- Braithwaite, J. W. and M. A. Molecke, "High-Level Waste Canister Corrosion Studies Pertinent to Geologic Isolation," Nuclear Waste Management and Technology, Vol. 1, No. 1, Pergamon Press, 1979.
- Brookins, D. G., "Retention of Transuranic Species and Actinide Elements and Bismuth at the Oklo Natural Reactor, Gabon: Application to Eh-pH Diagrams," Chem. Geol., 23, pp. 309-325, 1978.
- Cochran, J. K., "Geochemistry of 226-Ra and 228-Ra in Marine Deposits," PhD Dissertation, Yale University, New Haven, Connecticut, 1979.
- Erickson, K. L., "Radionuclide Sorption Studies on Abyssal Red Clays," Radioactive Waste in Geologic Storage, S. Fried, Ed., American Chemical Society, Washington, DC, 1979.
- Erickson, K. L., "Radionuclide Sorption Studies on Abyssal Red Clays," Scientific Basis for Nuclear Waste Management, Vol. II, C. J. Northrup, Ed., Plenum Press, New York, 1980.
- Fried, S., A. Friedman, R. Sjoblom, D. Cohen, K. Nash, and J. C. Sullivan, "The Effect of Radiation on the Oxidation States of Plutonium in Various Aqueous Solutions," Scientific Basis for Nuclear Waste Management, Vol. II, C. J. Northrup, Ed., Plenum Press, New York, 1980.
- Gartling, D. K. and C. E. Hickox, "MARIAH--A Finite Element Computer Program for Incompressible Porous Flow Problems, Part I: Theoretical Background," SAND79-1622, Sandia Laboratories, Albuquerque, NM, 1980A.
- Gartling, D. K. and C. E. Hickox, "MARIAH--A Finite Element Computer Program for Incompressible Porous Flow Problems, Part II: User's Manual," SAND79-1623, Sandia Laboratories, Albuquerque, NM, 1980B.

REFERENCES (cont)

- Gomez, L. S., R. R. Hessler, D. W. Jackson, M. G. Marietta, K. L. Smith, Jr., D. M. Talbert, and A. A. Yayanos, "Biological Studies of the U.S. Subseabed Disposal Program," SAND79-2073, Sandia Laboratories, Albuquerque, NM, January 1980.
- Heath, G. R., G. Epstein, and R. A. Prince, "Seabed Disposal Program: Geochemical and Sedimentological Studies of North Pacific Sediments," in "Seabed Disposal Program, Annual Report--Part II, January to December 1976," D. M. Talbert, Ed., SAND77-1270, Sandia Laboratories, Albuquerque, NM, 1977.
- Heath, G. R., School of Oceanography, Oregon State University, personal communication.
- Helgeson, H. C., J. M. Delaney, H. W. Nesbitt, and D. K. Bird, "Summary and Critique of the Thermodynamic Properties of Rock Forming Minerals," Amer. J. Sci., 278-A, p. 288, 1979.
- Helgeson, H. C., "Hydrothermal Transport and Deposition of Gold," Econ. Geol., 63, pp. 622-635, 1968.
- Hickox, C. E. and H. A. Watts, "Steady Thermal Convection from a Concentrated Source in a Porous Medium," 79-HT-69, ASME/AIChE, 18th National Heat Transfer Conference, San Diego, CA, August 1979.
- Hollister, C. D., et al., in "Seabed Disposal Program, Annual Report, January to December 1978," SAND79-1618, Sandia Laboratories, Albuquerque, NM, October 1979.
- Krumhansl, J. L. and G. R. Hadley, "Thermal and Chemical Properties of Saturated Marine Clays in a Near-Field Environment," presented at the Workshop on Argillaceous Materials for Isolation of Radioactive Waste, OECD Nuclear Agency, Paris, France, September 9-12, 1979.
- Li, Yuan-Hui and Sandra Gregory, "Diffusion of Ions in Sea Water and Deep-Sea Sediments," Geochimica et Cosmochimica Acta, Vol. 38, pp. 703-714, 1974.
- MacLeish, W. H., Ed., Oceanus, "High Level Wastes in the Seabed?" Vol. 20, No. 1, Winter 1977.
- McVey, D. F., C. M. Percival, L. D. Olson, and A. J. Silva, "The Sub-Seabed Disposal Program In Situ Heat Transfer Experiment (ISHTE)," SAND80-0202, Sandia Laboratories, Albuquerque, NM, 1980.

REFERENCES (cont)

- Nuttall, H. E., A. K. Ray, and E. J. Davis, "Ion Migration in Ocean Sediments: Subseafloor Radioactive Waste Disposal," Scientific Basis for Nuclear Waste Management, Vol. II, C. J. Northrup, Ed., Plenum Press, New York, 1980.
- Reed, M. H., "Geology and Geochemistry of the West Shasta Massive Ore Deposits," PhD Thesis, California University, Berkeley, 1977.
- Russo, A. J., "Prediction of the Migration of Several Radionuclides in Ocean Sediment with the Computer Code IONMIG, A Preliminary Report," SAND79-1666, Sandia Laboratories, Albuquerque, NM, to be published.
- Seyfried, W. E., Department of Geology, University of Minnesota, "Sediment/Seawater Interaction at Elevated Temperatures and 500 Bars Pressure," presented at Seabed Disposal Program Annual Workshop, La Jolla, CA, October 29-31, 1979.
- Seyfried, W. E., P. Gordon, and F. W. Dickson, "A New Reaction Cell for Hydrothermal Solution Equipment," Amer. Min., 64, pp. 646-649, 1979.
- Silva, A. J. and D. I. Calnan, "Geotechnical Aspects of Sub-Surface Seabed Disposal of High Level Radioactive Wastes," Annual Report No. 5, Department of Ocean Engineering, University of Rhode Island, January 1979.
- Talbert, D. B., Ed., "Seabed Disposal Program, Annual Report, January to December 1977, Vols. I and II," SAND78-1359, Sandia Laboratories, Albuquerque, NM, January 1979A.
- Talbert, D. B., Ed., "Seabed Disposal Program, Annual Report, January to December 1978, Vols. I and II," SAND79-1618, Sandia Laboratories, Albuquerque, NM, October 1979B.

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FIGURE 1. Seabed Canister, Model Geometry and Boundary Conditions

FIGURE 2. Maximum Sediment Temperature as a Function of Initial Thermal Power

FIGURE 3. Temperature at Seven Locations Radially Outward from Center of Canister as a Function of Time

SF. P = 0.58KW

FIGURE 4. Temperature at Seven Locations Radially Outward from Center of Canister as a Function of Time

FIGURE 5. Velocity at Three Locations Radially Outward from Center of Canister as a Function of Time, 1.5KW Initial Thermal Power, HLW

FIGURE 6. Isotherm Patterns Near the Canister at Two Times for 1.5KW Initial Thermal Power, HLW

Figure 7: Mineral Activity Diagram for the $MgO-SiO_2-Al_2O_3-H_2O$ System at 300°C, 500 Bars

○ Sediment A - Seawater Interaction
 □ Sediment B - Seawater Interaction
 Numbers within the symbols refer to the order in which the solution was sampled

FIGURE 8. Downcore variation in distribution coefficient of Eu for two concentrations in 0.68N NaCl in Sediment from Core LL44-GPC3 (from MPG-1)

FIGURE 9. Distribution Coefficients for Several Elements in 0.68N NaCl solutions contacting Smectite Rich Sediments

FIGURE 10. Distribution Coefficients for Sr and Ba in 0.68 N NaCl Solutions Contacting Smectite Rich Sediments

FIGURE 11. Distribution Coefficients for Plutonium, Americium and Uranium in 0.68 N NaCl Solutions Contracting Smectite Rich Sediments

FIGURE 12. Plutonium Concentration in the Sediment at 100,00 Years

FIGURE 13. Release Rate of ^{129}I from the Sediment Surface Covering a Single Canister at 30m Depth

FIGURE 14. Release Rate of ^{99}Tc from the Sediment Surface Covering a Single Canister at 30m Depth

Appendix K

Geotechnical Aspects of Subseabed
Disposal of High Level Radioactive Wastes

A. J. Silva, S. A. Jordan, W. P. Levy

GEOTECHNICAL ASPECTS OF SUBSEABED DISPOSAL OF
HIGH LEVEL RADIOACTIVE WASTES

BY

Armand J. Silva

Stephen A. Jordan

William P. Levy

DEPARTMENTS OF OCEAN AND CIVIL ENGINEERING

University of Rhode Island

DOE/SLA Contract No. 13-9927 (through September 30, 1980)

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for

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Sandia National Laboratories

Albuquerque, New Mexico

March, 1981

ABSTRACT

This is the seventh annual progress report, for calendar year 1980, of the University of Rhode Island geotechnical program which is part of the Subseabed Disposal Program concerned with high level radioactive wastes. Detailed data and results are presented for several activities.

Sediment characterization data related to site evaluations are presented for three areas: MPG-I, MPG-III N and MPG-IV. The new data for MPG-I fits in with previously reported trends. The upper several meters of the abyssal plain sediments of MPG-III N are soft and fine grained but a sandy layer of unknown thickness below 9 meters may present problems to the barrier concept. Of the areas examined in MPG-IV it appears that site E₂ has the best characteristics and additional studies are planned.

A comprehensive triaxial compression, stress-strain test program is partially complete and a technical report has been issued. The objectives of the program are to determine the stress-strain behavior of fine-grained deep sea sediments for a wide range of quasi-static stress histories and provide parameters for the modeling and analysis efforts. Summaries of completed portions are presented and preliminary results of on-going programs are discussed.

The first phase (room temperature) of the long term stress-strain-time (creep) program has been completed. New phenomenological equations are presented for illite and smectite materials of MPG-I that predict the long term drained deformation behavior. A one year test is underway to further investigate instabilities which occur under constant stress conditions. A preliminary creep test series at elevated temperature (up to 150°C) has been completed and the results indicate increasing resistance to deformation with increasing temperature.

Additional compressibility results for MPG-I are presented along with some preliminary results for MPG-III N and MPG-IV.

The data for MPG-I indicates essentially constant coefficients of permeability of 5×10^{-7} cm/sec. for the smectites and slightly higher values for the upper two meters of illite. Preliminary results for MPG-IV sediments indicate similar permeability coefficients. A limited number of tests at elevated temperatures up to 150°C suggest that changes in permeability are due entirely to variations in fluid viscosity. High fluid pressures (700 bars) do not effect permeability or conductivity of illitic sediments. Tests at high pressure and high temperature (200°C) are planned.

Involvement in the In-Situ Heat Transfer Experiment program includes a) site selection and sediment characterization studies, b) sediment-structure interaction testing, c) geotechnical analysis and design for the ISHTe platform, and d) project coordination for the scale model high-pressure simulation experiment. Progress and results on all these aspects are described.

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1. PROGRAM DESCRIPTION

1.1 INTRODUCTION

This is a progress report of research conducted during calendar year 1980 of the geotechnical program at the University of Rhode Island, Marine Geomechanics Laboratory (URI/MGL). The work is part of the Subseabed Disposal Program (SDP) sponsored by the Department of Energy through Sandia National Laboratories (SNL). The research is a continuing program which has been underway for several years and, therefore, this report supplements or extends what was previously reported. Interested readers should consult previous annual reports which are on file at SNL, Albuquerque, New Mexico (Dr. D.R. Anderson) and at URI/MGL.

Since issuance of last year's report (Silva and Calnan, 1980), two other detailed technical reports have been completed which are basically the theses of two students and others are in various stages of development. One of the completed reports is on the CIU triaxial compression studies (Akers and Silva, 1980) and the other is a final report of the laboratory Hole Closure Experiments (Bamford and Silva, 1980). The results of a third study on Consolidated Anisotropically Undrained (CAU) triaxial tests (Section 2.2) is in the form of an M.S. Thesis (Schwartz, 1980) and will be also issued as a technical report. The room-temperature creep program (Section 2.3) has been completed, the thesis is in final preparation (Moran, 1981) and a technical report will be issued in Spring 1981. The first phase of the high-temperature creep testing program is essentially complete at the writing of this report.

1.2 OUTLINE OF ACTIVITIES

The primary focus of the program during 1980 continued to be on experimental studies of geotechnical properties and behavior of deep sea sediments in relation to the Subseabed Disposal Program. The major aspects of the program are summarized in Figure 1.1. Following is a brief description of each task along with some comments on how the studies relate to various aspects of the overall Subseabed Disposal Program.

Sediment Characterization

This task consists primarily of general geotechnical analyses; such as water content, void ratio, specific gravity, Atterberg limits, and vane shear tests; which are useful to characterize sediments and determine vertical and areal variability of study sites. The results provide sediment data which, together with other information, can be used in preliminary evaluations of sites as potential SDP study areas. Some of the testing and analysis is performed on board ship when URI/MGL personnel participate in research cruises and the remainder is completed in shore labs.

Quasi-Static Stress-Strain Behavior

A technical report of the first phase of the CIU (Consolidated Isotropically Undrained) triaxial test program was issued in 1980 (Akers and Silva, 1980). The first phase of the CAU (Consolidated Anisotropically Undrained) triaxial test program was completed in late 1980 and a technical report will be issued in Spring 1981. Summaries of these results are included in this report.

A test program will begin in FY 1981 to study the effects of high consolidating stresses (2700 kPa) on the stress-strain behavior of sediments. Another program is underway to begin studying the effects of stress path history on the stress-strain properties and a program is underway to study the effects of radiation exposure on the properties. The stress-strain experiments are necessary to define constitutive relationships necessary for computer modeling studies.

Creep (long term stress-strain) Properties

The first phase of the drained creep experimental program, consisting of room temperature tests on illites and smectites, was completed in late 1980 and a technical report will be issued in Spring, 1981. The first set of experiments to study the effects of variable temperature on drained creep behavior was completed in late 1980, analysis of results is underway and it is expected that a technical report will be completed in FY 1981. A test to study the creep behavior using undrained, constant-load conditions has been completed and is reported here. All of these studies, including a new longer term (one-year) test, will be continued during FY 81 and FY 82.

These experiments are necessary to determine the long-term behavior of deep sea sediments for a variety of stress, drainage and environmental conditions as well as for providing relationships in computer modeling studies.

Compressibility Studies

Experimental studies are continuing to determine consolidation characteristics of core samples from the various SDP study sites. The results are used to help characterize the sediment, determine the stress history of the sediment column and provide compressibility parameters. The results are used to help evaluate the sites as potential containment media and for geotechnical analyses related to bottom supported structures.

Permeability Studies

Experimental programs are continuing to determine the permeability characteristics of deep sea sediments for a wide range of conditions. Permeability is a crucial property since the rate of water movement, and hence the effectiveness of the sediment as a barrier, is a direct function of this parameter. Some of the tests are used to characterize sediments from study sites to help evaluate these potential SDP study areas and others are necessary for the ISHTE program.

A special program is underway to study the effects of high pressure (60,000 kPa) and high temperature (200°C) on the permeability and conductivity of deep sea sediments. These tests will be useful in the study of near-field behavior around the canister

In Situ Heat Transfer Experiment (ISHTe)

This is a joint program with personnel from Sandia National Laboratories, University of Washington/Applied Physics Laboratory and University of Rhode Island/Marine Geomechanics Laboratory. The URI/MGL work is focused on the geotechnical aspects including: a) site characterization studies (classification, permeability, shear strength, etc.) related to selection of a suitable ISHTe site; b) laboratory experiments to determine important sediment-structure interactions; c) geotechnical analyses related to platform design, heater emplacement, sensor implantation and coring; d) design of an in situ vane shear device; e) participation in a simulation experiment and f) study of the geotechnical properties in the heat affected zone. The simulation experiment will be conducted at NSRDC, Annapolis, MD and URI/MGL has been assigned responsibility for project coordination.

Laboratory Hole Closure Experiment

This study has been completed, a comprehensive technical report was issued in 1980 (Bamford and Silva) and therefore the results are not included in this report.

1.3 PERSONNEL

The following URI/MGL personnel actively participated in the Subsea-bed Disposal Program during FY 80 and contributed to the writing of this report. Two full-time people have been added to the staff, Steve Jordan who has expertise in numerical modeling (finite element analysis) and William Levy who has expertise in many phases of testing. Graduate students are classified under two categories; Graduate Research Assistants (GRA) and Research Assistants (RA). Graduate Research Assistants devote half-time on research and half-time on studies during the academic year and full-time on research during most of the summer months. Research Assistants devote most of their time on research and are generally finishing up their theses. Also included is the general subject of each graduate student's research and telephone extensions of each individual (401-792-x).

Armand J. Silva, Principal Investigator, 6191, 6194, 6195, 2684
 Stephen A. Jordan, Research Program Manager, 6200, 6194
 William P. Levy, Geotechnical Research Specialist, 6200, 6194
 Stephen J. Criscenzo, Marine Research Associate III, ISHTe, 2647
 David I. Calnan, Research Associate III (part-time), 2684
 Gregory Chiarello, Research Technician, 6196
 John Babb, GRA, ISHTe (vane), 6148
 Kathryn M. Moran, RA, Geotech. Properties (creep), 4046, 5071
 Roger Morin, GRA, High Temp./High Press. Perm. & Conduct., 6148
 Osman Pekin, RA, ISHTe (vane) (part-time), 2684
 Pamela Sargent, GRA, Geotech. Properties (CAU), 5071

Sylvie Schwartz, RA Geotech. Properties (CAU) 4046. 5071
Gregory Walker, GRA. High Temp Perm., 6148
Jan C. Wildmen RA. Geotech. Properties (creep). 5071

Support staff includes: Martha Spinney, Prin. Clerk Steno. (part-time), Cynthia M. Thomas Ch. Clerk (part-time) and Cynthia D. Read, Clerk Typist (part-time). Part-time undergraduate technicians include: F. Balassone, D. Pry, P. Rafferty and F. Radcliffe.

Other URI personnel such as faculty and research staff served as consultants to the Subseabed Disposal Program. We wish to thank Dr P. Datseris, R. Gomes. W. Lamb, Jr., L. Simoneau and D.L. LeBlanc in their efforts which contributed to the program.

1.4 FACILITIES

The locations and functions of the URI/MGL research facilities have been outlined in previous Annual Reports. This year marked the completion of the high pressure/high temperature permeability and conductivity studies facility at the Narragansett Bay Campus (NBC). A TI FS 990 computer and data acquisition system has been installed and is in the process of being interphased with the consolidation equipment. A constant temperature bath for hydrometer and pipette work has been installed at the NBC and will further improve gradation analysis. The simple shear device is on order and due for arrival at URI/MGL in April 1981. The center of operations, including the main office of the Principal Investigator, has been relocated at the NBC, Ocean engineering 2 building.

At the URI main campus facilities, an improved vertical extrusion and core processing system has been developed and is in use. A new higher capacity air compressor system (250 psi) is being installed by the Department of Civil Engineering.

1.5 QUALITY ASSURANCE

With the acceptance of a URI/MGL Quality Assurance (QA) Program by Sandia National Laboratories and incorporation into the URI contract a Quality Assurance and Laboratory Development Team has been established. Bill Levy is QA Officer and Cindy Thomas is QA Clerk. Also on the team is Dave Calnan and Greg Chiarello. The team meets on a weekly basis to establish QA policy and communicate to the research group, compose any additional forms needed to define QA elements and to act on implementing all the QA elements outlined in the plan on a step-by-step basis. The QA Clerk is responsible for the establishment and maintenance of the official URI/MGL QA files where all material is available for review.

1.6 REPORT FORMAT

The technical contents of this report are formatted to follow the sequence of tasks as listed in contract document 13-9927 (FY 80). Three overall tasks are identified in the document and are covered under three chapters. Some of the overall tasks are separated into sub-tasks which

are covered as sections in this report. Two additional chapters are included in this report which describe the URI/MGL program and summarize our technical information.

1.7 PUBLICATIONS, REPORTS AND PRESENTATIONS

Following is a list of publications, reports and significant presentations made during 1980 in which URI/MGL participated.

Publications and Reports

- a) Akers, S.A. and Silva, A.J., "Stress-Strain and Strength Properties of Marine Sediments from the North Pacific," Technical Report, URI/MGL, June 1980.
- b) Bamford, S.R. and Silva, A.J., "Hole Closure Behavior of Marine Sediments Following Projectile Penetration," Technical Report, URI/MGL, June 1980.
- c) Dawson, P.R., Chavez, P.R., Lipkin, J., and Silva, A.J., "Creep of Ocean Sediments Resulting from the Isolation of Radioactive Wastes," Proceedings of 2nd Conference on Ocean Dumping, Woods Hole Oceanographic Institution, 1980.
- d) Silva, A.J., Laine, E.P., Lipkin, J., Heath, G.R., and Akers, S.A., "Geotechnical Properties of Sediments from North Pacific and Northern Bermuda Rise," Marine Technology '80--Proceedings: The Decade of the Oceans, 1980.
- e) Heath, G.R., Hayes, D.E., Silva, A.J., Hollister, C.D., and Leinen, M.S., "Characterization of Pelagic Sedimentation in the North Pacific: U.S. Subseabed Disposal Program," Marine Technology '80--Proceedings The Decade of the Oceans, 1980.
- f) Hadley, G.R., McVey, D.F., and Morin, R., "Thermophysical Properties of Deep Ocean Sediments," Marine Technology '80--Proceedings: The Decade of the Oceans, 1980.
- g) Percival, C.M., McVey, D.F., Olson, L.O., Silva, A.J., "In Situ Heat Transfer Experiment (ISHTe)," Marine Technology '80--Proceedings: The Decade of the Oceans, 1980.
- h) Karnes, C.G., Dawson, P.R., Silva, A.J., and Brown, W.T., "Sediment Mechanical Response Due to Emplacement of a Waste Canister," Marine Technology '80--Proceedings: The Decade of the Oceans, 1980.
- i) Morin, R.H. and Silva, A.J., "Design of Laboratory Equipment Used to Measure Physical Properties of Ocean Sediments in In Situ Conditions," Abstract Published in Proceedings of American Geophysical Union, Fall Meeting, 1980.
- j) Clukey, E.C. and Silva, A.J., "Permeability of Deep Sea Clays: North Western Atlantic, Marine Geotechnology, (In Press).

Presentations and Meetings

In addition to the following, several workshop meetings with SDP subgroups were attended by URI/MGL personnel during the year.

- a. Symposium on Mass-Wasting sponsored by USGS and WHOI at Woods Hole, MA in August, 1980.
- b. OCEANS '80 Conference, Seattle, Washington, September, 1980.

- 6
- c. Marine Technology Society, Annual Meeting, Washington, DC, 1980. A.J. Silva coordinator and co-chairman (with D.R. Anderson) of two special sessions on the Subseabed Disposal Program during which nine papers were presented with publication in the proceedings of the conference.
 - d. Geological Society of America, Annual Meeting, Atlanta, GA, November, 1980. Exhibit on Long Coring Facility (with A.H. Driscoll).
 - e. URI, Ocean Engineering Seminar, December, 1980, "Creep Behavior of Deep Sea Clays," by K. Moran.
 - f. American Military Engineers, Meeting, Narragansett Bay Post, North Kingston, RI, November 1980, "Overview of Subseabed Disposal Program."

Figure 1.1 URI/MGL SDP Program

2. GEOTECHNICAL PROPERTIES OF SEDIMENTS

2.1 SEDIMENT CHARACTERIZATION (G. Walker, S. Jordan, K. Moran)

Introduction

Sediment characterization properties such as specific gravity, water content, liquid limit, plastic limit, and grain size are important for classifying a type of sediment, and relating these to geotechnical properties such as permeability, compressibility, and strength.

Since the last annual report (Silva and Calnan, 1980), deep sea cores have been obtained from MPG-I (RAMA-1 cruise), MPG-III N, (HUDSON-80016 cruise) and the new MPG-IV (VEMA-36-12 cruise). Some testing has been completed on samples from all these cores but most of the new data reported here are from tests on samples from the MARA-02 and MARA-12 cruises in MPG-I. Table 2.1-1 lists the location of the cores from which classification samples were taken and tested. The results are presented with some data completed in FY 79 for comparison, but also to illustrate trends and compute overall averages. In addition, results (water content and shear strength vs. depth) from on board sampling are reported for the HUDSON and VEMA cruises; also results from sampling at Oregon State University are reported for the VEMA cruise. Results from the RAMA cruise are presented in Section 4.1

Atterberg limits were determined by approved standard procedures for liquid (ASTM D423-66) and plastic (ASTM D854-58) limits. Specific gravity measurements were also performed by a standard procedure (ASTM, D854048). Grain size was determined using the pipette procedure for fine grained soils (little or no sand fraction). All water contents were salt corrected for 35 ppt salt content.

2.1.1 North Central Pacific (MPG-I); Classification Results

Tables 2.1.1-1 (MARA-02) and 2.1.1-2 (MARA-12) list all the results obtained for sediment characterization during 1980, including some from 1979. Here, specific gravity along with in situ water content (taken during core extrusion) and buoyant unit weight are shown for the MPG-I area. The specific gravity results are consistent with those previously reported for MARA-02 and MARA-12 (Silva and Calnan, 1980). Most of the values fall within a range of 2.60-2.86 which would be expected for an illitic clay (Lambe and Whitman, 1969). The higher values can be attributed to the presence of heavy metals (Leinen and Heath, 1980).

The values of buoyant unit weight are fairly consistent in the MPG-I area. This consistency is a reflection of the homogeneity previously recognized at this site. Average values of 449 kg/m^3 and 454 kg/m^3 were calculated for the MARA-02 and MARA-12 cores respectively with an overall average of 452 kg/m^3 for the MPG-I area. These values are important when reducing compressibility results. Unit weights are used to find the in situ effective stress at any specific depth of interest. This stress is compared to the preconsolidation stress obtained from a compressibility plot (at the same depth) to determine the stress history.

2.1.2 Atlantic/Abyssal Plain (MPG-III N) - HUDSON 80016 Cruise (K. Moran)

Personnel from URI/MGL participated in a cruise to an area east of Bermuda, sponsored by the Canada Bedford Institute of Oceanography (BIO), with G. Vilks, Chief Scientist. The overall objective of the cruise was to find, survey, and sample a level area with approximately 200 meters of sediment thickness. The area chosen was within a grid 32° 26.6' N to 32° 32.3' N by 55° 55.0' W to 56° 01.4' W as shown in Figure 2.1.2-1. The sediment was sampled using three types of cores; standard piston (2.6 in.), gravity (4 in.) and box (0.5 m x 0.5 m x 0.5 m). A report of the URI/MGL results has been issued (Moran, 1980) which will become part of the BIO report.

A total of thirteen core lowerings were conducted; four piston cores, two box cores and four gravity cores were recovered with sediment (Table 2.1.2-1), the other three cores were recovered with no sediment. Following are brief discussions of preliminary analyses of these samples.

Results

a) Box cores 80016-012 (BC1) and 80016-020 (BC2)

Water content profiles of both box cores (Figure 2.1.2-2) display the same trends of water content with depth. Both cores show a large decrease in water content in the top 15 cm. Near 20 cm a zone of material of a higher water content (120%) appears in the profiles. The water content approaches a constant value of approximately 100% below 30 cm depth.

It should be noted that during extrusion, three layers of sediment were observed. The first layer, located approximately in the top 30 cm, was of grayish color. The next layer was a thin very wet material of about the same color. At this layer (35 cm), a significant decrease in shear strength is realized (Figure 2.1.2-2). The lower 10 cm was reddish in color and relatively homogeneous.

b) Piston cores 80016-015, 80016-024 (PC2), 80016-045 (PC3) and 80016-050 (PC4)

Figure 2.1.2-3 shows the water content profiles of PC1, PC2 and PC3. Generally, the water content in all piston cores decreases with depth although many fluctuations do occur as a result of the numerous layer changes. Sand and silty clay layers were observed below 900 cm in PC1 and PC2 which are reflected by much lower water contents, in relation to the rest of the core. The water content profile of PC3 is different below 900 cm (compared to PC1 and PC2) because the coarser material occurred near 1100 cm. Overall, the water content profiles of PC1, PC2 and PC3 are similar which indicate the same pattern of material deposition.

The shear strength (Figure 2.1.2-4) gradually increases with depth down to 900 cm below the seafloor. Shear strengths below 900 cm reduce substantially which is a reflection of the observed sand and silty clay material at this depth. However, it should be remembered that the vane shear method is intended for use on clays and therefore the values reported for coarser material are questionable. The shear strength profile for core PC3 shows an overall increase with depth and the sand

material at the bottom of the core was not tested.

c) Gravity core 80016-043 (GC3)

Only core GC3 was extruded and subsampled on board for determining geotechnical properties. Figure 2.1.2-5 contains the results obtained during the extrusion process.

Many layer changes were observed in core GC3 as indicated by the fluctuating water content profile. The shear strength above 200 cm gradually increases from a low of 3 g/cm² at 20 cm to a high value of 52 g/cm² at 191 cm. It should be noted that this region of high shear strength was not seen in the upper 2 meters of any of the piston cores. However, different depths of shear strength measurement in the piston cores and effects of disturbance may be a contributing factor.

2.1.3 Northwestern Pacific (MPG-IV) - VEMA 36-12 cruise (G. Walker)

During June 1980, an oceanographic's cruise, VEMA 36-12, to the Northwestern Pacific (MPG-IV) was conducted for the purpose of geologically sampling three sites of interest to the SOP (designated as C₁, B₁ & E₂). Piston cores and gravity cores taken during the cruise were sampled by members of the URI/MGL personnel to determine the geotechnical properties of this region. A summary of the coring operations is shown on Table 2.1.3-1. This table contains only the cores sampled by URI and Oregon State University (OSU). Three additional cores were sampled by Lamont Doherty Geological Observatory; their results are not contained here.

Water content samples from the piston cores were taken on board at intervals of approximately 150 cm. An attempt was made to determine the bulk density from these samples, however, it was decided that the quality of the sampling device was inadequate for accurate and consistent determinations. The water content was determined by oven drying the samples at 105°C.

Detailed (less than 150 cm intervals) water content determinations have been performed on all the piston cores since the cruise. URI personnel were only involved in cores PC-49 and 51 and used an oven drying technique. The remaining piston cores were tested by OSU personnel and used a freeze-dried technique. Reported here are shipboard water content results exclusive of PC-49 and 51 which are detailed plots. Shear strength results determined by using a miniature vane apparatus are also presented for cores PC-49 and 51.

Results

Figure 2.1.3-1 shows the water content profiles of piston cores (PC) 32, 33, 34, and 35; site C₁. These profiles are very similar with an average water content of approximately 140%. The water content profile for PC-34 does show more variability than the other three cores, however, a peak water content near three meters can be observed in all profiles.

Figure 2.1.3-2 shows the water content profiles for the cores from site B₁. Profiles of core PC-41 and PC-45 show some variability from each other as well as within each core with averages below 140%. PC-43

shows a more prominent variability with water contents averaging above 140%. It should be noted that during extrusion it was observed that core PC-43 contained mostly grayish sediment whereas PC-41 and PC-45 contained mostly brownish sediment. This would indicate that this site (B₁) is not consistent throughout; mineralogically and possibly geotechnically.

Figure 2.1.3-3 shows the shipboard determinations of water contents for site E₂; cores PC-46, PC-47 and PC-48. These profiles show small variations in water content with depth indicating a site of relatively uniform character. The detailed profiles (PC-49 and 51) of water content are shown in Figures 2.1.3-4 and 5. These profiles also show evidence of consistency in this site.

Shear strength profiles of PC-49 and 51 (site E₂) are also displayed in Figures 2.1.3-4 and 5. Both cores show low shear strengths (less than 10 kPa) for the upper five meters and peaks at approximately six meters. There are similar characteristics between five and seven meters; however, below seven meters the profiles appear to be different. Careful observation indicates that the lower four meters of PC-49 is similar to the lower 2 1/2 meters of PC-51. The pattern between eight and ten meters for PC-51 appears to be the same between seven and eight meters on PC-49. This observation implies layers of consistent strength in site E₂.

The profiles for site E₂ show more uniformity in water content with depth compared to sites B₁ and C₁. Also, comparison of all three sites reveals an overall consistence in water content vs. depth in the MPG-IV area compared to other MPG-areas. Some of the profiles show extreme maxima and minima in water content at various depths.

Table 2.1.3-2 contains the results of specific gravity tests conducted at URI/MGL in the MPG-IV area to date. These results (ranging from 2.66 to 2.73) are comparable to those in the MPG-I area, but the in situ water contents (taken during extrusion) are significantly higher in the upper zones than those in the MPG-I area. Using this data, buoyant unit weights have been calculated as shown in the table; ranging from 250 to 303 kg/m³ with an average of 281 kg/m³. These weights can be used to estimate the effective in situ stress at any depth below the seafloor in the MPG-IV area.

Generally, buoyant unit weights have decreased with depth in the other MPG areas, however, the effect of higher water contents in the upper zones of the MPG-IV area has apparently yielded relatively consistent values with depth. Further evidence of this consistency will be investigated in the future when testing for additional geotechnical properties is complete.

2.1.4 Summary and Future Work

Classification tests on samples from the MARA-02 and MARA-12 cores (MPG-I) are essentially complete and in early stages on the RAMA (MPG-I), HUDSON (MPG-III), and the new VEMA-36 samples (MPG-IV). Generally, specific gravity values have ranged between 2.6 and 2.9 and buoyant unit

weights averaged 452 kg/m^3 and 280 kg/m^3 (MPG-I and IV, respectively). The buoyant unit weight in the MPG-IV area is significantly lower and the water contents correspondingly higher. Future work in this area will include Atterberg Limits, specific gravity, grain size analysis compressibility and permeability which will continue to be used in an effort to geotechnically classify this area and help assess these sites for their desirability in waste disposal.

Results from the HUDSON cores has indicated that the area where the cores were taken has some disadvantages as a waste disposal site. The sand layer, which appeared in the piston cores, is a primary disadvantage due to the high penetration resistance of this material and higher permeability. Fluid migration is likely when dealing with layers of sediments whose seepage properties vary significantly. Additional preliminary analyses will be continued to expand the data base on these sediments. Since the piston corers did not penetrate through the sand layer, it is not possible to predict characteristics of the underlying sediments.

Table 2.1-1
Core Locations
MPG-I & MPG-IV

<u>CRUISE</u>	<u>CORE</u>	<u>LATITUDE</u>	<u>LONGITUDE</u>	<u>DEPTH (M)</u>
MARA-2	GC-4	30° 6.3' N	157° 51.7' W	5868
	GC-7	30° 30.9' N	158° 0.7' W	5883
MARA-12	GC-22	31° 4.8' N	159° 3.5' W	5811
	GC-24	30° 40.6' N	159 0.4' W	5821
	GC-28	30° 20.1' N	158 59.8' W	5801
VEMA 36-12	PC-48	32° 9' N	163° 29' W	5880
	PC-49	34° 24' N	164° 16' W	5991
	PC-51	32° 38' N	164° 46' W	6055

Table 2.1.1-1
Specific Gravity and Unit Weights, MPG-I
MARA-2

CORE	DEPTH (cm)	WATER CONTENT** %	SPECIFIC GRAVITY G_s	BUOYANT UNIT WEIGHT γ_b kg/m ³
GC-04	76-84	119.5	2.72	415.
	86-94	123.7	2.71	403.
	95-105	117.8	2.97	449.
	105-115	113.1	2.73	434.
	203-214	103.8	2.86	480.
	215-225	105.4	3.00	493.
	226-236	104.7	3.00	495.
	237-247	106.0	3.02	493.
	247-254	102.2	2.75	471.
	247-252*	102.2	2.73	468.
AVG...				460.
GC-07	10-20	114.8	2.83	442.
	12-16*	114.8	2.72	428.
	80-94	111.4	2.87	457.
	94-105	117.1	2.88	441.
	107-120	114.5	2.77	435.
	123-127	112.6	2.65	425.
AVG...				438.
MARA-2				AVG... 449.

* NEW DATA

** PREVIOUSLY REPORTED

Table 2.1.1-2
Specific Gravity and Unit Weights, MPG-I
MARA-12

CORE	DEPTH (cm)	WATER CONTENT %	SPECIFIC GRAVITY G_s	BOUYANT UNIT WEIGHT γ_b kg/m ³
GC-22	15-25*	110.3	2.77	448.
	148-158	110.0	2.73	443.
	160-170*	102.0	2.78	476.
	194-204	107.0	2.65	441.
				AVG... 452.
GC-24	139-149	109.0	2.62	431.
	151-161	109.0	2.62	431.
	162-172	100.0	2.68	468.
	173-183	103.0	2.61	447.
	255-260*	98.9	2.67	470.
				AVG... 449.
GC-28	5-10	113.9	2.73	432.
	30-35	107.2	2.78	459.
	50-55	109.6	2.74	446.
	70-75	114.5	2.77	435.
	90-95	110.3	2.77	447.
	123-130	109.1	2.70	442.
	130-138	102.9	2.74	467.
	140-150	103.0	2.70	461.
	152-162	101.0	2.70	468.
	164-174	100.0	2.68	468.
	176-186	101.0	2.84	488.
	215-220*	102.7	2.67	458.
	245-250	101.7	2.89	492.
	270-274	104.6	2.83	474.
	270-277	104.6	2.80	470.
				AVG... 460.
				MARA-12 AVG... 454.

* OLD DATA

Table 2.1.2-1
CORING SUMMARY HUD 80016

STATION NUMBER	LATITUDE	LONGITUDE	CORE TYPE	RECOVERED CORE LENGTH (cm)	COMMENTS
80016-012	32° 29.6'N	56° 0.1'W	Box	50	
80016-015	32° 30.8'N	56° 0.7'W	Piston	1170	40' Barrel
80016-020	32° 30.8'N	55° 57.0'W	Box	50	Overpenetrated
80016-024	32° 31.1'N	55° 57.0'W	Piston	1099	Nose cone material lost during recovery
80016-039	32° 28.9'N	56° 0.7'W	Gravity	325	10' Barrel
80016-040	32° 28.5'N	55° 55.2'W	Gravity	76	10' Barrel
80016-043	32° 32.1'N	55° 57.0'W	Gravity	394	15' Barrel w/coupling
80016-045	32° 30.0'N	55° 56.3'W	Piston	1282	60' Barrel
80016-050	32° 32.0'N	55° 58.6'W	Piston	1235	40' Barrel
80016-053	32° 30.9'N	55° 59.2'W	Gravity	435	16' Barrel w/coupling

Table 2:1.3-1

URI/MGL
CORING RESULTS
VEMA 36-12

Core	Site	Position (Deg-Min)	Uncorr. water depth (M)	Core Wt. (KG)	Barrel length (M)	Sed. Rec. (cm)	Comments
32-PC	C ₁	30-55.3 N 151-37.09 E	5717	816	12.3	952	Flat to hummochy 0.5 sec sediment
33-PC	C ₁	30-20.68 N 151-16.37 E	5730	816	12.3	982	Upper pipe bent Upper section Disturbed
34-PC	C ₁	30-45.59 N 152-16.24 E	5680	816	12.3	1172	Smooth - gently rolling
35-PC	C ₁	30-30.13 N 151-48.74 E	5783	816	12.3	989.5	Light color above 110 cm dark below
36-GC	C ₁	30-29.57 N 151-46.21 E	5794	227	3.05	275	
37-PC	C ₁	30-20.08 N 151-24.72 E	5825	816	12.3	0	Badly bent pipe pre Tripped Trig- ger core
39-GC	C ₁	30-27.1 N 151-49.9 E	5812	227	3.05	288	Over penetrated 0.5 sec sediment
40-PC	B ₁	33-29.12 N 152-13.19 E	5801	816	12.3	0	Strong current no hit after all wire out
41-PC	B ₁	33-21.12 N 152-3.05 E	5806	816	12.3	1266	Slightly bent 0.4 sec sediment
42-GC	B ₁	33-17.18 N 152-2.8 E	5750	227	3.05	45.5	Slow penetration at angle
43-PC	B ₁	33-44.84 N 151-45.91 E	5825	816	12.3	1247	Rolling hills periodic features 0.75 sec sediment
45-PC	B ₁	33-5.63 N 152-16.38 E	5695	816	12.3	1264	Mostly gray with dark layers 0.4 sec sediment
46-PC	E ₂	33-41.12 N 163-31.70 E	5956	816	12.3	1265	0.5 sec smooth
47-PC	E ₂	32-5.8 N 164-31.0 E	5914	816	12.3	1262	Hill nearby Hummochy
48-PC	E ₂	32-9 N 163-29 E	5880	816	12.3	1268.5	Gently rolling 0.6 sec sediment
49-PC	E ₂	34-24 N 164-16 E	5991	816	12.3	1192.5	0.4 sec sediment smooth
50-GC	E ₂	32-26 N 164-18 E	5975	227	3.05	289	0.4 sec sediment smooth
51-PC	E ₂	32-38 N 164-46 E	6055	316	12.3	1271	0.6 sec sediment scarp to south
53-GC	E ₂	32-24.57 N 164-8.89 E	5980	227	3.05	289	Smooth - gently rolling

Table 2.1.3-2
Specific Gravity and Unit Weights, MPG-IV
VEMA 36-12

CORE	DEPTH (cm)	WATER CONTENT %	SPECIFIC GRAVITY G_s	BUOYANT UNIT WEIGHT γ_b kg/m ³
PC-51	114-125	184.0	2.71	293.
PC-49	188-199	218.0	2.66	250.
PC-49	1183-1187	177.8	2.73	303.
PC-48	1255-1259	192.0	2.66	279.
PC-48	1260-1263.5	192.9	2.69	280.
AVG...				281.

80-016
1:75000

LEGEND

- ☆ ATB'S
- ⊙ PISTON CORE
- BOX CORE
- △ LEHIGH CORE
- X HEAT FLOW
- + CAMERA

Cruise: HUDSON 80016

Figure 2.1.2-1

Figure 2.1.2-2 Box Core Profiles
(Water contents corrected for 35 ppt salt)

Figure 2.1.2-3 Box Core Profiles of Water Content
(corrected for 35 ppt salt)

Figure 2.1.2-4 Piston Core Profiles of Shear Strength

DEPTH vs. WATER CONTENT
 HLD 88816-843 (GC3)
 UR1/M2L

DEPTH vs. SHEAR STRENGTH
 HLD 88816-843 (GC3)
 UR1/M2L

Figure 2.1.2-5 Gravity Core Profiles of Water Content and Shear Strength

VEMA 36-12 CRUISE

SITE C₁

* Corrected for 35PPT salt content

Figure 2.1.3-1 Piston Core Profiles of Water Content

VEMA 36-12 CRUISE - SITE B₁

* Corrected for 35PPT salt content

Figure 2.1.3-2 Piston Core Profiles of Water Content

VEMA 36-12 CRUISE

SITE E₂

*Corrected for 35PPT Salt Content

Figure 2.1.3-3 Piston Core Profiles of Water Content

VEMA 36-12 CRUISE

SITE E₂

Figure 2.1.3-4 Piston Core PC-49 Profiles

VEMA 36-12 CRUISE

SITE E₂

Figure 2.1,3- 5 Piston Core PC-51 Profiles

2.2 TRIAXIAL TESTS

Introduction

This section discusses the results, status, and future of the triaxial work at URI/MGL in support of the SDP. Subsections 2.2.1 and 2.2.2 mark the completion of the initial phase of testing for CIU and CAU triaxial studies of which technical reports are available. Further testing in both CIU and CAU is planned. Subsections 2.2.3 and 2.2.4 discuss the beginning of two new tests programs; one, investigating sediment response at high consolidation pressures for attaining mechanical properties to be incorporated into a numerical model, the other, examining the dependence of sediment response on the specific stress path to failure. A summary of our findings is presented in subsection 2.2.6.

2.2.1 Consolidated Isotropically Undrained (CIU) Triaxial Results (W. Levy)

The overall purpose of this particular program was to study the strength and stress-strain properties of "undisturbed" and remolded (reconstituted-reconsolidated) samples of two Pacific deep sea sediments; illite and smectite. Both sediments are from cores obtained in the study area MPG-I (Table 2.2.1-1). Reported here is a summary of the research done by S. Akers as a Masters of Science thesis including new data and analyses completed since the last annual report. Details of the program and additional results can be found in a recently published technical report (Akers and Silva, 1980). Specific goals of the testing program were to:

1. Determine Mohr-Coulomb stress-strain parameters for two different clay specimens; illite and smectite from MPG-I.
2. Compare the properties of undisturbed and remolded samples.
3. Compare the properties of illite and smectite.
4. Compare the properties of remolded samples taken in vertical and horizontal orientations.
5. Determine parameters for incorporating into the hyperbolic stress-strain relationship.
6. Measure lateral strain and determine values of Poisson's ratio for the sediments.

Test Program

Eleven series of standard isotropically consolidated undrained triaxial tests with pore pressure measurement were performed; a total of 40 individual specimens. Undisturbed and remolded series were tested. Each series typically consisted of three to four individually tested subsamples. Five series were done on good quality undisturbed samples of smectite (LL-44, GPC-3) and illite (VEMA-32, PC-115 and MARA-02, GC-04).

Remolded samples were obtained from large tanks, 132 cm high by 46 cm in diameter. Dredge samples of illite and disturbed core samples of smectite which were obtained during LL44 were homogenized in a large clay mixer. The material was then placed in the tanks and consolidated to stress-levels simulating predetermined in situ depths. Six series of

tests on remolded samples were performed; three for smectite and three for illite. One out of each three series was a group of horizontally oriented samples. The test program is summarized in Table 2.2.1-2.

Volume change versus time measurements were taken during the triaxial tests in order to determine the time for 90 percent consolidation and to assure the sample was in secondary compression. After consolidation, a back pressure of 276 kPa was applied in steps. This was found to achieve virtual saturation (B value > 0.95).

Strain-controlled undrained shear was then initiated at a deformation rate of 0.03 mm/min. Shear was continued until either 20 percent axial strain or rupture was reached. Axial deformation was measured by a Direct Current Differential Transducer (DCDT), load by a calibrated proving ring, and pore pressure by an absolute pressure transducer. A disk-ring gauge was developed for measurement of lateral deformation of the specimen at mid-height.

It should be noted that no corrections for the load carried by the filter paper drains or the membranes were included in the calculations.

Results

a) Mohr-Coulomb stress-strain parameters

Effective cohesion ($\bar{c}$) and the effective angle of internal friction ($\bar{\phi}$) were determined from stress path plots obtained from each sample series. Cohesion ranged from zero to a high of 9.9 kPa. Friction angle varied with material composition.

Undrained shear strengths (q_{fu}) were normalized with respect to effective vertical pressure (σ_{vo}). These normalized strength parameters (q_{fu}/σ_{vo}) were used to compare strength between samples (Table 2.2.1-3).

The failure parameters of effective cohesion ($\bar{c}$), effective internal angle of friction ($\bar{\phi}$) and pore pressure coefficient at failure ($\bar{A}_f$) were used to obtain an in situ q_{fu}/σ_{vo} . The equation used to find this is (Lee, 1974):

$$q_{fu}/\bar{\sigma}_c = \frac{(K_0 + \bar{A}_f (1 - K_0)) \sin \bar{\phi} + (\bar{c}/\bar{\sigma}_c \cos \bar{\phi})}{1 + (2 \bar{A}_f - 1) \sin \bar{\phi}} \quad \text{Eqn. 1}$$

Here, the differences in horizontal and vertical in situ stresses are taken into account by including the coefficient of earth pressure at rest, K_0 . The following values were input into this equation for three sediment types; Illite, Transition (Illite to Smectite) and Smectite in LL-44, GPC-03:

	$\bar{c}$ (kPa)	$\bar{\phi}$	$\bar{A}_f$	K_0
Illite	0.00	34.0	1.0	0.55
Transition	4.90	33.0	0.8	0.55
Smectite	1.57	35.5	0.8	0.60

K_0 is an estimated value. Buoyant unit weights were interpolated between closely spaced measurements of water content and specific gravity from LL44, GPC-3 to develop an effective overburden pressure profile for the core. Using the three values of $q_{fU}/\bar{\sigma}_{v0}$ and this profile, the undrained shear strength with depth profile was calculated for LL44, GPC-3 and plotted along with other data in Figure 2.2.1-1. In this figure, the solid dot points are from miniature vane shear measurements made on board ship, the line labeled Eq. 6-6 is the profile used in design of the new Long Coring Facility and the line labeled Eq. 6.5 is the plot of calculated undrained shear strength based on the triaxial CIU data. As indicated, the calculated undrained strengths compare very nicely with the miniature vane measurements.

b) Comparison of undisturbed and remolded samples

Average $\bar{\phi}$ values for undisturbed specimens were slightly higher than remolded values in most cases (Table 2.2.1-3). Cohesion, $\bar{c}$, and friction angle, $\bar{\phi}$, for smectite were essentially not affected by the remolding process.

However, undisturbed illite from core MARA-02, GC-04 showed much higher friction angles than remolded illite. The undisturbed samples from VEMA-32, PC-115 were from a transition zone and consequently do not reflect the larger differences seen upon remolding in the illites. Also, it is probable that the samples from this small diameter standard piston core were more disturbed than the GPC samples.

c) Comparison of smectite and illite

As mentioned above, illite appears much more sensitive to remolding than smectite. In LL-44, GPC-3 the sensitivity (S_u/S_v) measured by miniature vane shear decreases with depth from 6.7 in the upper 5 meters of illite-rich material to 4.8 in the transition zone to 2.5-2.9 below 10 meters where smectite dominates soil behavior. This was again observed in VEMA-32, PC-115.

Excluding PI-18 vertical, the undrained strength of smectite was greater than of illites tested. Vertically oriented remolded smectite showed considerably larger $\bar{\phi}$ values than vertically-oriented remolded illite.

d) Comparison of vertical and horizontal samples

Horizontally oriented remolded samples had consistently smaller friction angles than vertical samples, for all materials. Horizontal values of effective cohesion were consistently larger than vertical specimens. Due to the limited testing done on these samples undrained strength analysis of horizontal and vertically oriented remolded specimens was

inconclusive. It should be kept in mind, however, that strength anisotropy observed in these remolded (reconstituted-reconsolidated) specimens is not necessarily correlative with field anisotropy variations.

e) Young's modulus

Observed initial tangent modulus (E_i), in general, increases with consolidation stress. As the modulus value is usually very sensitive to test procedures and sample disturbance, a best fit line through all the points on a $\epsilon_a/\sigma_1 - \sigma_3$ vs. ϵ_a plot is used to determine E_i and ($\sigma_1 - \sigma_3$). These values can then be used to generate a hyperbolic stress-strain curve (Wong and Duncan, 1974).

Young's tangent modulus (E_t) can also be obtained using Janbu's (1963) relationships between modulus and consolidation pressure and values of $\bar{c}$, $\bar{\phi}$, and $\bar{A}_f$ derived from triaxial tests.

Curves of the hyperbolic fit and tangent modulus were superimposed over the experimental data and, in general, the methods give good approximations for the materials tested. Figure 2.2.1-2 shows the results for MARA-02, GC-4. Agreement with experimental results was much poorer for samples which exhibited strain softening.

f) Poisson's ratio

For a majority of samples, Poisson's ratio at small vertical strains exhibited peaks between 0.3 and 0.45 and then continued to increase with further vertical strain (Table 2.2.1-4). The strain at which the peaks occurred corresponded to the yield strain of the samples. Whether the sample was tested as overconsolidated (OC) or normally consolidated (NC) had an affect on Poisson's ratio with OC samples showing slightly lower values than NC in most cases. In some cases the calculated Poisson ratio derived from lateral strain measurements was greater than 0.5 for large strains. It should be kept in mind that Poisson's ratio is really only valid for small strains (elastic stress-strain). Values into the plastic region of the stress-strain curve are, therefore, of questionable relevance.

Analysis

The excellent agreement between triaxial and vane data in Figure 2.2.1-1 brings out several important points. It illustrates that the at-rest earth pressure coefficient, K_0 , should be incorporated into strength calculations. It suggests that the Giant Piston Corer takes a high quality sample for geotechnical testing. Vane shear tests that were run on board before any disturbance due to handling and sample preparation compare well with lab triaxial results. It also appears that miniature vane testing is an accurate way of obtaining undrained shear strength.

Comparison of Mohr-Colomb parameters of $\bar{c}$ and $\bar{\phi}$ obtained in this study seem very similar to other published data for the same types of marine sediments (Table 2.2.1-3). It should be noted that all tests were run at relatively low confining pressures (220 kPa maximum, most less than 165 kPa). Comparison with Pacific illite (MARA-12) CIU tests at higher confining pressures (2.7 kPa maximum) and MARA-02 illite from this

study (83 kPa maximum consolidation pressure) reveal significant differences in the Mohr-Coulomb parameters (See Section 2.2.2). At higher consolidation pressures some strain-softening is seen in the stress-strain curves while in this study the sediments exhibited predominantly strain-hardening behavior as well as a much less common occurrence of strain softening. If it is assumed that there are no significant differences in material properties of the illite from MARA-02 and MARA-12 then variations between these test series in ϕ and $\bar{c}$ appear to be due to higher consolidation pressures. Further testing is currently underway to investigate this.

Though the hyperbolic stress-strain relationship exhibited a good fit to many of the experimental curves, the limitations of this model must be noted. This relationship is only applicable for the analysis of stress and strain prior to failure (Wong and Duncan, 1974). For this reason, the complete experimental curves cannot be predicted by this relationship. Also since elastic theory requires an upper bound of 0.5 on Poisson's ratio, the hyperbolic relationship cannot account for volume changes in dilatant materials. Using Equation 1 to incorporate K_0 into computing normalized strength parameters, it is found that good agreement exists between these values and experimental results of CAU testing on MARA-12 illite (See Section 2.2.2). This again points to the benefits of including the coefficient of earth pressure at rest when applying these tests results to the in situ stress conditions.

Intact structural arrangement plays an important part in the strength of Pacific illite as remolded strengths are much lower than remolded smectite values. Smectite having a more amorphous clay platelet arrangement is usually much less sensitive to remolding than the hydrous micas (Mitchell, 1976) in the absence of cementation.

2.2.2 Anisotropically Consolidated Undrained (CAU) Triaxial Results (S. Jordan, W. Levy)

A routine method of examining stress-strain behavior is to perform a series of isotropically consolidated undrained (CIU) triaxial tests. However, many soils exhibit anisotropy, which cannot be accounted for in this type of test. One way to introduce anisotropy is to consolidate a sample under conditions of no lateral strain (K_0 - consolidation). Here, the horizontal effective stress, σ_{hc} , is related to the vertical effective stress, σ_{vc} , by a coefficient of earth pressure at rest $K_0 = \sigma_{hc} / \sigma_{vc}$.

The overall objective of this study is to investigate the effects of anisotropic consolidation on the stress-strain behavior of sediments. Parameters are determined and compared with those obtained from CIU tests. If these parameters and general behavior of CAU tests prove to be significantly different, then the results of CIU tests may be inadequate for modeling deep-sea sediments.

The first stage of the CAU test program has been completed and reported in detail in a technical report (Schwartz and Silva, 1980).

Test Program

The samples analyzed in this study are deep-sea clays from the MPG-I site. Both undisturbed and remolded sample series were tested. Table 2.2.2-1 lists the locations of these undisturbed samples.

Two undisturbed triaxial series of Pacific illitic clays subsampled from gravity cores during the MARA 12 cruise were used in this program. A series of three specimens from GC-28 were consolidated isotropically and served as control data. A series of four specimens from GC22 were used for CAU testing.

Reconstituted-reconsolidated (remolded) samples of Pacific illite and smectite were obtained from large tanks (see sec. 2.2.1). Both sediment types were reconsolidated to a simulated 9 meter depth (28 kPa). CAU triaxial tests were then performed on one series of three specimens of Pacific illite and another series of three Pacific smectite. These results could then be compared with CIU results of samples from the same tanks (see sec. 2.2.1).

The CIU equipment and procedures used are the same as described in section 2.2.1. For CAU triaxial testing a K_0 consolidation system was fabricated at URI/MGL. After a back pressure of 275 kPa was applied for a period sufficient to properly saturate the sample, K_0 anisotropic consolidation began. A servo loop system takes the output of the lateral strain gauge, (see sec. 2.2.1) and upon manually increasing the cell pressure, triggers a linear actuator that applies an axial load. The equipment is shown in Figure 2.2.2-1. The axial load is controlled to maintain a zero lateral strain condition throughout the consolidation stage (Figure 2.2.2-2). Top and bottom drainage was connected to the sample with the top drainage serving only as a part to measure pore pressure. This made it possible to measure the difference in pore pressure between both ends of the sample during consolidation and allowed the choice of the proper rate of cell pressure increase. The consolidation phase typically takes about 3 days.

After consolidation the drainage valve was closed and shearing was initiated at 0.03 mm/min. Corrections were made for the load carried by the membranes and filter strips. The total of these two corrections amounts to 5 - 10% reduction in deviator stress values in this test program. Corrections were also made for piston friction effects (Schwartz and Silva, 1981).

Presentation of Results and Comparisons

a) K_0

Table 2.2.2-2 shows the values of K_0 for each sample as well as the average value for each series. The value of K_0 was determined by the ratio of σ_{3c}/σ_{1c} which ranged from .47 to .58 for the undisturbed illite and .40 to .53 for the remolded smectite with average values of .52 and .48 respectively. These results will be discussed later.

b) Deviator stress

The deviator stress (CIU) plots for MARA 12 GC28 (Figure 2.2.2-3) shows an important strain softening (i.e., decrease in the deviator

stress after the peak has been reached), for tests consolidated at higher pressure (138 kPa for MARA 12 GC28 152-162 cm and 207 kPa for 164-174 cm). These plots are quite different from those obtained by Akers (Akers and Silva, 1980) on similar material which exhibited minimal strain softening. However, the consolidation stress for each of Akers' seven tests was less than 83 kPa. It is therefore possible that some of the observed differences may be due to the higher consolidation stresses. Additional tests are planned to investigate this.

In the remolded smectite series (Figure 2.2.2-4), CIU test PS 9 #3 was conducted at a very low consolidation pressure (13.8 kPa). Here, the deviator stress is greatly modified when corrections for membranes and filter strips are applied. As a matter of fact, Duncan and Seed (1965) recommended that their corrections be used only for consolidation pressures greater than 35 kPa. However, it does not seem logical to compare data processed with and without corrections and therefore, only the results on PS9 #1 and PS9 #2 will be used for shear strength comparisons with CAU tests. It should be noted that no significant strain softening occurred in the CIU remolded smectite tests.

The deviator stress (CAU) plots, Figures 2.2.2-5 and 6, show the data of the undisturbed illite (MARA 12-GC22) and remolded smectite (PS 9B-70) samples. All CAU deviator stress plots have a lower axial strain at failure (approximately three times less) than for CIU tests. Also, the undisturbed illite samples show a very significant strain softening after the peak deviator stress. High stress CIU tests on undisturbed illite show a strain softening of approximately the same order on the same material. On the other hand, CAU tests on remolded smectite show almost no strain softening. These effects suggest that strain softening pertains more to the original structure of the sample than to the effect of anisotropic consolidation itself.

c) Pore pressure

Figure 2.2.2-7 shows the pore pressure vs. axial strain plots of CIU tests for the MARA 12-GC28 samples. Here, the pore pressure attains its maximum value around 10% axial strain and stays relatively unchanged thereafter. Pore pressure plots for the CAU tests are shown in Figures 2.2.2-8 and 9 for undisturbed illite (MARA 12 GC 22) and remolded smectite (PS 9B-70) respectively. It can be seen that the MARA 12 GC22 122-132 cm test exhibits a sharper bend around 1% axial strain (compared to a more gradual change for the other three tests) and the final pore pressure is much lower than for the 110-120 cm test made at a similar consolidation pressure. This behavior is not explainable with the information available. However, it may be due to a difference in the sample composition since its depth is near the zone of transition (illite to smectite) which was observed in the core. The pore pressure curves for the MARA12 GC22 samples are still increasing slightly at 20% strain, while the curves for PS 9B samples have attained their maximum values at about 12% strain.

Lo's (1969) method is used to compare CIU and CAU pore pressure data (Figures 2.2.2-10 and 11), where p is the vertical effective consolidation stress σ_{1c} . The same distinct behavior as predicted by Lo can be observed between the CIU $\Delta u/p$ data and the CAU $\Delta u/p + (1-K_0)$ data, with the CAU curves being significantly higher than the CIU curves.

d. Poisson's ratio

Since the lateral strain was measured only at mid-height, the Poisson's ratio can be computed by:

$$\mu = 0.67 \epsilon_l / \epsilon_a \quad \text{Eq. 3}$$

where: ϵ_l = lateral strain
 ϵ_a = axial strain

The coefficient 0.67 is used to average the lateral strain on the whole sample (Akers and Silva, 1980), based on the assumption that the lateral strain distribution is parabolic with the maximum at mid-height. Figures 2.2.2-12 and 13 show values of μ for the two CAU series. However, the lateral strain measured at points close to or past failure are probably unreliable because of the significant bulging of the sample that occurs at those strains. Hence, values of μ computed by this method should be considered only for small axial strains. In Tables 2.2.2.-3 and 4 are listed values of μ computed at half the axial strain at failure (defined as the point of maximum deviator stress). The average value is 0.44 for undisturbed illite and 0.49 for remolded smectite. These values are larger than those reported by Akers at small axial strains for CIU tests on varied materials.

e) Shear strength parameters

The p-q plots for CIU and CAU tests are shown in Figures 2.2.2-14 through 17. The p-q plots for CAU tests (Figure 2.2.2-16 and 17) show stress conditions at the end of consolidation and the beginning of shearing to be different. This is a result of reducing the effects of piston friction to zero before initiating shear. A comparison of these plots reveal two distinct approaches to failure for CIU and CAU tests. Generally, for CAU tests a maximum value of p and q is reached followed by a relaxation of p to failure, whereas, CIU tests display a gradual and continuous increase in p and q to failure. However, this does not have a significant affect on the shear strength parameters (Table 2.2.2-5).

Table 2.2.2-5 shows the friction angle ϕ for the undisturbed at $(\sigma_1 - \sigma_3)_{\max}$ to be approximately equal for CAU and CIU tests. However, for the $(\sigma_1/\sigma_3)_{\max}$ criterion the CAU tests give a larger value of ϕ than CIU's.

The data for the remolded smectite series is very preliminary, since in each series only two tests have been considered for computations. At $(\sigma_1 - \sigma_3)_{\max}$ the ϕ angle is the same for both CIU and CAU, but if the CIU series includes the PS 9 #3 data without corrections, this leads to a much higher value of the angle (36.7° instead of 32.7°). This higher value compares well with $c=1.4$ kPa and $\phi = 37.3^\circ$ for all uncorrected values reported by Akers (Akers and Silva, 1980). However, comparison between corrected data shows that the shear strength parameters are almost identical for CIU and CAU tests on remolded smectite.

Discussion of Results and Conclusions

The values of K_0 computed according to Jaky (1948) are listed in Table 2.2.2-2 together with the average value of K_0 for each series. The averaged experimental K_0 values at the end of consolidation vary

slightly from those predicted by Jaky's expression: $K_0 = 1 - \sin \phi$. Here, K_0 is equal to 0.52 for undisturbed illite and 0.48 for remolded smectite. It is recommended that future studies use the no lateral strain condition for anisotropic consolidation because K_0 is a function of the stress history of the sample and it may not be sufficient to use a single value throughout the consolidation phase.

Tables 2.2.2-3 through 5 show tabulated CIU and CAU test results. According to most authors, the value of the ratio S_u/σ_{1c} ($S_u = 1/2 \times (\sigma_1 - \sigma_3)_{\max}$) is practically the same for CIU and CAU. In the data presented in Tables 2.2.2-3 and 4, there are larger differences within a single series rather than between the two types of tests. Tables 2.2.2-3 and 4 also show much lower values of the axial strain at maximum deviator stress for the CAU tests. This is a result of applying a significant amount of the deviator stress during consolidation, and then the maximum is reached at lower strains during undrained shear. Finally, these tables show the A-factor under $(\sigma_1 - \sigma_3)_{\max}$ to be relatively unchanged, whereas, under $(\sigma_1/\sigma_3)_{\max}$ a significant increase is realized (from CIU to CAU). This is due to the fact that in the CAU tests, the deviator stress plots show a large reduction of stress after the maximum is reached while the pore pressure plots show a constant value (of pore pressure) after the strain corresponding to that maximum value of stress.

In the literature, there is no general agreement on whether the angle is changed at $(\sigma_1 - \sigma_3)_{\max}$. Ladd (1965) found that ϕ decreased from CIU to CAU. From Table 2.2.2-5 it can be seen that this is what happened in the data presented. However, considering the uncertainties on the failure envelopes, there does not seem to be significant effect. At $(\sigma_1/\sigma_3)_{\max}$, most authors found that ϕ is unchanged, here there is a difference of 2.6° .

From the data shown several preliminary conclusions can be made:

1. CAU triaxial tests results on undisturbed illite-rich clay and remolded smectite-rich clay show that the normalized shear strength s_u/σ_{1c} is about 15% less for CAU than for CIU, while the A-factor at maximum deviator stress is unchanged.
2. The axial strain at maximum deviator stress is at least three times lower for CAU tests than for CIU's.
3. Although CAU tests on both materials show a decrease in deviator stress beyond the peak, this effect is much more dramatic for the undisturbed illite as compared to remolded smectite and is also noticed in CIU tests at high consolidation pressure on this material.
4. At maximum obliquity the ratio σ_1/σ_3 decreases by about 20% from CIU to CAU tests, while the A-factor is much larger.
5. The normalized pore pressure plotted vs. axial strain gives one single curve for all CIU tests and another higher one for all CAU's. This shows two distinct behaviors and is in agreement with Lo's (1969) work on normally consolidated clays.
6. Using the $(\sigma_1 - \sigma_3)_{\max}$ failure criterion for undisturbed illite, CAU tests exhibit a ϕ angle of 29.5° which is 3° larger than for the CIU tests and a 9.4 kPa cohesion intercept compared to 8.2 kPa for CIU. The shear strength parameters do not appear to

change for remolded smectite.

2.2.3 Effects of Stress Path on Triaxial Tests (S. Jordan, D. Calnan)

The triaxial compression test program is being expanded to investigate the stress-strain behavior of deep sea sediments for various types of loading and unloading conditions. These data will be of direct importance in hole closure calculations and other situations where the stress history is different than the usual ones simulated with the CIU and CAU test. A representation of a complete program of stress path testing using a triaxial device is shown in Figure 2.2.3-1.

Figure 2.2.3-1 PROJECTIONS OF STRESS PATHS ON TRIAXIAL PLANE

Here HC = Hydrostatic Compression.,
 CTC = Conventional Triaxial Compression,
 CTE = Conventional Triaxial Extension,
 RTE = Reduced Triaxial Extension,
 RTC = Reduced Triaxial Compression,
 TC,SS = Triaxial Compression or Simple Shear and
 TE = Triaxial Extension.

The first stages of an investigation on the stress-strain properties of marine sediments under various stress paths to failure was begun at the end of calendar year 1980. Reported here are the results of two tests (RTE) completed to date which are compared qualitatively to previous data from CIU (or CTC) tests on remolded illites from the Hole Closure study. This data is preliminary in nature because the equipment and test methods are being modified. Reliable equipment and procedures will (for the most part) be developed by early FY 1981.

Some of the specific goals (but not limited to) of this investigation are:

1. Determine and compare Mohr-Coulomb stress-strain parameters.
2. Compare levels of stress and strain at failure.
3. Examine the behavior of the sediment beyond failure [have displayed strain-hardening under CIU (Akers and Silva, 1980)].
4. Examine and compare the overall response of the sediment.
5. Induce unloading conditions prior to and after failure.

Test Program

The equipment being used at this time is a triaxial cell utilized in the room temperature creep study modified to provide a threaded connection between the piston and the loading cap. Other changes (ball bearing washers) were incorporated into the loading piston to allow a rigid connection in the vertical direction and to minimize the problem of lateral friction during uplift. Details of the final test equipment will be provided once a satisfactory system is attained.

The test procedure used for the two RTE tests was to first, isotropically consolidate a sample in the creep test frame (which compensates for the chamber pressure's uplift effect on the piston). Then, the piston was locked in place and the cell transferred to a load press where the sample was sheared. Shearing was initiated in the undrained state with cell pressure maintained constant and the vertical load gradually reduced. The strain rate was approximately 0.015 mm/min or about half of that used during a typical compression test.

Test Results

Figure 2.2.3-1 shows the results from two RTE tests on reconstituted/reconsolidated (remolded) illite samples which were taken from Hole Closure Tank PI-2. The samples were consolidated to stress levels comparable to compression tests by Akers (Akers and Silva, 1980) which are also shown in Figure 2.2.3-1. The RTE results are not corrected for the effects of the membranes or filter strips.

In order to obtain a qualitative plot for comparison between the RTE and CTC (CIU) tests, it is convenient to represent the resulting shearing stress in invariant form. Here, the octahedral shearing stress τ_{oct} is used:

$$\tau_{oct}^2 = 1/9 [(\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \quad \text{Eq. 1a}$$

Under a triaxial test condition [intermediate principal stress σ_2 is equal to the minor principal stress σ_3 (compression) or major principal stress σ_1 (extension)], equation 1a reduces to:

$$\tau_{oct} = 0.47 |(\sigma_1 - \sigma_3)| \quad \text{Eq. 1b}$$

Examining equation 1b, it can be seen that pore pressure measurements have no effect on a resulting plot.

In Figure 2.2.3-1, the shear stress at failure is essentially equal for both tests (RTE and CTC) under a consolidation stress $\sigma_c = 55$ kPa (8 psi), but for $\sigma_c = 98$ kPa (14 psi) there is clearly a difference. Here, the shear stress at failure (approximately 60 kPa) in the extension (RTE) test is considerably greater than the compression (CTC) test (49 kPa); an increase of approximately 22%. This result was not expected since previous work on marine clays (Campanella and Vaid, 1972) indicated that the undrained strength in extension was approximately 70% of that in compression. However, Campanella and Vaid's tests were performed under K_0 consolidation and used an undisturbed sample. In contrast, Figure 2.2.3-1 shows strains at failure to be considerably less for the RTE tests; approximate values of 2.2% for CTC and 1.9% for RTE ($\sigma_c = 55$ kPa) and 6.8% for CTC and 2.5% for RTE ($\sigma_c = 98$ kPa).

During axial extension the membrane has considerable effect on the recorded results. Therefore, until its effect is evaluated, no positive conclusion can be made with regard to the strength of this sediment in extension. However, this is not so for strain. It is noticeably clear that the strains at failure are significantly less in the RTE tests especially under the higher consolidation stress.

2.2.4 High Pressure Isotropically Consolidated Undrained (HPCIU) Triaxial Testing Program (P. Sargent, S. Jordan)

The main purpose of this program will be to determine and study the effective stress parameters and sediment behavior of remolded and undisturbed Pacific illite from the MPG-1 area under high pressure conditions. For a HPCIU test, samples will be isotropically consolidated to various higher stresses [than the series just completed in the CIU program (see section 2.2.1)] simulating high pressures created by the emplacement of waste canisters. Here, the sediment response will be examined during both quasi-static loading and unloading conditions. This response can be directly related to the Hole Closure experiments and analysis. These tests will be coordinated with similar work being done by The Army Corps of Engineers at Waterways Experiment Station.

Some of the immediate specific goals of the high pressure testing program are:

1. Provide stress-strain properties for Pacific Illite at high consolidation pressures.
2. Compare the properties of remolded and undisturbed samples of Pacific illite at high consolidation pressures.
3. Provide effective stress parameters for a computer model developed at Waterways Experiment Station.
4. Compare stress-strain parameters of previous CIU testing at low pressures with that of HPCIU testing.

Test Program -

a) Samples

Early stages of the program will involve testing remolded samples from the Sediment-Structure Interaction Testing (SSIT) Laboratory Tank PI-5-8 (see section 4.2). The designation PI-5-8 represents Pacific illite Tank #8 consolidated to a simulated depth of 5 meters (22.07 kPa). The undisturbed samples will be obtained from a cruise (during FY 81) in MPG-I area.

b) Equipment

The triaxial cells are standard Wykeham-Farance triaxial cells (Akers and Silva, 1980) with some modifications. Major modifications include replacing the plexiglas chamber with an aluminum chamber for pressures above 14.5 kPa and possibly replacing the solid bushing around the piston with a linear bushing(s).

c) Procedures

Full back pressure will be attained before consolidation is initiated to ensure complete saturation of the samples. Then the cell pressure is increased (incrementally, if necessary) to create various effective consolidation pressures. Consolidation occurs under these high pressures until a minimum of 90 percent consolidation is reached. Shearing the sample will then be induced at a rate of 0.030 millimeters per minute until 20 percent axial strain is reached or collapse of the sample.

2.2.5 Additional Triaxial Studies

Five triaxial samples of reconstituted-reconsolidated (remolded) deep sea smectite that has a simulated 8 meter (25 kPa) depth have been selected for a special CIU test series evaluating the effects of exposure to high level gamma radiation on sediment shear strength. Exposure will be done at Sandia National Laboratories using a Cobalt 60 radioisotope source. A steady dose rate of approximately 10^6 roentgen/hr is emitted from this source with insignificant decay (5.5 yr. half life). Each specimen will receive varying amounts of total dosage and CIU testing will take place at URI/MGL. Comparison with a control CIU series on unexposed smectite specimens can then be made to evaluate any change in sediment response.

2.2.6 Summary of Triaxial Tests

During FY 80 a comprehensive series of isotropically consolidated undrained (CIU) tests was completed and a preliminary series of anisotropically consolidated undrained (CAU) tests was completed. The program has been expanded to investigate the effects of stress path and high pressures and a study of CIU tests on radiated samples is to begin during FY 81. The following is a summary of our findings.

CIU Tests:

- 1) Mohr-Coulomb failure parameters of effective cohesion ($\bar{c}$) and effective friction angle ϕ are comparable with other published

- values for marine illites and smectites (Table 2.2.1-4).
- 2) The coefficient of at-rest earth pressure K_0 should be incorporated into the determination of normalized undrained shear strength parameters.
 - 3) Vane shear results correlate well with experimentally derived values of undrained shear strength. The giant piston corer takes a high quality undisturbed sample for geotechnical testing purposes.
 - 4) Average values of shear strength parameters for undisturbed specimens were slightly higher than remolded values in most cases. Cohesion and friction angle for smectite were essentially unaffected by the remolding process.
 - 5) Undisturbed smectite samples had friction angles greater than the undisturbed illite as well as higher normalized undrained shear strength. This coupled with the greater sensitivity of illite to remolding is an important consideration to canister emplacement.
 - 6) The stress-strain properties of remolded samples indicate strength anisotropy. Vertically oriented remolded samples showed slightly larger friction angles and lower cohesion intercepts than horizontal samples. Further study of strength anisotropy is indicated by this test program and would be of concern in the sediment barrier concept.
 - 7) Hyperbolic stress-strain analysis seems to work well as a relationship for stress-strain conditions prior to failure. Post-failure behavior which could be important to canister emplacement cannot be predicted this way.
 - 8) Analysis of Poisson's ratio using the disk-ring lateral strain gauge have yielded some questionable results. Values seem more reasonable for the elastic ($2.4\% \epsilon_L$) portions of the stress-strain curves. In the future alternative methods for measurement of Poisson's ratio should be used.

CAU tests:

- 1) The average value of K_0 is 0.53 for undisturbed illite and 0.48 for remolded smectite.
- 2) Comparison between CIU and CAU tests indicates that the axial strain at failure is at least three times less for CAU samples than for CIU's.
- 3) The strain softening after the peak deviator stress is observed for CAU tests on undisturbed illite, and can also be noticed for CIU tests on this material when the consolidation pressure is greater than 20 kPa.
- 4) The normalized pore pressure curve of $\Delta u/p + (1-K_0)$ vs. axial strain for CAU tests is significantly higher than the curve of $\Delta u/p$ for CIU tests.
- 5) CIU and CAU tests have the same A-factor at $(\sigma_1 - \sigma_3)_{\max}$ for undisturbed illite and remolded smectite. However, at large strains, the A-factor remains constant in CIU tests while it increases steadily in CAU tests.
- 6) The shear strength ratio s_u/σ_1 (where $s_u = 1/2 (\sigma_1 - \sigma_3)_{\max}$ and σ_3 is the vertical effective consolidation stress) is about 15% less for CAU than for CIU's.
- 7) At $(\sigma_1 - \sigma_3)_{\max}$, the friction angle ϕ and cohesion intercept, c , are unchanged for CIU and CAU tests, however, at σ_1/σ_3

- 3) $\max c$ is essentially the same but ϕ is different.
- 8) The value of the Poisson's ratio at half the axial strain at failure is between 0.4 and 0.5 for each CAU sample.

Stress path tests:

- 1) Strains at failure appear to be significantly less for the extension (RTE) tests compared to the CTC (compression) tests.

Further CAU tests will continue at URI/MGL to substantiate our findings in an overall effort to assess the effects of anisotropic consolidation. To date, it appears that these tests have demonstrated a significant change in material parameters and general behavior of the sediment as compared to tests conducted under isotropic consolidation.

Stress path testing will continue, investigating the differences and similarities between remolded and undisturbed specimens, at various stress paths to failure especially those more in line with the anticipated field conditions. Future testing will include this approach with a careful study of pore pressure effects.

URI/MGL standard (CIU) triaxial test program is continuing with some changes. Here, samples will be isotropically consolidated to various high consolidation pressures which will simulate emplacement of a waste canister. The sediment response will be examined and mechanical parameters determined for incorporation into a material model. In addition, standard tests will be conducted on remolded smectite samples previously exposed to gamma radiation.

Table 2.2.1-1: Undisturbed Sample Coordinates

<u>Cruise Designation</u>	<u>Core Designation</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Undisturbed Length</u>
LL-44	GPC-3	30°19.9'N	157°49.4'W	24.4 m
MARA-II	GC-4	30°06.3'N	157°51.7'W	2.5 m
VEMA-32	PC-115	30°36'N	158°53'W	10.0 m

Table 2.2.1-2 CIU TEST PROGRAM

UNDISTURBED SAMPLES

Illite

MARA-02 GC-4

VEMA-32 PC-115

76-84 cm	203-214 cm	206-216 cm	483-493 cm
86-94	216-224	219-229	499-509
95-105	228-235	232-242	523-533
105-115	238-245		

Smectite

LL-44 GPC-3

1845-1857 cm
 1859-1868
 1873-1883

RECONSTITUTED-RECONSOLIDATED SAMPLES

Illite

Vertically oriented - 2 meter simulation
 - 18 meter

Horizontally oriented - 2 meter

Smectite

Vertically oriented - 9 meter simulation
 - 18 meter

Horizontally oriented - 18 meter

Table 2.2.1-3

MOHR-COULOMB PARAMETERS

SAMPLE SERIES	$\bar{c}$ (kPa)	$\bar{\phi}$ degrees	$q_{fu}/\bar{\sigma}_c$
<u>SMECTITE</u>			
LL-44, GPC-3, 1800 cm	1.57	35.5	0.437
PS-9 Vertical	1.08	37.3	0.440
PS-18 Vertical	0.88	36.3	0.468
PS-18 Horizontal	2.45	33.4	0.460
<u>ILLITE</u>			
MA-02, GC-04, 200 cm	0	34.8	0.374
MA-02, GC-04, 100 cm	3.04	33.0	0.374
PI-18 Vertical	9.90	30.4	0.449
PI-2 Vertical	1.27	24.6	0.362
PI-2 Horizontal	2.45	22.8	0.284
V-32, PC-115, 200 cm	4.02	22.9	0.316
V-32, PC-115, 400 cm*	5.00	28.3	0.400
Lee and Hamilton (1974)			
Illite (depth: upper 10 meters)	1.77-3.33	35-36	
Smectite (depth: upper 10 meters)	3.43-4.12	37-38	
Silva and Clukey (1975)			
Illite (depth: upper meter)	0	34	
	0	35.8	
Noorany			
Pelagic Clay (Illite)	1.96	32	

*Transition: illite to smectite

Table 2.2.1-4
Lateral Strain and Poisson's Ratio

Sample I.D.	ϵ_L % at		ν at	
	2.4%	10%	2.4%	10%
Smectite:				
LL-44 GPC-3				
1845-1857	1.12	7.36	0.31	0.49
1859-1868	1.28	7.23	0.35	0.48
PS-9 Vertical				
#3	0.88	6.05	0.24	0.40
#4	1.26	4.79	0.35	0.32
PS-18 Vertical				
#1	1.28	6.91	0.36	0.46
#3	1.10	6.91	0.30	0.46
PS-18 Horizontal				
#8	0.62	4.38	0.17	0.29
#10	1.04	4.64	0.29	0.31
Illite:				
MA-02 GC-04				
216-224	1.19	7.10	0.33	0.47
228-235	1.44	8.87	0.40	0.59
238-245	1.94	9.90	0.54	0.66
76-84	0.66	4.65	0.18	0.31
86-94	1.35	8.39	0.37	0.56
105-115	1.61	8.18	0.45	0.54
PI-2 Vertical				
#4	0.54	1.85	0.15	0.12
#5	1.09	4.12	0.30	0.28
PI-2 Horizontal				
#6	2.09	10.16	0.58	0.68
#7	1.97	11.11	0.54	0.74
#8	0.70	5.22	0.19	0.35
#9	0.33	1.30	0.09	0.09

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Table 2.2.2-1
CAU TEST PROGRAM

Illite

Sample I.D.	Test	Location	Type Sample
MARA 12 GC 28		30° 20.1' N 158° 59.8' W	Undisturbed
140 - 150 cm	CIU		
152 - 162 cm	CIU		
164 - 174 cm	CIU		
MARA 12 GC 22		31° 04.8 ' N 159° 03.5 ' W	Undisturbed
86 - 96 cm	CAU		
98 - 108 cm	CAU		
110 - 120 cm	CAU		
122 - 132 cm	CAU		
PI 9-80-1	CAU	(from disturbed LL-44)	Remolded
PI 9-80-2	CAU		
PI 9-80-3	CAU		

Smectite

Sample I.D.	Test	Location	Type Sample
PS 9B-70-1	CAU	(from disturbed LL-44)	Remolded
PS 9B-70-2	CAU		Remolded
PS 9B-70-3	CAU		Remolded

TABLE 2.2.2-2

CAU CONSOLIDATION DATA

MARA 12 GC 22

(Undisturbed Illite)

SAMPLE DEPTH	$\bar{\sigma}_3_c$ (kPa)	$\bar{\sigma}_1_c$ (kPa)	K_o
86-96 cm	125.9	213.9	0.58
98-108 cm	71.7	149.8	0.47
110-120 cm	107.5	202.0	0.52
122-132 cm	103.8	204.4	<u>0.50</u>
			0.52 = Ave.

For $\bar{\phi} = 25.9^\circ$: $K_o = 0.56$ (Jaky, 1948)

PS 9B-70

(Remolded Smectite)

SAMPLE ID	$\bar{\sigma}_3_c$ (kPa)	$\bar{\sigma}_1_c$ (kPa)	K_o
PS9B-70-1	45.5	122.8	0.40
PS9B-70-2	140.4	265.1	0.53
PS9B-70-3	85.9	174.1	<u>0.49</u>
			0.48 = Ave.

For $\bar{\phi} = 32.9^\circ$: $K_o = 0.46$ (Jaky, 1948)

TABLE 2.2.2-3

UNDISTURBED ILLITE CIU TEST DATA

MAR 12 GC 28

SAMPLE DEPTH	$\bar{\sigma}_{1c}$ kPa	$\Delta t (\sigma_1 - \sigma_3)_{max}$					$\Delta t (\bar{\sigma}_1 - \bar{\sigma}_3)_{max}$				
		$(\sigma_1 - \sigma_3)$ kPa	ϵ_f %	$\bar{\sigma}_1 / \bar{\sigma}_3$	Λ_f	$s_u / \bar{\sigma}_{1c}$	$(\sigma_1 - \sigma_3)$ kPa	ϵ %	$\bar{\sigma}_1 / \bar{\sigma}_3$	Λ	$q / \bar{\sigma}_{1c}$
140-150 cm	69.0	49.4	11.9	3.84	1.02	0.358	49.3	12.5	3.94	1.04	0.357
152-162 cm	137.9	127.9	4.4	3.36	0.64	0.464	122.5	7.3	3.48	0.71	0.444
164-174 cm	206.8	146.1	5.0	2.80	0.84	0.353	142.4	7.9	3.10	0.96	0.344
					Ave. =	0.392				Ave. =	0.382

UNDISTURBED ILLITE CAU TEST DATA

MAR 12 GC 22

SAMPLE DEPTH	$\Delta t (\sigma_1 - \sigma_3)_{max}$					$\Delta t (\bar{\sigma}_1 - \bar{\sigma}_3)_{max}$				
	$\sigma_1 - \sigma_3$ kPa	ϵ_f %	$\bar{\sigma}_1 / \bar{\sigma}_3$	Λ_f	$s_u / \bar{\sigma}_{1c}$	$\sigma_1 - \sigma_3$ kPa	ϵ %	$\bar{\sigma}_1 / \bar{\sigma}_3$	Λ	$q / \bar{\sigma}_{1c}$
86-96 cm	159.4	2.0	3.05	0.66	0.373	148.7	5.8	3.51	1.09	0.348
98-108 cm	105.2	1.4	3.19	0.86	0.351	85.4	7.8	3.59	6.25	0.285
110-120 cm	136.7	0.9	2.75	0.68	0.338	117.9	9.2	3.56	2.75	0.292
122-132 cm	134.2	2.6	3.09	1.19	0.328	125.2	6.8	3.23	2.00	0.306
				Ave. =	0.348				Ave. =	0.308

TABLE 2.2.2-4
REMOLDED SMECTITE CIU TEST DATA

PS 9

SAMPLE IDENTIFICATION	$\bar{\sigma}_{1c}$ kPa	At $(\sigma_1 - \sigma_3)_{max}$					At $(\bar{\sigma}_1 / \bar{\sigma}_3)_{max}$				
		$\sigma_1 - \sigma_3$ kPa	ϵ_f %	$\bar{\sigma}_1 / \bar{\sigma}_3$	A_f	$s_u / \bar{\sigma}_{1c}$	$\bar{\sigma}_1 - \bar{\sigma}_3$ kPa	ϵ %	$\bar{\sigma}_1 / \bar{\sigma}_3$	A	$q / \bar{\sigma}_{1c}$
PS 9 #1	48.9	43.4	17.4	4.85	0.86	0.443	43.0	16.1	4.76	0.86	0.439
PS 9 #2	83.5	66.5	12.9	4.15	0.92	0.398	65.7	16.2	4.22	0.94	0.394
PS 9 #3	13.8	15.6	9.5	3.59	0.50	<u>0.562</u>	15.4	10.1	5.27	0.66	<u>0.558</u>
					Ave. =	0.468				Ave. =	0.464

REMOLDED SMECTITE CAU TEST DATA

PS9B-70

SAMPLE IDENTIFICATION	At $(\sigma_1 - \sigma_3)_{max}$					At $(\sigma_1 / \sigma_3)_{max}$					POISSON'S RATIO at $\frac{1}{2} \epsilon_f$
	$\sigma_1 - \sigma_3$ kPa	ϵ_f %	$\bar{\sigma}_1 / \bar{\sigma}_3$	A_f	$s_u / \bar{\sigma}_{1c}$	$\sigma_1 - \sigma_3$ kPa	ϵ %	$\bar{\sigma}_1 / \bar{\sigma}_3$	A	$q / \bar{\sigma}_{1c}$	
PS9B-70-2	181.6	5.4	3.61	1.24	0.343	180.3	10.8	4.02	1.45	0.340	0.51
PS9B-70-3	131.2	4.0	3.70	0.87	<u>0.377</u>	127.3	10.4	4.14	1.17	<u>0.365</u>	0.46
				Ave. =	0.360				Ave. =	0.353	

TABLE 2.2.2-5
SHEAR STRENGTH PARAMETERS
CAU PROGRAM

SEDIMENT SERIES	NUMBER OF SAMPLES	At $(\sigma_1 - \sigma_3)$ max		At $(\bar{\sigma}_1 / \bar{\sigma}_3)$ max	
		$\bar{c}$ kPa	$\bar{\phi}$ DEGREES	$\bar{c}$ kPa	$\bar{\phi}$ Degrees
<u>Illite</u>					
MARA 12 GC 28 CIU	3	8.2	26.4°	5.9	29.1°
MARA 12 GC 22 CAU	4	9.4	25.9°	5.3	31.7°
<u>Smectite</u>					
PS9 CIU	2 3*	4.6 1.4	32.7° 36.7°	3.8	33.9°
PS9B-70 CAU	2	4.3	32.9°	4.1	35.4°

* This includes sample PS9 #3 with uncorrected values of stresses, since its consolidation pressure is very low.

Figure 2.2.1-1

STRAIN %
 DEV. STRESS vs. STRAIN
 KA-02 GC-04 200 CM.

HYPERBOLIC CURVES (SOLID LINES) SUPERIMPOSED ON EXPERIMENTAL CURVES

Figure 2.2.1-2

Figure 2.2.2-1 CAU Triaxial Test Apparatus

Figure 2.2.2-2 Example of K_0 Consolidation Curve

MARA12 GC22 110-120 cm

AXIAL STRAIN (%)
DEVIATOR STRESS vs. AXIAL STRAIN
MARA 12 - GC 28
URI/MGL

Figure 2.2.2-3 CIU tests

AXIAL STRAIN (%)
DEVIATOR STRESS vs. AXIAL STRAIN
P.S. 9
URI/MGL

Figure 2.2.2-4 CIU tests

DEVIATOR STRESS vs. AXIAL STRAIN
MARA 12 - GC 22
URI/MGL

Figure 2.2.2-5 CAU tests

DEVIATOR STRESS vs. AXIAL STRAIN
P.S. 9B-70
URI/MGL

Figure 2.2.2-6 CAU tests

AXIAL STRAIN (%)
PORE PRESSURE vs. AXIAL STRAIN
MARA 12 - GC 28
URI/MCL

Figure 2.2.2-7 CIU tests

AXIAL STRAIN (%)
PORE PRESSURE vs. AXIAL STRAIN
MARA 12 - GC 22
URI/MCL

Figure 2.2.2-8 CAU tests

AXIAL STRAIN (%)
 PORE PRESSURE vs. AXIAL STRAIN
 P.S. 98-78
 URI/MGL

Figure 2.2.2-9 CAU tests

AXIAL STRAIN (ϵ)
 NORMALIZED PORE PRESSURE vs. AXIAL STRAIN
 MARA 12- GC 22 & 28
 URI/MGL

Figure 2.2.2-10 Combined CIU and CAU tests

AXIAL STRAIN (ϵ)
 NORMALIZED PORE PRESSURE vs. AXIAL STRAIN
 P.S. 9 & P.S. 98-70
 URI/MGL

Figure 2.2.2-11 Combined CIU and CAU tests

POISSON'S RATIO vs. AXIAL STRAIN
MARA 12 - GC 22
URI/MGL

Figure 2.2.2-12 CAU tests

POISSON'S RATIO vs. AXIAL STRAIN
P.S. 9B-70 CAU
URI/MGL

Figure 2.2.2-13 CAU tests

Figure 2.2.2-14 CIU tests

Figure 2.2.2-15 CIU tests

Figure 2.2.2-16 CAU tests

Figure 2.2.2-17 CAU tests

τ_{oct} vs. AXIAL STRAIN
PI-2 EXT & COMP

URI/MCL

Figure 2.2.3-1

2.3 CREEP STUDIES

Introduction

Creep studies at URI/MGL have basically been carried out in two phases. The first phase examined the drained triaxial creep behavior of deep sea sediments under constant stress at room temperature. This work has been completed, analyzed and published and a follow-up long term test (1 year) has been started. The second phase provides a first look at the effects of elevated temperatures on the drained creep behavior under constant stress loading conditions. These preliminary results are reported here and more detailed analyses with additional testing are underway. Results of a single undrained constant load creep test are also included in this report.

2.3.1 Room Temperature (K. Moran)

As previously reported in Silva and Calnan, 1980, creep characteristics of the sediment are being studied to determine parameters necessary for assessment of canister displacement after emplacement and hole closure behind the canister. The initial creep studies at URI/MGL consist of a series of room temperature, drained, constant stress, triaxially loaded tests. The materials in this phase of testing are undisturbed illite (UI), undisturbed smectite (US), and remolded smectite (RS). The undisturbed smectite material was sampled from three MARA-02 cores: GC-07, GC-08, and GC-09. The remolded smectite material consists of sediment from GPC-02, LL-44 that was reconstituted and reconsolidated (remolded) in large tanks. Table 2.3.1-1 lists the positions and lengths of the cores used in this study. Figure 2.3.1-1 is a graphical representation of the core locations within MPG-I. A more detailed technical report based on the Master of Science thesis of K. Moran will be issued in Spring, 1981.

Test Program

The equipment, which was designed and fabricated at URI, consists of a triaxial compression system modified for long-term testing. A detailed description of the creep apparatus is reported in Silva and Calnan (1979) and in Moran (1981).

The stress levels of the room temperature tests are 10%, 25%, 40-45% and 65% of the Mohr-Coulomb material strength as determined from isotropically consolidated, undrained, triaxial compression tests (Akers and Silva, 1980). A detailed description of stress level determination is discussed in Silva and Calnan, 1980. The revised test program, shown in Table 2.3.1.-2, has been completed.

Prior to testing, all samples were stored in either 1.4" or 2.0" diameter sealed stainless steel tubes in seawater at 40° C. Sample set-up involved: extrusion; filter paper and porous stone emplacement; and securing 2 latex jackets around the specimen with 'o' rings. In some tests, a lateral strain gauge was placed at mid-height on the sample. See Akers and Silva (1980) for a detailed description of the lateral strain gauge and sample preparation.

Testing began with 69 kPa increments of back pressure applied every 12 hours until a total pressure of 276 kPa was reached. The consolidation pressure (σ_3) of 93 kPa was applied in three increments and maintained for 2 days. Creep deviator loading began by taking the final, consolidated sample height and volume change measurements and loading the frame to compensate for piston uplift.

Readings of volume change, axial strain, and pressures were taken at 30 second intervals for the first hour of each loading and increased to 1 hour intervals for the remainder of each test. Tests continued until failure (creep rupture) or until the maximum planned test time was reached (Silva and Calnan, 1979).

Results

Axial strain data for all tests is defined as positive in compression. The axial strain is calculated as:

$$\epsilon_a = \frac{\Delta L}{L_0} \quad \text{Eq. 1}$$

where L_0 is the initial sample length (after consolidation) and ΔL is the change in length. Axial strain as a function of time is the relationship most reported in the study of the creep phenomena.

In the UI series, all of the samples tested below 65% began in primary creep and moved into a secondary creep phase. Samples were tested at nominal deviator stresses of 10%, 25%, 45%, and 65% of the peak strength. Figure 2.3.1-2 is a composite plot of the illite series at the various stress levels. The general shape of the curve of the samples tested below rupture (65%) is quite similar. With the exception of UI-7 (25%), the magnitude of axial strain increases with increasing stress level. However, as noted later this sample is compositionally somewhat different than the other illites. Of interest in this series are the relatively sharp increases in strain which occur at irregular times in samples UI-2C and UI-7 at 43,230 min. and 46,300 min. respectively. Similar increases are exhibited in the smectite series.

In the US series, samples were tested at 10%, 25%, 40%, and 65% of the material strength. The axial strain as a function of time for these samples are shown in Figure 2.3.1-3. As the stress level increases, the maximum axial strain increases. In two of the tests (10% and 40%), there are sharp increases in the axial strain connecting intervals of stable creep movement, similar to those reported above for two of the illite tests. These increases occurred at 24,500 min. and 15,700 min. for the 10% and 40% tests respectively.

Sample US-2 is of special interest because it was tested at a 25% stress level for a period of 68,973 min. (47.9 days) and then step-loaded to a 65% stress level. An intermediate level of 40% was maintained for a limited time (9250 min. or 6.4 days). The complete test record is shown in Figure 2.3.1-4. The 40% stress level, although short compared to the other tests, has been extrapolated for comparison to US-4 (tested at 40%

only). The magnitude of the axial strains compare well as US-2 (40% extrapolated) reaches a strain of 15% at 55,400 min. and US-4 reaches a strain of 14.3% at 55,400 min. (Figure 2.3.1-5).

The remolded smectite test, RS-2A, exhibited very low strains as compared to the other 40% tests (Figure 2.3.1-6). The sample reached an axial strain of 7.8% at 23,400 min. (16.3 days), after which an abrupt increase in strain occurred due to a reduction in the cell pressure. Following this increase, the creep movement became more stable and the final axial strain was 8.9%.

The calculated lateral strains are reported here as positive in extension. This is opposite to the axial strain sign convention, but reported in this way to more easily compare it to previously published data. The lateral strain was calculated during each test as:

$$\epsilon_L = \frac{\Delta D}{D_0} \quad \text{Eq. 2}$$

where D_0 is the initial, consolidated diameter. The determination of the change in diameter, ΔD , was made using the volume measurements and the axial measurements as follows:

$$\text{Area} = \frac{V - \Delta V}{L - \Delta L} \quad \text{Eq. 3}$$

where ΔV is the change in volume. The diameter was then calculated using this area.

Due to the dependency of the calculation on the volume measurements, any small leak in the system can mask the true lateral strain. In some cases where leaks were detected, the data was corrected after the completion of the test.

The lateral strain for the UI material is plotted in Figure 2.3.1-7. The samples tested below the rupture stress exhibit lateral strains between 2.5% and 5%. This is equivalent to an increase in diameter between approximately -0.1 and 0.25 cm. The ruptured test (65%) had a final lateral strain of 32%.

The US material, as a series, strained laterally to a lesser degree than the UI sediment (Figure 2.3.1-8). The samples tested at 25% and 10% stress levels exhibited some dilation with strain reaching a maximum of -2% or approximately -0.1 cm. The 40% sample (US-4), unlike the lower stresses, did strain to values in the range of the UI material.

The RS sample displayed a variable lateral strain (Figure 2.3.1-9), due to the inaccuracy of the measurement in its range of deformation. The sample strained to a maximum of 0.6% or 0.2 cm. Therefore, considering the error in the measurement, the sample retained an almost constant diameter throughout the test.

Analysis

The long-term, drained creep characteristics of the deep sea sediments follow general trends similar to those reported for terrestrial data by Bishop and Lovenbury (1969). The axial strain, following initial loading deformation, displays a decreasing rate (primary creep). For samples tested at lower stress levels (25% and 10%), the axial strain rate becomes constant (secondary creep) for limited time periods. At stress levels in the 40-45% range, the strain rate decreases throughout the test. Samples tested at the 65% stress level moved into tertiary creep (increasing axial strain rate) and terminated in creep rupture. Although, the trends follow the terrestrial data, the individual stages of creep (primary, secondary, and tertiary) for the deep sea sediments occurred at lower levels of stress.

The magnitude of the axial strain increased with increasing stress level with the exception of sample UI-7 (refer to Figure 2.3.1-2). However, sample UI-7 is most likely a sample of transitional material with appreciable amounts of smectite. This observation is substantiated in two ways. First, the magnitude of the axial strain for UI-7 (25% stress level) is very close to that of the 25% (US-2) smectite sample (Figure 2.3.1-3). Second, some properties of UI-7 (water content, Atterberg limits, grain size, and mineralogy) are similar to those of the smectite-rich samples (Moran, 1981).

When contrasting the illite-rich material with the smectite-rich material, the most apparent difference is the magnitude of axial deformation. The illite-rich material axially deforms less than the smectite-rich material when tested at the same stress level (Figure 2.3.1-2 and 2.3.1-3 respectively). Also, as shown in Figure 2.3.1-5, samples of the same material (in this case smectite), loaded to the same deviator stress (40%), axially deform to nearly the same magnitude, regardless of the previous loading condition. Sample UI-7 also corroborates this statement when it is considered as part of the smectite group; the sample, as mentioned above, deformed axially to nearly the same magnitude as sample US-2 at the same stress level (25%). For the remolded smectite material the axial deformations were similar to the illite-rich material.

The above observations in axial strain can also be explained by the initial sample water content (Table 2.3.1-3). For example, at the 25% stress level for UI-7 and US-2 which strained almost the same degree, the initial water contents are high and within 10%. Similarly, at the 40% stress level for samples UI-2 and RS-2A, the initial water contents were within 8%. The initial water content in the undisturbed case is indicative of the material type; however, in the remolded case, this is untrue. Consequently, the inter-relationship of the initial water content with creep movement should be considered in further study.

Because the lateral strain measurements had a much greater uncertainty than the axial strain measurements, an analysis similar to that done for the axial data was not performed. Qualitatively, however, the lateral data displayed some observable trends. The lower-stressed smectite-rich samples displayed very little lateral movement as seen by the small negative strains in Figure 2.3.1-8. Alternatively, Figure 2.3.1-7 shows the lateral strains for the illite material which are

larger than the smectite samples, although the axial deformations for the smectites are larger. The magnitude of the lateral strains for all samples tested below the rupture stress are less than 5% which is approximately .25 cm. (.1 in.). As previously discussed, the remolded smectite sample also laterally strained a small amount. In general, the lateral deformations are of small significance in the drained condition, especially at lower stress levels. However, further tests with more accurate measurements should be made.

Sharp increases in axial strain occurred in the majority of tests after the primary creep stage. These increases, which will hereafter be referred to as instabilities, appear to be real (i.e., not due to inherent equipment properties but to basic structural material change). This is true for all instabilities except that of sample RS-2A. The increase in strain in test RS-2A was due to a malfunction of a constant pressure cell which caused a decrease in cell pressure as noted in Figure 2.3.1-6.

As reported by Bishop and Lovenbury (1969), Pusch (1979), Ter-Stepanian (1975), and Trollope and Chan (1960), deformations occur in clay sediments in a step-like manner. Pusch, developed the most complete explanation of the phenomenon in which he describes the creep mechanism as a matrix of smaller particles linking larger clay aggregates which, during deviatoric loading, breakdown to form "domains". The deformation of the smaller particles (slip units) results in a more rigid matrix with a lower strain rate. For the URI/MGL tests, the decrease in strain rate was observed in tests where periods of constant axial strain occurred prior to and following the instability (Table 2.3.1-4). Marine clay typically has a structure of the cardhouse type which consequently has a greater potential for slip units than fresh water clay. This is apparent in the material tested here as four of the six undisturbed samples tested at stresses below the creep rupture stress exhibited instabilities.

The sample data for UI-2C and UI-2 was used to determine a stress-strain-time relationship for the undisturbed illite at stress levels less than rupture (65%). Additionally, data from tests which were terminated early due to equipment or test failure was extrapolated using a hyperbolic fit and was used to determine the stress-strain-time relationship. An example of the hyperbolic fit used for extrapolation is shown in Figure 2.3.1-10 for sample UI-3 at the 17% stress level. Log axial strain rate vs. stress level was plotted for each of the above mentioned tests for times of 6000 min., 12000 min., 18000 min., 24000 min., 30000 min., 36000 min., and 42000 min. (see Figure 2.3.1-11). A linear fit was made at each time and the slope was calculated. The slope of the curves decreases with increasing time. The slope of these curves ($d \log \dot{\epsilon}_a / d \text{stress}$) was then plotted vs. time as shown in Figure 2.3.1-12 and again a linear fit was made. From Figure 2.3.1-12, the stress-strain-time relationship for drained creep at stress levels below rupture is

$$\log \dot{\epsilon} = mts + bs + k$$

Eq. 4

where:

s = stress level
 t = time
 m = slope of $\log \dot{\epsilon}_a / ds$ linear fit vs. t
 b = intercept of $\log \dot{\epsilon}_a / ds$ linear fit vs. t
 k = constant

The slope (m) for the undisturbed illite material is -6.6×10^{-7} , the intercept (b) is 3.2×10^{-2} and the constant, k, is -5.7 for units of time in minutes and stress level expressed as a percent of the Mohr-Coulomb strength.

Similarly, test data for samples US-2, US-3, and US-4 was plotted to determine m, b, and k for the undisturbed smectite-rich material. Figure 2.3.1-13 shows the increasing value of $\log \dot{\epsilon}_a / ds$ with decreasing time. The plot of $\log \dot{\epsilon}_a$ vs. time (Figure 2.3.1-14) results in $m = -6.4 \times 10^{-7}$, $b = 3.6 \times 10^{-2}$, and $k = -5.6$. Thus, the relationship for each material is:

$$\log \dot{\epsilon}_a = -6.6 \times 10^{-7} ts + 3.2 \times 10^{-2} s - 5.7 \quad \text{Illite} \quad \text{Eq. 5}$$

$$\log \dot{\epsilon}_a = -6.4 \times 10^{-7} ts + 3.6 \times 10^{-2} s - 5.6 \quad \text{Smectite} \quad \text{Eq. 6}$$

Equation 4 was based on the behavior of the undisturbed deep sea material. In order to establish its validity, the method for determining the equation was duplicated using Pancone clay data (after Bishop and Lovenbury, 1969). Plots of $\log$ axial strain rate vs. stress level were made for times of 144, 5760, 11520, 28800, and 86400 minutes using 50, 75, and 85% stress levels (Figure 2.3.1-15). The plot of $\log \dot{\epsilon}_a / ds$ vs. time (Figure 2.3.1-16) results in values (for units of %/MIN) of -1.4×10^{-7} , 2.18×10^{-2} , and -5.1 for m, b, and k respectively. The empirical relationship displays a larger error for the terrestrial material which is most likely due to the limited data points used for analysis. However, the variable slope, which is the basis of the function, is apparent in Figure 2.3.1-15.

When comparing the relationship developed herein with that of Singh and Mitchell (1969), one major difference is apparent. The Singh and Mitchell general equation assumes $\dot{\epsilon}_a$ vs. deviator stress, plotted on a log scale, is constant for all times throughout creep. This suggests that the strain rate decreases linearly as a log function. For long-term drained creep data, this generality does not hold. Equation 4 more closely represents the creep behavior because it includes the variability of the slope of the $\log \dot{\epsilon}_a$ vs. deviator stress curve. Also, it has been developed empirically using curve fitting techniques which generalize the behavior. Consequently, the relationship will give a good estimate of the creep deformation behavior.

2.3.2 Variable Temperature (J. Wildman)

The variable temperature creep program was designed to use a large range of temperature to investigate the applicability of the creep models over the range of temperatures accepted in the canister vicinity. This

is especially important in the proposed models for studying possible canister migration and sediment displacement.

The samples used were Pacific illite from the gravity cores taken in MPG-I during MARA-12.

<u>Samples</u>	<u>Core</u>	<u>Depth (cm)</u>	<u>Core Location</u>
triax samples (3)	GC-28	104-150	30°20.1'N 159°59.7'W
		152-162	
		164-174	
4	GC-22	194-204	31°04.8'N 159°03.5'W
23	GC-23	102-112	
75	GC-23	142-152	31°00.5'N 159°24.2'W
150	GC-23	184-194	

It was not possible to use only samples from one core and depth region, consequently variations exist between test samples. The variable temperature creep program was begun in 1980 and is still under development. Therefore, the data presented here should be viewed as preliminary. The results are still being analyzed and will be included in more detail in a Master's thesis by J. Wildman.

Test Program

The equipment for a variable temperature creep-test consisted of a main test cell, two constant pressure cells, a volume change burette system, a temperature control system and transducers. Different main cells and temperature control systems were used for the lower temperature (40, 230°C) and higher temperature (750, 1500°C) tests. The lower temperature tests used the equipment from the room temperature creep program. For both tests (4 + 230) the set-up was placed in a temperature controlled room. The higher temperature tests used specially fabricated Hastalloy main cells which are fully described by Silva and Calnan (1980). The main cell was temperature controlled by a heating jacket and thermocouple system.

The four tests were planned to involve multiple stress levels on each sample in the sequence 10, 20, 40, 50, and 70 percent unless failure occurred at a lower stress level. The stress level is a percent of the drained strength as calculated from the 230°C triaxial test parameters (see section 2.2.2). However, the CIU tests used as a control for this study showed some significant differences in behavior as compared to similar earlier tests (see section 2.2.1) and therefore additional experiments are planned to check this.

The procedure differed between the lower and higher temperature tests. The lower temperature tests were first brought to the proper temperature, then consolidated, backpressured and loaded, respectively. The higher temperature tests were backpressured, then the temperature was increased and finally the sample was consolidated and loaded.

Results

As indicated earlier, these results are in a preliminary stage of analysis and additional tests are planned.

a) 40° test

The 40° test showed several areas of instability during the 10% loading (Figure 2.3.2-1). The 20% loading showed in contrast, a smooth strain versus time curve at which the final strain rate was almost unmeasurable. The 40% loading for the 40° test was preceeding normally until a large increase in strain rate occurred which led to rupture.

There are several possible errors associated with this test. Since the entire equipment set-up was placed in the 40°C room, the constant pressure cells seemed to experience some piston friction problems due to the contraction of the different materials. The sample did not strain to 20% because of an error in equipment set-up, but it is obviously failed.

b) 230° test

The 230° test was of the longest duration (98 days) and preceeded normally (Figure 2.3.2-2). All the loadings seem similar except the 40% which has an area of increasing strain rate at approximately 13 days after application of this load.

c) 750° test

At 750° the sample failed during the 10% loading (Figure 2.3.2-3). This test appears anomalous with most of the trends suggested by the rest of this data set. The 750° test is being checked with a previous 750° test that failed prematurely due to an equipment failure. Another test in this temperature range is planned to confirm the creep behavior at this point.

d) 1500° test

The 1500° test strained very rapidly during the first loading (Figure 2.3.2-4). At approximately 13% strain the strain rate became very low and continued at an almost imperceptable rate. There was no strain rate increase during the 20, 40, and 50 percent loadings. The sample was then loaded at ten minute intervals monitoring strain. The loading increments were 20% of strength and continued until sample failure at 210%. When the sample was removed from the cell it was found to be in two pieces and the membrane fractured. The results for the unusual behavior of this sample are not fully understood at this time and further testing is planned.

Analysis

The rate process theory used to model creep of soil predicts an increase in strain rate with temperature. These preliminary tests indicate that the behavior may be more complex and heating may alter the

physio-chemical properties of the soil.

It should also be noted that the sediment used was illite whereas the sediment around the canister in the MPG-I area would be smectite. There are marked differences in the double layer and electro-chemical bonding forces between these two sediments which may lead to different behavior at high temperatures.

Table 2.3.2-1 illustrates the volume change behavior during each test. A hyperbolic curve is suggested by the relationship between change in void ratio and test temperature. There are too few data points to state this with certainty as the 75° test does not conform. The next two tests on undisturbed illite will be at 100° and 200°C and they should be very helpful in further defining the physio-chemical effects that heat has on sediment stress-strain properties.

The future work for this study should include a comprehensive creep study using smectite to determine the properties around the heat affected area.

2.3.3 Undrained Constant Load Creep Test (W. Levy)

A preliminary undrained constant load creep test has been completed. The objective of this single test was to observe the effects of undrained conditions under constant load as compared to the drained behavior under constant stress which has been the emphasis in our creep experiments.

Test Program

A single sample of undisturbed Pacific illite from MARA-12, GC-23 was selected for this test. Sample preparation and test procedures were the same as for the variable temperature creep tests (see sec. 2.3.2) and the same apparatus was used. The exceptions were that the test was performed at room temperature with the drainage valve closed, constant load conditions were maintained and pore pressures were measured. A back pressure of 147.3 kPa was applied to ensure saturation of the sample. A consolidation pressure of 93.1 kPa was used (same as MGL drained creep).

The drainage valves were then closed and shear was initiated. A lateral strain gauge (LSG) was used to measure lateral deformations during shear (Akers and Silva, 1980). These LSG results should only be used for qualitative purposes as there is substantial drift over the extended time period involved in this test. This test involved two loadings, the first was 10% of undrained peak shear stress from a control static triaxial test (see section 2.3.2) and the second was 25% of undrained peak shear stress. The equation used to determine these undrained load levels was:

$$(\sigma_1 - \sigma_3)_f = \frac{2 \bar{c} \cos \bar{\phi} + 2 \bar{\sigma}_3 \sin \bar{\phi}}{1 - \sin \bar{\phi} + 2 A_f \sin \bar{\phi}} \quad \text{Eq. 1}$$

It should be noted that the stress levels for the other URI/MGL creep test programs were computed using an equation for drained test conditions (see sections 2.3.1 and 2.3.2). Thus a 10% undrained stress level is equivalent to 4% drained and a 25% undrained to a 10.5% drained using the same control CIU tests.

This creep test was ended after 60 days due to loss of back pressure.

Results and Analysis

The results of this test are presented in Figures 2.3.3-1, 2.3.3-2 and 2.3.3-3. The first load was maintained until day 23. The axial strain at the 10% loading became constant at about 0.6% strain (Figure 2.3.3-1). The second loading was then initiated. The initial axial strain response was similar to the first but then a period of large instabilities was observed. These instabilities are seen in the strain vs. time, diameter vs. time and pore pressure vs. time plots.

The instabilities characterized by step increases in axial strain appear to exist in all creep testing done to date at URI/MGL (see section 2.3.1, section 2.3.2). The instabilities observed in this undrained test appear much more significant on the strain vs. time plot indicating large scale particle rearrangement. Apparently, this mechanism is greatly influenced by build-up of excess pore pressure during shear. Close examination of the pore pressure vs. time plot (Figure 2.3.3-2) suggests a stress-strain behavior mechanism of pore pressure build-up, then rearrangement with resulting pore pressure dissipation. This mechanism needs further study and development.

Comparing the results with room temperature drained creep under stress control (section 2.3.2, Figure 2.3.2-2) and the results of this test, some significant differences in stress-strain-time behavior are observed. The undrained constant load test only reached 0.6% strain when it assumed a relatively constant strain rate while the drained test reached about 3% strain for the 10% load increment. At the 20-25% load increment large instabilities occurred in the undrained test while only minor instabilities appear under drained conditions. At this stress level the drained test reached a steady state condition at about 4.5% strain while the undrained test reached almost 7% strain before the test was terminated and still never approached a constant strain rate condition. Further testing is needed to examine these phenomena more closely.

It must also be kept in mind that the way this test was performed allows no rational way of isolating and examining the effect of constant load conditions on the behavior as compared with the constant stress conditions.

2.3.4 Summary of Creep Tests

The deep sea sediments reported herein exhibit larger strains than terrestrial and "bay" material tested at the same stress levels (Bishop and Lovenbury, 1969; Singh and Mitchell, 1968). This behavior appears to be a function of the in situ water content. However, in order to separate the effects of mineralogy from the water content effects,

further testing is necessary.

When comparing the stress-strain-time relationship reported here for drained, room temperature creep with the phenomenological equation developed by Singh and Mitchell (1969), one major difference is apparent. The Singh and Mitchell general equation assumes that the change in axial strain rate with deviator stress is constant for any time. This suggests that the strain rate decreases linearly with time at the same stress level. Consequently, for the material presented here, the Singh and Mitchell formulation does not hold. In a long-term condition (i.e. drained), the strain rate decreases nonlinearly with time. Therefore, the relationship shown in Equation 4 (section 2.3.1) better predicts the deformation behavior of these deep sea clays in the long term condition.

As mentioned above, in order to fully understand the creep characteristics in a long-term problem, more tests are essential. Due to the time constraint, the amount of information obtained from each test should be maximized. Some suggestions for further testing are:

1. Run a series of one-dimensional consolidation tests on undisturbed samples of the same material but with variable initial water contents to establish the gross deformation behavior and to isolate the effect of in situ water content.
2. Test, simultaneously, the same material at one of the above stress levels in triaxial compression for longer periods (>1 year) to more accurately define microstructural instabilities.

The variable temperature creep program has completed its initial testing matrix and detailed analysis will soon be available in J. Wildman's M.S. thesis. This initial series indicates that heating may substantially alter the physio-chemical properties of the soil. A trend of increasing resistance of illites to creep rupture and increasing Δe (change in void ratio) with increasing temperature of illites is indicated and further tests at intermediate temperatures are planned. Instabilities in the stress-strain-time plots were noted in almost all temperature tests which were similar to room temperature creep results (sec. 2.3.1). Rate process theory may not be appropriate in evaluating the creep behavior of these deep sea sediments at temperature.

A single undisturbed illite specimen was tested under undrained constant load conditions. A stress-strain behavior mechanism of pore pressure build-up, then particle rearrangement with resulting pore pressure dissipation is suggested as an explanation of the large scale instabilities observed. It appears that undrained creep behavior is totally different than drained response for the same sediment and conclusions about one may not apply to the other.

TABLE 2.3.1-1
CORING RESULTS
ROOM TEMPERATURE CREEP SAMPLES

CRUISE DESIGNATION	CORE DESIGNATION	LATITUDE	LONGITUDE	UNDISTURBED LENGTH (m)
LL-44	GPC-3	30 19.9'N	157 49.4'W	32.60
MARA-02	GC-07	30 30.9'N	158 0.7'W	2.32
MARA-02	GC-08	31 3.0'N	157 49.4'W	2.20
MARA-02	GC-09	31 2.5'N	157 48.6'W	2.42

TABLE 2.3.1-2
ROOM TEMPERATURE
CREEP TESTING PROGRAM

SAMPLE DESIGNATION	STRESS LEVEL (%)	DEVIATOR STRESS (kPa)	TEST DURATION (DAYS)
UI-1	*	*	12
US-1	*	*	12
RS-1	*	*	12
UI-2C	10	25	62
UI-7	25	62	70
UI-2	45	111	65
UI-2A	65	161	20
US-3	10	26	60
US-2 +	25	66	48
US-2 +	40	106	6
US-4	40	106	45
US-2 +	65	172	1
RS-2A	40	90	40

* CIU SERIES

+ STEP-LOADED TEST

TABLE 2.3.1-3

WATER CONTENT AND DENSITY

SAMPLE DESIGNATION	INITIAL WATER CONTENT (%)	FINAL WATER CONTENT (%)	INITIAL BULK DENSITY (g/cm ³)	FINAL BULK DENSITY (g/cm ³)
US-2	232	206	1.26	1.22
US-3	252	190	1.30	1.30
US-4	180	138	1.25	1.35
RS-2A	125	117	1.42	1.42
UI-2A	107	73	1.55	1.50
UI-2C	117	82	1.47	1.47
UI-2	115	69	1.49	1.56
UI-7	207	123	1.31	1.35

TABLE 2.3.1-4
INSTABILITY SUMMARY

SAMPLE DESIGNATION	AXIAL STRAIN RATE BEFORE INSTABILITY (%/MIN)	AXIAL STRAIN RATE AFTER INSTABILITY (%/MIN)
UI-2C	1.03×10^{-5}	7.9×10^{-6}
UI-7	8.5×10^{-6}	8.6×10^{-6}
US-3	1.61×10^{-5}	4.1×10^{-6}
US-4	$1.2 \times 10^{-4*}$	$2.9 \times 10^{-5*}$

*NOT A CONSTANT RATE

TABLE 2.3.2-1

CREEP-VARIABLE TEMPERATURE
 MARA-12 Cruise
 Undisturbed Illite
 Consolidation Stress ($\bar{\sigma}_3$) = 93.1 kPa

SAMPLE (cm)	TEST	w _c (%) before	w _c (%) after	Δw (%)	APPROX.* SP. GR. (G _s)	Δe
GC-22 194-204	4°C	101.5	68.4	33.1	2.73	.92
GC-23 102-112	23°C	119.2	75.7	43.5	2.71	1.18
GC-23 142-152	75° C	116.1	86.6	29.5	2.71	.80
GC-23 184-194	150° C	101.9	51.2	50.7	2.71	1.37

*FROM ANNUAL REPORT (SILVA & CALNAN, 1980)

GC-22 160-170 cm G_s = 2.78

GC-23 125-135 cm G_s = 2.71

FIG. 2.3.1-1
CORE LOCATIONS IN MPG-I
Room Temperature Creep Program

AXIAL STRAIN vs. TIME
UNDISTURBED ILLITES
URI/MGL

FIG. 2.3.1-2

AXIAL STRAIN vs. TIME
UNDISTURBED SMEECTITE
URI/MGL

FIG. 2.3.1-3

AXIAL STRAIN vs. TIME
US-2; COMP#2
UR1/MGL

FIG. 2.3.1-4

AXIAL STRAIN vs. TIME
40% SMECTITES

FIG. 2.3.1-5

AXIAL STRAIN vs. TIME
RS-2A₁ COMP#2
URI/MGL

FIG. 2.3.1-6

LATERAL STRAIN vs. TIME
UNDISTURBED ILLITES
URI/MGL

FIG. 2.3.1-7

LATERAL STRAIN vs. TIME
UNDISTURBED SMEECTITE
URI/MGL

FIG. 2.3.1-8

LATERAL STRAIN vs. TIME
RS-2A; COMP#2
URI/MGL

FIG. 2.3.1-9

TIME (MIN/1000)
 AXIAL STRAIN vs. TIME
 UI-3
 URI/MGL

FIG. 2.3.1-10

FIG. 2.3.1-13

FIG. 2.3.1-14

STRESS LEVEL (X)
LOG STRAIN RATE vs. STRESS LEVEL
BISHOP&LOVENBURY1969
URI/MGL

FIG. 2.3.1-15

TIME (MIN)
dLOG RATE/dSTRESS vs. TIME
BISHOP&LOVENBURY1969
URI/MGL

FIG. 2.3.1-16

TIME (DAYS)
STRAIN vs. TIME
4 Deg TEST
URI/MGL

CREEP TESTING
MARA 12, GC 22, 197. cm
10, 20, 40% stress levels

Figure 2.3.2-1

TIME (DAYS)
 STRAIN vs. TIME
 20 Deg TEST
 URI/MGL

CREEP TESTING
 MARA 12, GC 23, 107 cm
 10, 20, 40, 50, 70% stress levels

Figure 2.3.2-2

TIME (DAYS)
STRAIN vs. TIME
75 Deg TEST
URI/MGL

CREEP TESTING
MARA 12, GC 23, 147 cm
10% stress level

Figure 2.3.2-3

TIME (DAYS)
STRAIN vs. TIME
150 Deg TEST
URI/MGL

CREEP TESTING
MARA 12, GC 23, 189 cm
10, 20, 40, 50, 70-210 stress levels

Figure 2.3.2-4

TIME (days)
 STRAIN vs. TIME
 UNDRAINED CONSTANT LOAD TEST
 UNDISTURBED ILLITE; MARA 12, GC-23
 DEPTH IN CORE 114-124 CM

Figure 2.3.3-1

TIME (days)
 EX PORE PRESSURE vs. TIME
 UNDRAINED CONSTANT LOAD TEST
 UNDISTURBED ILLITE; MARA 12, GC-23
 DEPTH IN CORE 114-124 CM

Figure 2.3.3-2

TIME (days)
 DIAMETER vs. TIME
 UNDRAINED CONSTANT LOAD TEST
 UNDISTURBED ILLITE; MARA 12, GC-23
 DEPTH IN CORE 114-124 CM

Figure 2.3.3-3

2.4 COMPRESSIBILITY STUDIES

Introduction

Since the beginning of our involvement in the SDP, consideration has been given to consolidation studies of deep sea sediments for determination of the sediment column stress history. Early studies were dedicated to the MPG-I and MPG-II study sites in the North Central Pacific. More recent studies have included cores from the MPG-III N (HUDSON 80016 cruise) and MPG-IV (VEMA-36-12 cruise) areas; Northwestern Atlantic and Northwestern Pacific respectively. A site specific study in the MPG-I (RAMA 1 cruise) area has been initiated to provide parameters necessary for a settlement analysis related to ISHTe program (see Chapter 4.0).

Compressibility data presented here is from work conducted during calendar year 1980. Previous test results have been reported in our Annual Reports No. 1 through 6. Both standard, one-dimensional and back-pressured consolidometers are used in these studies. The equipment is described in previous reports. The standard consolidometer procedures for testing follow ASTM standard D2435-70 with minor modifications and the back-pressured units procedures have been described elsewhere (Nickerson, 1978; Beverly, 1975).

2.4.1 MPG-I (D. Calnan, G. Chiarello)

The main focus of the consolidation testing on MPG-I samples this year has been to substantiate previous results in order to attain a dependable set of parameters for settlement computations for the ISHTe platform. This will permit a confident prediction of magnitude of displacement under load. A total of five samples were tested from the MPG-I area. Table 2.4.1-1 is a summary of locations, core type and unit used.

Results

Figure 2.4.1-1 through 5 show e (void ratio) vs. $\log \bar{\sigma}_v$ (applied stress) plots for the five samples tested. The dashed lines in some of these figures represent the most probable path of the curve (which indicates slight measurement errors).

The two RAMA-1 samples show compressibility curves (e vs. $\log \sigma_v$) that indicate very high quality (Figures 2.4.1-1 and 2). These curves show a distinct parabolic shape during initial recompression and a nearly perfect straight line representing the breaking down and rearrangement of the grains (virgin compression line). Both samples are clearly overconsolidated ($OCR \gg 1.0$) which will be discussed later.

The VEMA-32-11, PC115 and LL-44, GPC-3 e vs. $\log \bar{\sigma}_v$ curves show relatively good quality samples (Figures 2.4.1-3 and 4, respectively). The VEMA sample exhibited some overconsolidation which was not unexpected at that shallow depth. The LL-44 sample displays a high compression index which is typical of a soft sediment containing a high percentage of smectite minerals.

The MARA-02, GC-04 sample appears to have been tested in somewhat of a disturbed state. This is reflected by the lack of a clean parabolic shape (Terzaghi and Peck, 1967) near the beginning of the e vs. $\log \bar{\sigma}_v$ curve (Figure 2.4.1-5). The swelling index (C_s) was determined at both decompression curves (curve representing removal of load). A value of approximately 0.07 was determined for both decompression curves. This implies the belief that the swelling index is not a function of in situ void ratio.

Discussion of Results and Conclusions

A summary of the compressibility results is presented in tabular form in Table 2.4.1-2. As was seen in previous results, the virgin compression line of the compressibility curves is significantly steeper for the deeper, smectite-rich samples. This steepness is reflected in Table 2.4.1-2 by the larger values of C_c and C_{cf} ; the laboratory and field corrected compression indices respectively. These high values (about 3 times those of shallower samples) do not have serious implications at the present time when considering the ISHTE program but do indicate that emplacement, remolding or any significant mechanical agitation of this strata does require a detailed investigation to reveal the type and behavior of the sediment involved.

Table 2.4.1-2 also shows two of the tests (MARA-02 and LL-44) with OCR values less than 1.0, which would indicate underconsolidation in the sediment column. However, the MARA-02 sample was tested in a disturbed state resulting in an unreliable estimate for OCR. Also, it is known that values of OCR become less accurate for high void ratio samples ($e = 2.5$) (Bryant, Deflache and Trabant, 1974). Table 2.4.1-2 shows the initial void ratio, e_0 , to be 5.82 in the LL-44 test, therefore the OCR value for this sample is questionable. The results of C_c and OCR are plotted along with previously reported data (Figures 2.1.1-6 and 7). In Figure 2.1.1-6 the new data (C_c) agrees well except for the MARA sample. This is not surprising because the compressibility curve showed the sample to be disturbed. In Figure 2.1.1-7 the OCR values agree very well with the previous data. The OCR at the shallower depth (14-19 cm) extends the simulated curve almost asymptotically to the seafloor. This curve clearly shows that the surficial (upper 2 meters) sediment is indeed "apparently" overconsolidated; which is most likely predominantly a result of high interparticle bonding and/or cementation.

Any calculation made to determine total settlement under an applied load in the MPG-I area should consider the phenomenon of "apparent" overconsolidation as one of primary importance.

2.4.2 MPG-III N (D. Calnan, G. Chiarello)

Our main task for MPG-III N area is to continue a compressibility and permeability investigation of the Abyssal Plain sediments and compare them to other sites. Additional samples were obtained from box, gravity and piston cores during the summer of 1980 (sec. 2.1.2).

A summary of cores tested this past calendar year are included in Table 2.4.2-1. Although testing of ENDEAVOR cores was not directly

funded under the FY 80 contract document, it has been determined that they are important in the overall assessment of MPG-III N area and therefore are included in our program. Samples obtained during the HUDSON 80016 cruise will continue to be tested to further augment this study.

Results

Figures 2.4.2-1 through 6 are the e vs. $\log \bar{\sigma}_v$ (void ratio vs. stress) curves for the samples listed in Table 2.4.2-1. Generally, all the curves show samples of relatively undisturbed quality with the exception of the EN-023 LGC-17 sample (Figure 2.4.2-6). In all these tests, except one, the sample was unloaded twice enabling the determination of the swelling index (C_s) at two decompression curves. It has been suggested that the swelling index increases as a soil is consolidated (Perloff, 1975), however, a single value for C_s was determined for both decompression curves which indicates that this sediment does not appear to be directly dependent on the in situ void ratio (or state of consolidation). Values of overconsolidation ratio (OCR) in the upper 2 meters reveal positive signs of overconsolidation.

Table 2.4.2-2 summarizes the compressibility data for the past calendar year.

Discussion of Results and Preliminary Conclusions

Table 2.4.2-2 shows some interesting results. The OCR value of two EN LGC-04 samples (115-120 and 149-152) are significantly lower than those reported in the MPG-I area at the same depth (Figure 2.4.1-7). This is in direct correlation with much higher void ratios and compression indices for these samples compared to previously reported data in both areas (MPG-I and III N) at the same depth. The HUD sample did not show evidence of this at all, however, this core is approximately 107 miles from the EN core. An examination of the OCR values for the HUD sample and the other samples in the EN series indicates "apparent" overconsolidation in the surficial sediments (upper 2 meters). "Apparent" is used because it is believed that the indications of overconsolidation for the Abyssal Plain sediments are a result of interparticle bonding and cementation rather than removal of overburden by erosional processes. Tests are scheduled to examine the mineralogy to possibly explain the variability in the compressibility properties of these sediments.

A continuing effort to understand the feasibility of this site as a possible study site for SDP is part of the overall program at URI/MGL. To date, no compressibility evidence has discounted this site for study, however, the HUDSON cruise piston cores showed sand layers which would be a significant disadvantage (section 2.1). These new HUDSON samples are being tested during FY 81 to gain more data related to site criteria.

2.4.3 MPG-IV (G. Walker)

The VEMA 36-12 cruise to the MPG-IV area in the Northwestern Pacific produced many piston cores and gravity cores for geotechnical testing. Since this area is a new study site, determining the stress history of this area is important.

At this time, only three consolidation tests have been completed for this area; all are from site E₂ (see Table 2.1.1-2 for locations of these samples). Two were tested in standard consolidometers and one in the backpressured consolidometer producing both consolidation results and direct permeability measurements (see section 3.1.3). All three samples (2.0" diameter) were from piston cores. The gravity cores from this area were extruded and sampled in early January, 1981; therefore, no results from gravity core samples are available at this time.

Results

Plots of e vs. $\log \bar{\sigma}_v$ are shown in Figures 2.4.3-1 through 3. Figure 2.4.3-1 shows the e vs. $\log \bar{\sigma}_v$ sample (PC-49 186-190). Values for C_c and C_s are very high indicating a high degree of compressibility and swelling. The high OCR (overconsolidation ratio) for this sample (2.4) is probably due to "apparent" overconsolidation as previously discussed. This test showed signs of an extra sensitive undisturbed clay sample as reflected by the straight line portion in the plot (during the early part of the test) followed by an abrupt turn downward (Terzaghi and Peck, 1967). Further evidence of this type of behavior will be noted as testing continues. Sample PC-49 1176-1180 (Figure 2.4.3-2) was accidentally unloaded early in the test but it occurred after the point of maximum curvature and allowed for data to be acquired from this test. Notice that the values for C_c and C_s are relatively low for this deeper sample. An investigation of the mineralogy at this depth will be conducted to possibly explain the low values.

A summary of the consolidation results in tabular form is presented in Table 2.4.3-1. Here, it can be seen that OCR values (>1) are shown within the upper 2 meters indicating samples that are "apparently" overconsolidated. The OCR values were obtained by an estimated effective overburden stress (based on limited MPG-IV data). The deeper samples (Table 2.4.3-1) indicate that the sediment column is normally consolidated at those depths.

Preliminary Conclusions (Site E₂)

From the limited compressibility tests in site E₂, it appears that the sediment is highly compressible and also very susceptible to swelling if unloaded. The upper two meters of this site show apparent overconsolidation as has been previously reported in the MPG-I area, (Silva and Calnan, 1980). Two samples at greater depth indicate the sediment column is normally consolidated.

A more detailed analysis of site E₂ will be possible with continued testing. A concentrated effort on site E₂ with a general test program on sites C₁ and B₁ will be the subject of a Master's thesis to be completed later this year.

2.4.4 Summary and Future Work

Compressibility studies are continuing in the MPG-I and MPG-III N areas and has begun in the MPG-IV area. The MPG-I study has reached an advanced stage and will ultimately provide a reliable set of parameters

for settlement computations of the ISHTE platform. The MPG-III N and MPG-IV studies are in preliminary stages for assessing these areas as study sites for SDP.

Consolidation tests on MPG-I samples conducted during calendar year 1980 agree well with previously reported data. The surficial (upper 2 meters) sediment is clearly "apparently" overconsolidated; which is believed to be a result of high interparticle bonding and/or cementation. Calculations performed to determine total settlement under an applied load must consider this fact of "apparent" overconsolidation.

Consolidation results for the past calendar year in the MPG-III N area show "apparent" overconsolidation in the surficial sediments as discussed for the MPG-I area. However, overconsolidation ratios (OCR) for some of the samples are significantly lower than those reported in the MPG-I area at the same depth. Tests scheduled to examine the mineralogy will possibly explain this variability.

Three consolidation tests have been completed on samples from the MPG-IV area, site E₂. Again, "apparent" overconsolidation is indicated in the upper sediments. To what extent is not known at this time. Testing is continuing followed by a detailed analysis on site E₂ with an overall assessment of the other two sites (B₁ and C₁) in the MPG-IV area.

Table 2.4.1-1

Summary of Core and Consolidation Sample Locations: MPG-I

Cruise NO.	Core No.*	Core Location	Sample Depth (cm)	Test Type
MARA-02	GC-04	30° 06.3' N 157° 51.7' W	247-252	Back-pressured
V32-11	PC-115	30° 36' N 158° 53' W	116.5-120	Back-pressured
LL-44	GPC-3	30° 19.9' N 157° 49.4' W	1114-1118	Back-pressured
RAMA-1	GC-14	30° 23.6' N 157° 44.3' W	14-19	Standard
RAMA-1	GC-19	30° 23.9' N 157° 41.3' W	38-43	Standard

* GC = Large-diameter gravity core
 PC = Standard piston core
 GPC = Giant Piston Core

Table 2.4.1-2

SUMMARY OF CONSOLIDATION TEST RESULTS, MPG-I

CRUISE	CORE NO.	DEPTH (cm)	INIT. VOID RATIO e_o	COMPRES. INDEX C_c	FIELD CORR. COMPRES. INDEX C_{cf}	SWELL INDEX C_s	MAX EFFECT. PRECONSOL. $\bar{\sigma}_c$ (kPa)	OVERCONSOL. RATIO OCR
RAMA-1	GC-14	14-19	2.84	0.87	0.88	0.04	15.2	21.7
RAMA-1	GC-19	38-43	2.93	1.05	1.17	0.05	26.1	14.9
V32-11	PC-115	116.5-120	2.87	0.85	0.92	0.06	12.9	2.4
MARA-02	GC-04	247-252	2.65	0.70	0.75	0.07	9.9*	.82
LL-44	GPC-3	1114-1118	5.82	2.86	3.23	0.16	45.3	.94

*Disturbed Sample

Table 2.4.2-1

Summary of Core and Consolidation Sample Locations: MPG-III N

Cruise No.	Core No.*	Core Location	Sample Depth (cm)	Test Type
EN-023	LGC-04	33° 03.4' N 57° 42.3' W	57-67	Standard
EN-023	LGC-04	33° 03.4' N 57° 42.3' W	115-120	Standard
HUD-80016-043	GC-03	32° 32.1' N 55° 57.0' W	129-132	Back-pressured
EN-023	LGC-04	33° 03.4' N 57° 42.3' W	147-152	Standard
EN-023	LGC-04	33° 03.4' N 57° 42.3' W	250-255	Standard
EN-023	LGC-17	32° 32.1' N 55° 57.0' W	365-370	Back-Pressured

* LGC-GC = Large-diameter Gravity Core

Table 2.4.2-2

SUMMARY OF CONSOLIDATION TEST RESULTS, MPG-III N

CRUISE	CORE NO.	DEPTH (cm)	INIT. VOID RATIO e_o	COMPRES. INDEX C_c	FIELD CORR. COMPRES. INDEX C_{cf}	SWELL INDEX C_s	MAX EFFECT. PRECONSOL. $\bar{\sigma}_c$ (kPa)	OVERCONSOL. RATIO OCR
EN-023	LGC-04	57-67	2.34	0.65	0.73	0.05	16.5	4.9
	LGC-04	115-120	5.25	2.51	2.56	0.17	6.9	1.3
HUD-80016	GC-03	129-132	4.60	1.20	1.28	0.13	16.0	2.5
EN-023	LGC-04	147-152	5.61	2.76	2.78	0.11	9.4	1.5
	LGC-04	250-255	3.85	2.41	2.46	0.10	17.0	1.7
	LGC-17	365-370	2.41	0.82	0.93	0.14	14.0	1.0

Table 2.4.3-1

SUMMARY OF CONSOLIDATION TEST RESULTS: MPG-IV

CRUISE	CORE NO.	DEPTH (cm)	INIT. VOID RATIO e_o	COMPRES. INDEX C_c	FIELD CORR. COMPRES. INDEX C_{cf}	SWELL INDEX C_s	MAX EFFECT. PRECONSOL. $\bar{\sigma}_c$ (kPa)	OVERCONSOL. RATIO OCR
V32-12	PC-49	186-190	7.29	3.70	3.25	0.22	12.5	2.4
	PC-49	1176-1180	4.86	1.61	1.88	0.10	51.0	1.1
	PC-48	1247-1251	5.13	2.83	3.24	0.19	65.0	1.1

Figure 2.4.1-1

Figure 2.4.1-2

Figure 2.4.1-3

Figure 2.4.1-4

Figure 2.4:1-5'

Compression Index, C_c , vs. Depth - MPG-I

Figure 2.4.1-6

Figure 2.4.1-7

Figure 2.4.2-1

Figure 2.4.2-2

Figure 2.4.2-3

Figure 2.4.2-4

Figure 2.4.2-5

Figure 2.4.2-6

Figure 2.4.3-1

Figure 2.4.3-2

Figure 2.4.3-3

3. PERMEABILITY AND CONDUCTIVITY STUDIES

3.1 STANDARD PERMEABILITY (G. Walker)

Introduction

Data from a new SDP site, MPG-IV, along with some additional permeability tests from the MPG-I and MPG-III N sites are included in this section. The permeability coefficients are obtained from direct flow measurements and from analysis of one-dimensional consolidation data. The results from these tests are used to characterize and compare the different SDP sites, and for water migration studies relevant to canister emplacement studies. The locations of samples are listed on Tables 2.1-1, 2.2.1-1, 2.4.2-1, and 4.1-1.

The older cores, LL-44 GPC-3, VEMA 32-11 PC-115, and MARA 02 cores are brought to completion with this annual report. The new cores from MPG-I, RAMA-01, and from MPG-III N, HUDSON, and from MPG-IV, VEMA 361-12 will be analyzed during FY 81. Procedures for running the direct permeability tests in the back-pressured modified Anteus permeameter/consolidometer and diagrams of the equipment have been described in previous annual reports. Calculated values for the coefficient of permeability are also obtained from consolidation tests.

3.1.1 MPG-I Results

A summary of results for the MPG-I areas is listed on Table 3.1.1-1. These new values of permeability are plotted in Figure 3.1.1-1 along with previously reported results. These new values can be seen to be consistent with what has previously been reported. However, the two results from RAMA-01 for 14-19 cm, and 38-43 are higher than has been previously reported.

From Figure 3.1.1-1, it appears that the average coefficient of permeability value below 2 meters is approximately 5×10^{-7} cm/sec. In Figure 3.1.1-1, it can be seen that the values fall within the range of 2×10^{-7} cm/sec. to 1×10^{-5} cm/sec. for the upper two meters with an average value of approximately 3×10^{-6} cm/sec. The two highest values are from two RAMA-1 samples. There are no results from index properties tests yet, but these two tests seem to indicate a region with different geotechnical characteristics.

These new results are very consistent with previous results reported for MPG-I, except for the two RAMA samples. Therefore, for MPG-I, it is tentatively concluded that the coefficient of permeability of the upper two meters is considerably greater (3×10^{-6} cm/sec.) than the zone from 2 to 24 meters where the permeability is relatively constant at about 5×10^{-7} cm/sec.

3.1.2 MPG-III N Results

Core LGC-17 from EN-23 was taken on the abyssal plain east of the Bermuda Rise. The results are listed on Table 3.1.2-1. This value is

similar for the square root of time values reported in annual report No. 6 (Silva and Calnan). The direct measurement data is the first reported for this area. These values are similar to those reported for MPG-I and therefore it appears that, from a permeability point of view, the sediments in MPG-III N would be as effective as a containment medium. However, the variability of properties is not known in as much detail as MPG-I and as indicated in section 2.1, it appears that this area has some sandy layers at depth.

3.1.3 MPG-IV Results

A summary of the permeability results is listed on Table 3.1.2-1. The individual values fall in the range of 6×10^{-7} cm/sec. to 1×10^{-6} cm/sec. for the square root of time method. Only one sample has been tested in the back pressured consolidometer/permeameter at this time with a direct measurement value of 3.4×10^{-6} cm/sec. at a depth of 12.5 meters. The locations of the samples used are listed on Table 2.1-1. All the tested samples are from site E₂ which is considered to be the most favorable SDP site in this region.

Comparing this data to Figure 3.1.1-1, it can be seen that for the upper two meters of site E₂ the coefficients of permeability fall into the same range of values for the MPG-I area above two meters. The average value at twelve meters is somewhat higher than the average value for MPG-I below two meters. Note also that the direct measurement taken at site E₂ is 3.4×10^{-6} cm/sec. whereas for MPG-I no direct measurements below one meter are higher than 1×10^{-6} cm/sec. Associated classification tests must be performed in order to make any conclusions about the geotechnical property differences between MPG-IV and MPG-I. Based on the very limited data, it appears that the coefficient of permeability of MPG-IV is slightly greater than for MPG-I. Additional tests will be conducted on samples from this region.

3.1.4 Summary of Standard Permeability Results

The new data from MPG-I falls within the ranges of previously reported values indicating that a consistent pattern is evident for values of coefficient of permeability in the MPG-I area. The range for the upper two meters is from 2×10^{-7} cm/sec. to 1×10^{-5} cm/sec. with an average of approximately 3×10^{-6} cm/sec. Below two meters the range narrows to 1×10^{-7} cm/sec. to 1.1×10^{-6} cm/sec. with an average of approximately 5×10^{-7} cm/sec. These changes with depth are apparently due to mineralogical changes. Future work in MPG-I will concentrate on the upper few centimeters of RAMA-I cores in association with work for the ISHTe program.

Preliminary data from MPG-III N indicates it to be similar in permeability characteristics to MPG-I.

In the new area, MPG-IV values range from 6×10^{-7} cm/sec. to 1×10^{-6} cm/sec. A detailed test program concentrating on site E₂ is now underway.

TABLE 3.1.1-1
SUMMARY OF PERMEABILITY RESULTS, MPG-1

CRUISE	CORE	DEPTH (cm)	IN SITU VOID RATIO e_0	COEFFICIENT OF PERMEABILITY (LLSF), k at e_0 (cm/sec)	
				SQUARE ROOT TIME METHOD	DIRECT MEASUREMENT
MA-02	GC-07	12-16	3.12	----	9.8×10^{-7}
RAMA-1	GC-14	14-19	3.18	9.9×10^{-6}	
RAMA-1	GC-19	38-43	2.93	1.2×10^{-5}	-----
RAMA-1	GC-14	79-84	1.74	----	8.1×10^{-7}
VEMA-32	PC-115	116.5-120	3.03	4.9×10^{-7}	2.0×10^{-7}
MA-02	GC-04	247-252	2.94	1.0×10^{-6}	5.4×10^{-7}
VEMA-32	PC-115	938-941.5	5.66	7.3×10^{-7}	3.3×10^{-7}
LL-44	GPC-3	1047	6.05	5.7×10^{-7}	-----
LL-44	GPC-3	1114-1118	5.82	7.6×10^{-7}	3.9×10^{-7}
LL-44	GPC-3	1601	7.03	3.0×10^{-7}	-----
LL-44	GPC-3	2241	5.49	1.9×10^{-6}	3.5×10^{-7}

Table 3.1.2-1

Summary of Permeability Results, MPG-III N

Cruise	Core	Depth (cm)	In Situ Void Ratio e_o	COEFFICIENT OF PERMEABILITY (LLSF), k at e_o (cm/sec)	
				Square Root Time Method	Direct Measurement
EN-023	LGC-17	365-370	2.41	1.2×10^{-7}	3.1×10^{-7}

Summary of Permeability Results, MPG-IV

Cruise	Core	Depth (cm)	In Situ Void Ratio e_o	Square Root Time	Direct Measurement
VEMA 36-12	PC-51	114-118	4.65	1.0×10^{-6}	-----
VEMA 36-12	PC-49	186-190	6.25	2.7×10^{-6}	-----
VEMA 36-12	PC-49	1176-1180	2.73	9.7×10^{-7}	-----
VEMA 36-12	PC-48	1237-1251	4.97	5.9×10^{-7}	3.4×10^{-6}

Figure 3.1.1-1
(Includes all data for this area)

3.2 TEMPERATURE EFFECTS ON PERMEABILITY (G. Walker)

Introduction

A program was initiated some time ago to attempt to determine the effect of high temperatures (up to 200°C) on permeability characteristics of deep sea sediments. At the time, funds were limited and it was decided to modify our back-pressure permeability equipment and install it in an oven. Because of corrosion problems and other equipment difficulties encountered at elevated temperatures, only one series of tests at 80°C have been previously reported. Since last year, most of the material problems have been overcome and the testing program was resumed at a more modest level.

Measurement of the coefficient of permeability at high temperatures is necessary in evaluating the response of the sediment due to canister emplacement.

Test Program and Results

In 1980, three samples were successfully tested at higher than room temperature. These samples were reconstituted-reconsolidated (remolded) illite taken from consolidation tanks at URI/MGL. The tests were performed in the back-pressured Anteus permeameter/consolidometer placed inside an oven.

The method of testing has been to run permeability tests at room temperature to determine the "base" coefficient of permeability of a particular sample. Then, the entire apparatus and sample are slowly heated up to a specified temperature by increasing the oven temperature. Permeability tests are then performed and compared to the room temperature values.

The results are shown in Table 3.2-1. Two samples were tested up to 120°C and one sample was at 150°C. All three samples of illite showed that at 120°C, the increased coefficients of permeability can be accounted for by changes in viscosity of the permeating fluid (Table 3.2-1). This is in agreement with the previously reported test at 80°C (Silva and Calnan, 1980). The test at 150°C showed a slightly higher than expected coefficient of permeability, however, this was only a 10% increase which is considered to be within the margin of error of the experiment.

Summary

Based on these limited results, we conclude that up to 150°C, there appears to be no increase in the coefficient of permeability due to changing sediment character. There is a significant increase in permeability with increasing temperature which is due entirely to the decrease in viscosity of water.

Attempts have been made to test samples at 200°C but severe corrosion problems were encountered. At this time new parts are waiting to be machined to refit the variable temperature Anteus permeameter/consolidometer unit so that the testing can continue.

The future test program will include testing of undisturbed illite samples obtained from MPG-I cores and remolded smectite samples. The results from these tests will be compared to the results from high pressure/high temperature tests performed by Roger Morin (see section 3.3).

Table 3.2-1
High Temperature/Low Pressure Permeability
Reconstituted/Reconsolidated Illite

Sample Designation*	Applied Stress (kPa)	Direct Measurement (cm/sec)	Temperature °C	Coefficient of Permeability corrected to 20 °C.** (cm/sec)
PI 5-8 92-97 cm	21.4	2.2×10^{-7}	23	2.1×10^{-7}
#101	21.4	8.2×10^{-7}	120	2.0×10^{-7}
	21.4	1.2×10^{-6}	150	2.3×10^{-7}
PI 5-8 7-12 cm	44	1.0×10^{-7}	23	9.6×10^{-8}
#28	44	4.7×10^{-7}	120	1.1×10^{-7}
PI 5-8 7-12 cm	74	1.4×10^{-7}	25	1.3×10^{-7}
#27	74	3.5×10^{-7}	80	1.3×10^{-7}
	74	5.4×10^{-7}	120	1.3×10^{-7}

*PI 5-8 Pacific Illite consolidated to an equivalent depth of five meters; (22.1 kPa) tank #8.

** Values corrected by using ratios of viscosity of water at temperature.

3.3 HIGH TEMPERATURE AND HIGH PRESSURE EFFECTS ON PERMEABILITY AND CONDUCTIVITY (R. Morin)

Introduction

The High Temperature/High Pressure Program was initiated over a year ago in an effort to determine various physical properties of deep sea sediments at their in situ conditions. The sediment's response (along with that of the interstitial water) to changes in temperature and pressure is examined, simulating its proper environmental conditions. The goal of the program is to measure the permeability and thermal conductivity of a few specific samples at various stages of consolidation.

During the past year, the apparatus has been fabricated, installed, calibrated, and tested. After correcting a few minor equipment problems, an initial set of tests has just been completed and a second series is underway. The samples used in these studies are undisturbed illite samples obtained from MPG-I (MARA-12, GC 26) and remolded smectite samples, also from MPG-I. The specimens are approximately 5 cm in diameter by 10 cm long.

Test Program

The equipment used in these tests has been described in previous reports and a design schematic is included in Figure 3.3-1. The Inconel 600 pressure vessel has a loading piston arrangement which allows samples to be consolidated to various void ratios. Two dead weight testers are connected to the system and produce a small hydraulic gradient across the sample at large hydrostatic pressures. These, along with the volume change devices, provide the means for measuring permeability. Thermal conductivity is determined through the use of a hypodermic needle inserted axially through the base of the sample. The equipment has the capability of working up to pressures of 700 bars and temperatures up to 220°C.

The testing program for 1981 will be performed in total on both illite and smectite samples as follows:

<u>Test no.</u>	<u>Consolidation</u>	<u>Temp (°C)</u>	<u>Pressure (Bars)</u>
1	no	22	Variable (20-650)
2	yes	80	600
3	yes	150	600
4	yes	220	600

Results, Analysis and Summary

Test #1 listed in the preceding table has been performed on an illite sample. The purpose of this test, as well as the one to be performed on a smectite sample, is to determine whether or not large hydrostatic

pressures have any effect on sediment permeability and thermal conductivity. The results are illustrated in Figures 3.3-2 and 3.3-3, where both of these parameters were measured at pressures ranging from 20 to 600 bars.

It has been thought that sediments with sizable diffuse double layers may experience changes in permeability with increases in hydrostatic pressure. The double layer refers to the assemblage of hydrated ions which cling to the surface of clay particles through electro-chemical forces (Mitchell, 1976). Lang (1969) has proposed that large pressures may cause a systematic breakdown of this double layer, thereby increasing the effective void volume and the corresponding permeability of a sediment sample. The objectives of this first series of tests are to confirm the existence of this phenomenon and determine the degree to which it affects permeability.

As indicated from the limited data of Figure 3.3-2, there is no significant dependency of this physical property on hydrostatic pressure for the particular sediment type tested. The error bars represent fluctuating differential pressures across the test specimen. A new, more stable pump has been ordered to replace the present one, and it is anticipated that this item will improve the accuracy of the permeability measurements.

The thermal conductivity data was obtained by the standard needle probe method (von Herzen and Maxwell, 1959; Jaeger, 1958) and are plotted in Figure 3.3-3. Again, for the illite sample under study, this parameter showed no dependency on hydrostatic pressure. In future tests, where samples are to be consolidated, both the permeability and the thermal conductivity will be plotted as a function of water content. The behavior of this latter property will be compared to that predicted analytically by Hadley et al., (1980), where sediment and water conductivity are combined into a parallel circuit model.

DIAGRAM OF APPARATUS

- 1 - High Pressure Triaxial Cell
- 2 - Heating Jacket
- 3 - Loading Frame
- 4 - Sediment Sample
- 5 - Confining Ring
- 6 - Thermal Conductivity Probe

- 7 - Porous Filter
- 8 - Dead Weight Tester
- 9 - Recirculating Pump
- 10 - Volume Change Device
- 11 - High Pressure Pump
- 12 - Oil/Sea Water Interface

FIGURE 3.3-1

PACIFIC ILLITE
MARA-12 GC-26
172-182 cm.

FIGURE 3.3-2

PACIFIC ILLITE
 MARA-12 GC-26
 172-182 cm.

FIGURE 3.3-3

4.0 IN SITU HEAT TRANSFER EXPERIMENT (ISHTe)

4.1 ISHTe SITE SELECTION AND SEDIMENT CHARACTERIZATION (S. Criscenzo, A. Silva)

Introduction

The ISHTe working group has determined that the first full scale ISHTe will be conducted in the illitic sediments of MPG-I. Since all the pertinent geotechnical data for this region has been obtained by the URI/MGL group and the site selection work is being coordinated by E. Laine of URI, it was decided that the site selection work for ISHTe would be organized by this group. Arrangements were made to share a cruise to MPG-I with the MANOPS program in April 1980 and one person from URI (S. Criscenzo) participated in the field work. This section reports results of the geotechnical portion of the work as related to ISHTe.

4.1.1 RAMA 1 Cruise

During April 1980, URI personnel participated on a research cruise RAMA 1 aboard the R.V. Thomas Washington. One of the purposes of the cruise was to select a site within MPG I suitable for the deployment of ISHTe. Ideally, the ISHTe site should be a flat area with minimal manganese nodule cover and sufficient illite sediment thickness.

Most of the background data for the cruise was collected and compiled by URI personnel and details are available in our files. The cruise preparations for RAMA 1 included the compiling of all available topographical and coring data from MPG I. From this data, it was decided that the prime study area would be a site Northeast of LL-44 GPC 3. A final decision was made on board ship to survey an area approximately 10 km square bounded by the coordinates, 30°18' N to 30°27' N latitude and 157°40' W to 157°52' W longitude. The location of the survey area within MPG I is shown in Figure 4.1-1

The equipment used for the site selection survey included a Scripps Institute of Oceanography Deep Tow, a 10 cm ID gravity corer and a 50 cm x 50 cm box corer.

Coring Summary

A total of three box cores and ten gravity cores were successfully recovered in the study area. The core locations are listed in Table 4.1-1 and shown in Figure 4.1-2.

a) Box cores

The three box cores, BC 15, BC 18 and BC 20, were processed on board immediately after recovery. Included in the box core processing were:

- 7.6 cm diameter piston subsamples penetrated the length of the core. These samples are being used for laboratory geotechnical studies.

- 3.6 cm diameter x 10 cm long subsamples to be used for triaxial stress-strain studies.
- 6.3 cm diameter x 4 cm long subsamples to be used for consolidation, permeability, and sediment structure interaction studies.
- Detailed water content sampling to obtain water content profiles for each core.

The first successful box core (BC15) recovered a sample 32 cm deep. The surface of the core had scattered nodules with approximately 50% nodule coverage. The largest nodule was 8 cm x 5 cm x 5 cm and the mean size of the 104 nodules recovered in the core was approximately 3 cm diameter. All the nodules were processed and retained by the MANOPS personnel on board.

The core was a homogeneous red clay with no visible layering. The top 2 cm was very wet and loose with a slightly irregular surface. From 2 to 6 cm the sediment was stiffer than at the surface but still very soft and wet. From 6 to 10 cm the sediment became less wet and stiffer. Below 10 cm the sediment appeared to have a constant water content and consistency.

After the 7.6 cm samples were inserted into the core, the side of the box was removed. During this procedure the core became slightly disturbed causing some cracking of the sediment. This cracking reduced the amount of additional undisturbed subsampling which could be accomplished. The sampling summary for BC 15 is as follows: two 7.6 cm subsamples, seven 3.6 cm subsamples and 17 water content samples.

Box core 18 appeared to have penetrated at an angle, causing several cracks running the width of the corer, as well as a 3-4 cm void along one side. The surface nodule coverage was less (approximately 40%) than in BC 15 but the average size was much larger with several nodules greater than 10 cm in length. Once again, the sample was a homogeneous red clay with the same visual description as BC 15. The 7.6 cm subsamples were inserted along the front edge of the sample before the side was removed, however, the cracks in the sample made extensive subsampling impossible. The sampling summary for BC 18 is as follows: four 7.6 cm core subsamples, six 3.6 cm subsamples and 26 water content samples.

Box Core 20 penetrated 45 cm, provided the best quality sample of the three box cores and had the same visual descriptions. The surface of the core had approximately 70% nodule cover with the average size being between 3-5 cm in length. The good quality sample of BC 20 allowed extensive undisturbed sampling to be accomplished. The sampling summary for BC 20 is as follows: three 7.6 cm core subsamples, nineteen 3.6 cm subsamples, twenty 6.3 cm subsamples and 19 water content samples.

The water content samples from the three box core were processed at URI/MGL and the results are shown in Figures 4.1-3, 4.1-4 and 4.1-5. The water content profiles confirm the visual observations made onboard ship. All the cores exhibit a high water content between 0-5 cm, slowly decreasing between 5 and 15 cm where it becomes nearly constant for the remainder of the core. The wet zone between 0 and 10 cm is significant

for ISHTE foundation analysis and will be considered when designing the foundation pads for the ISHTE structure. All three cores showed a thin zone of lower water content (less than 120%) within the upper three centimeters.

The 7.6 cm subsamples will be processed at URI/MGL. The emphasis on this processing will be to obtain detailed shear strength profiles for the top 40 cm of sediment and to take consolidation and permeability samples from the top 20 cm of sediment. Attempts were made to measure shear strength in the box cores during sampling but it was not possible to do so with available equipment.

b. Gravity cores

All ten of the successful gravity cores were capped and sealed after recovery and placed in cold storage for the remainder of the cruise. Three of the cores, GC 14, GC 19, and GC 21, were shipped to URI/MGL for processing and the remaining cores, GC 8, 10, 12, 16, 22, 23, and 24 were shipped to Oregon State University (OSU). The cores shipped to OSU were processed by MANUPS personnel assisted by personnel from URI/MGL for geotechnical analysis. The processing of all ten gravity cores is complete and a summary is included in Table 4.1-2. The water content and shear strength profiles for each of the gravity cores are included in Figures 4.1-6 to 4.1-15 and a summary of the data for the top two meters of each core is shown in Table 4.1-3.

The core descriptions for all the gravity cores are similar; a homogeneous red clay with subtle modeling approximately 100 to 130 cm down core. There was a thin (5 cm) wetter layer in GC 10 at approximately 80 cm depth (Figure 4.1-7). It has not been determined, however, if this wet layer actually occurred in situ or if it was caused by core disturbance.

Conclusion

After an analysis of the Deep Tow data from RAMA 1, a primary ISHTE site was selected and two long-life transponders were deployed. The location of the prime ISHTE site is illustrated in Figure 4.1-2. While the site does have nodule cover heavier than desired, it is a flat area with ample sediment thickness. The goals of the RAMA 1 cruise were met; first, a suitable site was found for ISHTE deployment and second, thirteen good quality cores were taken within the survey area from which sufficient data will be obtained to complete the geotechnical analysis necessary for ISHTE.

4.1.2 Revised Sediment Strength Parameters for ISHTE Design

Recommended Parameters

The sediment strength parameters for ISHTE design have been revised based on undrained shear strength data from RAMA 1 gravity cores. The revised values are as follows:

For platform foundation analysis and design 47 g/cm² (4.6 kPa)

For penetration force analysis

69 g/cm² (6.8 kPa)

A variety of averaging techniques are available for interpreting shear strength data. To ensure a high degree of confidence in the recommended design values, three different averaging methods were used and the results compared. The following section is a synopsis of the methods used and the results for each.

Averaging Technique for Foundation Design Analysis

Based on the stress distribution on the sediment, it has been estimated that the failure zone will extend to a depth of approximately one meter below the bottom edge of the skirt (15 cm deep). Therefore, only the vane shear data between the depths of 15 and 115 cm were included in this analysis.

The first method used to determine the strength parameters for foundation design involved averaging the shear strength data between 15 and 115 cm for each core of the RAMA cruise (see Table 4.1-4). The high value of 48 g/cm² (4.7 kPa) for GC 19 was omitted and the mean values from the remaining 9 cores averaged. The results of this calculation gave an overall average for undrained shear strength of 39 g/cm² (3.8 kPa).

The second averaging method was similar to the first except that in this case the cores with the highest and lowest shear strength values, GC 19 and GC 21 respectively, were both omitted and the remaining 8 cores averaged with the result once again being 39 g/cm² (3.8 kPa).

In the third and final averaging method only the three cores nearest the proposed ISHTE site, GC 14, GC 19 and GC 21 were averaged. This method resulted in a value of 40 g/cm² (3.9 kPa).

Based on the results of the three averaging procedures stated above, a value of 39 g/cm² (3.8 kPa) has been selected as a representative core shear strength from the RAMA gravity cores between the depths of 15 and 115 cm. Adding an in situ factor of 20% to this, the recommended design shear strength for ISHTE foundation design is 47 g/cm² (4.6 kPa).

Averaging Technique for Penetration Force Analysis

The methods used for selecting a design shear strength for ISHTE penetration force analysis is similar to that used for the foundation design value with a few exceptions. For this analysis, the shear strength was averaged for the top two meters of each gravity core (see Table 4.1-3).

In the first averaging method the core with the lowest mean shear strength (GC 12, 41 g/cm²) was omitted and the remaining 9 cores averaged resulting in a value of 46 g/cm² (4.5 kPa).

In the second method, the core with the highest value (GC 23, 52 g/cm²) and the core with the lowest value were both omitted and the remaining 8 cores averaged with a result of 46 g/cm² (4.5 kPa).

In the third method, just the cores nearest the proposed ISHTE site were averaged with a result again of 46 g/cm^2 (4.5 kPa).

Once again, the results of each method were consistent and a representative shear strength for the top two meters was determined to be 46 g/cm^2 (4.5 kPa). Adding an in situ factor of 50% to this, the recommended design shear strength for ISHTE penetration force analysis is 69 g/cm^2 (6.8 kPa).

4.1.3 - Summary

During April 1980 URI/MGL personnel participated in a research cruise (RAMA-I) for the purpose of selecting a site in the MPG-I area which would be suited for deployment of the ISHTE platform. A 10 km square area, bounded by the coordinates $30^{\circ} 18' \text{N}$ to $30^{\circ} 27' \text{N}$ latitude and $157^{\circ} 40' \text{W}$ to $157^{\circ} 52' \text{W}$ longitude (Northeast of LL-44 GPC 3) was selected as the prime study area. A total of three box cores and ten gravity cores were successfully recovered.

In all three box cores (BC 15, 18, and 20), a relatively homogeneous red clay with no visible layering was observed during extrusion. These cores exhibited high water contents (approximately a 135% average) within the upper 15 cm decreasing to nearly a constant value (approximately 115%) for the remainder of the core. Shear strength data are unavailable for these cores.

All the gravity cores (GC 08, 10, 12, 14, 16, 19, 21, 22, 23, and 24), as in the box cores, displayed a homogeneous red clay sediment during extrusion. A wet thin layer was observed in one gravity core (GC 10) at approximately 5 cm, however, it has not been determined that this is a result of core disturbance. Both water content and shear strength data are available for these cores.

As a consequence to the RAMA-I cruise, revised sediment strength parameters for the ISHTE design have been completed. Based on three averaging techniques and an added 20% in situ factor, the recommended design shear strength for the pad design of the ISHTE platform is 4.6 kPa. Based on three averaging methods (different than previously reported) and a 50% in situ factor, the recommended design shear strength for the ISHTE penetration force analysis is 6.8 kPa.

Thus, the objectives of the RAMA-I cruise were satisfied. That is, a suitable deployment site was found for the platform and satisfactory cores were obtained for laboratory testing to complete a revised geotechnical analysis for ISHTE.

Table 4.1-1

RAMA 01 CORE LOCATIONS AND LENGTH

CORE #	LATITUDE	LONGITUDE	LENGTH OF CORE (cm)
GC-8	30° 20.9'N	157° 51.5'W	300
GC-10	30° 21.9'N	157° 47.9'W	300
GC-12	30° 23.0'N	157° 46.9'W	240
GC-14	30° 23.6'N	157° 44.3'W	233
BC-15	30° 22.1'N	157° 44.6'W	32
GC-16	30° 22.3'N	157° 44.8'W	269
BC-18	30° 25.9'N	157° 43.3'W	47
GC-19	30° 23.9'N	157° 41.3'W	252
BC-20	30° 24.0'N	157° 41.3'W	45
GC-21	30° 22.3'N	157° 42.5'W	234
GC-22	30° 22.0'N	157° 46.1'W	284
GC-23	30° 20.9'N	157° 49.6'W	280
GC-24	30° 23.1'N	157° 45.6'W	300

BC = Box Core (50 cm x 50 cm)
 GC = Gravity Core (10 cm I.D.)

TABLE 4.1-2

SAMPLING SUMMARY OF RAMA 1 GRAVITY CORES

CORE #	WATER CONTENT SAMPLES	VANE SHEAR MEASUREMENTS	5.08cm TRIAXIAL SAMPLES	5.08cm CONSOLIDATION SAMPLES	6.3cm CONSOLIDATION SAMPLES	CLASSIFICATION SAMPLES
GC 8	42	15	--	--	--	4
GC 10	44	18	--	--	--	8
GC 12	47	17	--	--	--	4
GC 14	59	17	5	--	7	4
GC 16	53	19	--	--	--	5
GC 19	65	19	5	2	6	5
GC 21	56	12	5	--	5	6
GC 22	60	22	--	--	--	5
GC 23	56	19	--	--	--	5
GC 24	62	19	--	--	--	5

TABLE 4.1-3
WATER CONTENT AND SHEAR STRENGTH VALUES
FOR THE TOP 2 METERS OF RAMA 1 GRAVITY CORES

CORE #	<u>WATER CONTENT</u> (Corr. for 35 ppt salt)			<u>SHEAR STRENGTH</u>		
	# OF TEST	MEAN %	STANDARD DEVIATION	# OF TESTS	MEAN g/cm ² (kPa)	STANDARD DEVIATION
GC 08	32	108	5.6	9	42 (4.1)	10.1
GC 10	35	116	11.3	13	47 (4.6)	17.5
GC 12	41	109	6.5	17	41 (4.0)	11.5
GC 14	53	116	10.2	15	42 (4.1)	14.7
GC 16	40	107	17.1	14	50 (4.9)	19.2
GC 19	51	107	12.8	14	50 (4.9)	6.4
GC 21	48	113	15.3	10	49 (4.8)	11.6
GC 22	42	114	5.8	18	41 (4.0)	10.1
GC 23	41	119	6.9	14	52 (5.1)	24
GC 24	44	120	7.5	15	46 (4.5)	6

Table 4.1-4

MEAN UNDRAINED SHEAR STRENGTH 15-115 cm

RAMA 1 GRAVITY CORES

CORE	NO. OF TEST	MEAN g/cm ²	(kPa)	STANDARD DEVIATION
GC 08	5	41	(4.0)	12
GC 10	5	35	(3.4)	6
GC 12	9	39	(3.8)	8
GC 14	10	37	(3.6)	13
GC 16	9	43	(4.2)	6
GC 19	7	48	(4.7)	9
GC 21	6	34	(3.3)	10
GC 22	10	39	(3.8)	10
GC 23	7	39	(3.8)	6
GC 24	8	42	(4.1)	8

CORE LOCATIONS IN MPG-1

Core Locations at MPG-1 (LL = Long Lines;
 M = MARA; V = VEMA; GPC = Giant Piston
 Core: PC = Piston Core; GC = Gravity
 Core;

URI-MGL 3/80

Figure 4.1-1

Figure 4.1-2 RAMA 1 Core Locations

Figure 4.1-3
(corrected for 35 ppt salt)

Figure 4.1-4
(corrected for 35 ppt salt)

Figure 4.1-5
(corrected for 35 ppt salt)

DEPTH vs. WATER CONTENT
RAMA 1 GC 8 VC
URI/MCL

DEPTH vs. SHEAR STRENGTH
RAMA 1 GC 8B SS
URI/MCL

Figure 4.1-6
(corrected for 35 ppt salt)

DEPTH vs. WATER CONTENT
RAMA 1 GC 18 VC
URI/MCL

DEPTH vs. SHEAR STRENGTH
RAMA 1 GC 18 SS
URI/MCL

Figure 4.1-7
(corrected for 35 ppt salt)

DEPTH vs. WATER CONTENT
RAMA 1 GC 12 VC
URL/NGL

DEPTH vs. SHEAR STRENGTH
RAMA 1 GC 12 SS
URL/NGL

Figure 4.1-8
(corrected for 35 ppt salt)

DEPTH vs. WATER CONTENT
RAMA 1 GC 14 VC
URL/NGL

DEPTH vs. SHEAR STRENGTH
RAMA 1 GC 14 SS
URL/NGL

Figure 4.1-9
(corrected for 35 ppt salt)

DEPTH vs WATER CONTENT
RAMA 1 GC 16 VC
URL/MCL

DEPTH vs SHEAR STRENGTH
RAMA 1 GC 16 SS
URL/MCL

Figure 4.1-10
(corrected for 35 ppt salt)

DEPTH vs WATER CONTENT
RAMA 1 GC 19 VC
URL/MCL

DEPTH vs SHEAR STRENGTH
RAMA 1 GC 19 SS
URL/MCL

Figure 4.1-11
(corrected for 35 ppt salt)

DEPTH vs. WATER CONTENT
RAMA 1 GC 21 VC
URL/MGL

DEPTH vs. SHEAR STRENGTH
RAMA 1 GC 21 SS
URL/MGL

Figure 4.1-12
(corrected for 35 ppt salt)

DEPTH vs. WATER CONTENT
RAMA 1 GC 22 VC
URL/MGL

DEPTH vs. SHEAR STRENGTH
RAMA 1 GC 22 SS
URL/MGL

Figure 4.1-13
(corrected for 35 ppt salt)

Figure 4.1-14
(corrected for 35 ppt salt)

Figure 4.1-15
(corrected for 35 ppt salt)

4.2 SEDIMENT STRUCTURE INTERACTION TESTING (S. Criscenzo)

Introduction

The Sediment Structure Interaction Testing Program (SSIT) is covered under three sections; Inconel-Sediment Interaction Studies, Thermal Probe Penetration Studies, and Core Penetration Studies. Each section will be discussed independently and focus on the results of tests run in calendar year 1980. The Sediment Structure Interaction Testing Program is scheduled for completion during FY 81. After completion of the remaining tests, a technical report will be prepared with a summary of final results, conclusions and recommendations. Details of the equipment and procedures for the program have been described in our Annual Progress Report No. 6 (Silva and Calnan, 1980).

4.2.1 Inconel-Sediment Interaction Studies

The purpose of the Inconel rod penetration phase of the SSIT program is two fold: first, to determine the most suitable surface finish for the ISHTE heater canister assembly and second, to determine the penetration force. The testing program has been divided into two areas; penetration testing and direct shear adhesion testing.

Penetration Testing

The penetration testing involves the penetration and pullout of three Inconel samples (2.5 cm outside diameter and 125 cm long) into a reconstituted and reconsolidated illite sample consolidated with a stress of 22.1 kPa. Each rod has a different surface finish: polished bright, sandblasted matte, and annular (emery cloth) rings. Penetration force, pullout force and the amount of sediment adhering to each sample are measured. In addition the bearing capacity factor and the traction stresses are calculated for each test.

The results to date indicate that surface roughness has no significant effect on the traction stress, and therefore the penetration force required is essentially the same for all samples as shown in Figure 4.2-1. However, there is a very significant difference in the amount of sediment adhering to each sample after pullout, with the roughest sample having the most sediment adhering to it. The traction stresses and the weights of the sediment adhering to each sample are listed in Table 4.2-1 for the latest series of tests.

An additional aspect of the Inconel penetration testing is to determine the zone of influence in the sediment after the sample has been penetrated. Both laboratory procedures as well as analytical methods will be applied in order to determine changes in water content, porosity, and shear strength profiles extending radially outward from the sample after penetration.

Direct Shear Testing

The second phase of the Inconel-Sediment Interaction studies is the direct shear and direct shear adhesion studies. The goal of these tests

is to study the stress-strain properties at the sediment structure interface in more detail. The program involves running standard direct shear tests using remolded illite samples taken from the SSIT test tanks. In addition, a modified shear test is run where the sediment sample is pulled across one of the three flat inconel plates, with surface finishes corresponding to those of the inconel rods used in the penetration testing.

The direct shear testing is currently underway and to date only one series of tests has been completed. This testing program is slightly behind schedule because of some equipment modification problems but will be accelerated for completion in FY 81.

The results of the first series of tests are shown in Figure 4.2-2. In this series three tests were run with increasing vertical stresses. While still preliminary, the data shows the expected trends and will be analyzed further as the testing program continues.

The tests utilizing the Inconel plates had not been completed at the conclusion of 1980. The results will be compared to the direct shear results and to the traction stresses calculated for the penetration tests.

4.2.2 Thermal Probe Testing

The thermal probe penetration testing is continuing as part of the ISHTE Sediment Structure Interaction Testing Program. The objective of this aspect of testing is to determine the penetration forces for the thermal probes. The laboratory testing consists of penetrating an 8 mm O.D. hollow glass rod, similar to the ISHTE thermal probe, into either a reconstituted, reconsolidated illite sediment sample, or into an undisturbed gravity core sample from MPG-1.

Remolded Testing

To date eight tests have been run using remolded illite samples. For this testing the same test frames and data collection system was used as for the Inconel penetration testing. The load vs. displacement curves for one series of tests are included in Figure 4.2-3. In this series of tests the glass rod was driven into the sediment at three different rates ranging from 3.5 cm/sec to 7.5 cm/sec. The sediment for this series was consolidated with a stress of 22.1 kPa and the average undrained shear strength was 3.6 kPa.

The analysis for this series of tests included calculating the Bearing Capacity Factors, calculating the traction stresses, and determining the sensitivity index. The Bearing Capacity Factor, N_c , was calculated by applying the equation

$$N_c = \frac{Q_T}{AS_u}$$

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where N_c = Bearing Capacity Factor
 Q_t = Tip Resistance (Determined from the Load Displacement Curve; Point Z, Figure 4.2-3)
 A = Area of tip
 S_u = Undrained Shear Strength of the surface of the sediment sample.

The traction stresses were calculated by taking the slope of the linear portion of the load displacement curve and then dividing by the perimeter. The sensitivity index was determined by dividing the average undrained shear strength of the sediment by the traction stress. The sensitivity index provides an opportunity to compare the sediment-glass adhesion from tests run in sediment of varying shear strengths. The results of these calculations are shown below:

Test #	Penetration Speed cm/sec	Bearing Capacity Factor	Traction Stress kPa	Sensitivity Index
GP-3	3.5	11	2.16	1.9
GP-4	5.2	11	2.55	2.1
GP 5	7.5	11	2.84	2.6

The results of this series exhibit the expected trends, i.e., the greater the penetration rate the higher the traction stress. As shown in Figure 4.2-3, the tip resistance is the same for all three tests and, therefore, the Bearing Capacity Factor is also the same.

The current design criteria for ISHTE specifies a thermal probe, the longest being 180 cm, to be penetrated into sediment with a undrained shear strength of 6.8 kPa at a rate of 10 cm/sec. To obtain penetration force estimates for the above criteria the results from GP 3, GP 4, and GP 5 were extrapolated to yield the following results. It should be noted that these force estimates are based solely on test results and no factor of safety has been applied.

ISHTE Estimated Thermal Probe Penetration Forces
for 6.8 kPa Sediment Strength

Probe Length	Penetration Speed			
	3.5 cm/sec.	5.2 cm/sec.	7.5 cm/sec.	10 cm/sec.
50 cm	4 kg	4 kg	5 kg	5 kg
100 cm	7 kg	8 kg	9 kg	10 kg
150 cm	10 kg	12 kg	13 kg	15 kg
180 cm	12 kg	14 kg	16 kg	17 kg

Undisturbed Testing

In an effort to further define in situ penetration forces for the thermal probes, it was decided to penetrate a glass probe into gravity core sections from the RAMA 1 cruise. The tests consisted of penetrating an unguided probe 120 cm long into a gravity core section prior to core processing. Five successful tests were run and once again traction stresses and sensitivity index were calculated with the following results:

RESULTS OF THERMAL PROBE PENETRATION IN GRAVITY CORE SECTIONS

Sample #	Average Shear Strength kPa	Drive Weight kg	Penetrated Length cm	Traction Stress kPa	Sensitivity Index
GC12 #1	4.5	5.4	84	2.5	1.8
GC16 #1	5.3	5.9	119	1.9	2.7
GC22 #2	3.9	4.1	72	2.2	1.8
GC22 #1	4.4	5.0	116	1.7	2.6
GC23 #1	6.9	4.5	70	2.5	2.7

While the penetration tests run in the gravity cores were not as accurately controlled as the tests run in the remolded sediment there is a good correlation between the two series of tests. The sensitivity indexes for the gravity core tests are in the same range as in the remolded tests, leading to the conclusion that the sediment-glass adhesion is similar for both undisturbed and remolded samples of the same shear strength. This data indicates that the penetration force estimates made from the remolded testing results are reasonable.

4.2.3 Core Penetration Testing

In order to determine the driving force for the slowly driven (10 cm/sec.) cores taken at the completion of ISHTE, a laboratory test has been conducted using a large diameter gravity core (LGC) barrel (.32 cm wall) complete with a standard URI cutter and catcher assembly. The core was pushed into a remolded reconstituted illite sample which was consolidated with a stress of 22.06 kPa. The average shear strength of the sediment sample was 3.62 kPa and the penetration speed was 7.0 cm/sec.

The result of the penetration test is illustrated in Figure 4.2-4. The curve has been divided into three sections. Section 1 represents the penetration of the nose cone-core catcher assembly and shows the highest traction stresses. Since the nose cone has a larger outside diameter than the remainder of the core barrel, there is no increase in drive force until the sediment rebounds to come in contact with the core barrel as shown in Section 2. of the curve. Once the sediment comes in full contact with the core barrel, the drive force once again increases as shown in Section 3 of the curve. The results for the pullout test (Figure 4.2-5) show an initial suction force of 88 kg, a sudden drop in force and then a second increase to 100 kg before suction is broken. The pullout force then decreases as the core is removed. Upon examination after pullout it was noted that the core catcher had deformed downward

allowing the sediment to move down in the core barrel. This was the cause for the initial decrease in pullout force before the suction was broken.

The results of both the penetration and pullout tests are consistent with the analysis performed for ISHTE core penetration forces. Based on current design sediment shear strength of 6.8 kPa for ISHTE the estimated core penetration force in the unheated region is 350 kg. Assuming the worst case of a possible ten fold increase in shear strength in the heated zone the penetration force has been estimated to be 3000 kg per core in the heated zone.

4.2.4 Summary

The Sediment Structure Interaction Testing (SSIT) program comprises three component studies; Inconel-Sediment Interaction, Thermal Penetration and Core Penetration. In the Inconel Sediment Interaction studies, a conclusion has been reached that the surface finish on an Inconel rod has no effect on penetration or pullout force but does have an effect on adhesion characteristics of the sediment.

In the Thermal Probe study, a series of tests to determine the penetration force for the ISHTE thermal probe has been completed. The tests involved penetrating thermal probe casings into both remolded and undisturbed illite. From these tests revised penetration forces for a variety of penetration speeds have been calculated.

In the Core Penetration study, the driving force for a slowly driven (10 cm/sec) core taken at the completion of ISHTE is required. A laboratory test has been conducted using a large diameter gravity core barrel complete with a standard URI cutter and catcher assembly. The results of this test indicate the penetration force for an ISHTE core in the unheated region is 350 kg and in the heated region may be as large as 3000 kg.

The SSIT program is being continued in FY 81.

Table 4.2-1

SUMMARY OF TEST RESULTS
FOR EFFECTS OF SURFACE FINISH ON
INCONEL-SEDIMENT INTERACTION

SURFACE FINISH	ARITHMETIC AVERAGE SURFACE ROUGHNESS (micro-inches)	TRACTION STRESS (kPa)	SEDIMENT ADHERED TO SAMPLE (g)
Polished Bright	5-10	1.97	0.3
Sandblasted-Matte	80-85	1.97	49.7
Annular Ring 200 Emery	45-55	1.97	9.6

DISPLACEMENT (CM)
LOAD (KG) vs. DISPLACEMENT (CM)
COMPOSITE PLOT
SERIES S TANK PI 2-5
URI/WOL
Figure 4.2-1

DISPLACEMENT (MM)
SHEAR STRESS (G/CM^2) vs. DISPLACEMENT (MM)
DIRECT SHEAR RESULTS
REMOLDED ILLITE
URI/NDL

Figure 4.2-2

Figure 4.2-3

LOAD vs. DISPLACEMENT
CORE PENETRATION
TEST # PI 5-0/CPI
URI/MQ

Figure 4.2-4

DISPLACEMENT (CM)
LOAD vs. DISPLACEMENT
CORE PULLOUT
TEST # PI 5-8/CVI
URI/ML

Figure 4.2-5

4.3. SIMULATION EXPERIMENT (S. Criscenzo, A. Silva)

Introduction

As a precursor to the in situ experiment, a scale model experiment will be conducted in the high pressure vessel at the Naval Ship Research and Development Center (NSRDC), Annapolis, Maryland. The purpose of the experiment is to conduct a carefully controlled thermal experiment in reconstituted and reconsolidated Pacific illite, which simulates as closely as possible the in-situ conditions anticipated at the first ISHTe site in MPG-I. Specifically, the simulation experiment will provide an opportunity to verify computer models currently being used for ISHTe design, by monitoring the thermal field around the heater, measuring the thermal conductivity of the sediment at elevated temperature and pressure, and measuring the interstitial pore water pressure in the heat affected zone. In addition, tests and sampling will enable an evaluation to be made of the effects of heat on the geotechnical and geochemical properties of the sediment. The simulation experiment will also enable other ISHTe components such as temperature probes and hydrostatic actuators to be tested at pressure while providing an opportunity for ancillary experiments, such as ion diffusion, to be conducted.

The simulation experiment will be run at pressure vessel conditions of 50 C and 9,000 psi for 30 days at the Ocean Environment Simulation Facility of NSRDC. The pressure vessel has an interior length of 8.2 meters and a diameter of 3.0 m. This facility will easily accommodate the simulation experiment as well as other experiments which can be conducted simultaneously.

The scale of the simulation experiment has been determined by applying a mathematical heat transfer model similar to the ones being used for ISHTe design. Most of these calculations have been made by C. Hickox of Sandia Laboratories. Based on a test duration of 30 days and taking into account the physical constraints of the test facilities, it has been calculated that the simulation experiment should be a .278 scale of ISHTe in order for thermal equilibrium to be reached using a 115 watt heater 2.2 cm outside diameter inserted into a sediment sample. It also has been determined that a sediment sample, 1.0 m diameter and 1.0 m high, will be of sufficient size that boundary effects will not significantly affect the thermal field near the heater.

4.3.1. Sample Preparation

The sediment to be used for the simulation experiment is from dredge samples taken within MPG-I. The illite sediment was shipped to URI/MGL where it was sieved to remove any nodules and then reconstituted by placing the sediment in a clay mixer, adding sea water, and mixing until a homogeneous sample was achieved.

The consolidation tank assembly used for preparing the sediment sample prior to the simulation is illustrated in Figure 4.3-1. An upper sleeve is fitted to the main tank and the entire assembly is lined with drainage fabric. A layer of sand is placed in the bottom of the tank and then covered with filter material. A series of drainage outlets will be

provided in the base of the tank.

The illite slurry will then be placed into the tank in 15-20 cm increments. At each increment a plate will be attached to the top flange and a vacuum applied. When the sediment reaches a depth of 150 cm a layer of filter material will be placed on top of the sediment and the sample will be ready for loading.

The consolidation stress of 22.1 kPa will be applied in three stages using steel loading plates at the surface of the sediment. A head of sea water will be maintained above the sediment to assure the sample remains saturated throughout the 8 to 10 week consolidation period. During consolidation the entire tank assembly will be enclosed in a cold room or cooled with a circulating water jacket to a temperature of 5° C.

Once consolidation is complete the loading plates and upper sleeve will be removed and the sediment will be trimmed flush with the top flange of the main tank. At this time the sample preparation phase will be complete and ready for placement of instrumentation and transfer into the pressure vessel.

4.3.2 Testing Hardware

A schematic of the instrumentation and testing hardware is shown in Figure 4.3-2. The heater will be inserted into the sediment followed by an array of thermal probes and a pore pressure probe. A T.V. camera and an in situ vane shear device will be installed along with the upper tank which is secured to the top flange of the main tank.

Once sealed the upper tank will be filled with sea water and an electronics check will be conducted. After the instrumentation is checked, the entire assembly will be placed inside the pressure vessel and then the pressure vessel sealed, filled, pressurized and cooled.

When temperature and pressure equilibrium are reached a series of vane shear tests will be run near the perimeter of the tank. Another series of vane shear tests will be conducted in the heated zone at the conclusion of the test. The results of these two series of tests will be compared and an evaluation of the effects of heat on sediment shear strength will be made.

After the initial series of vane shear tests is complete the heater will be turned on and temperature and pore pressure will be monitored for 30 days. When all testing is complete the heater will be switched off and the sediment will be cooled at pressure to avoid boiling. Once cooled, the test assembly will be removed from the pressure vessel and sampling for geotechnical and geochemical analysis will commence. The geotechnical sampling will include samples for consolidation, permeability, shear strength, water content, microstructure (fabric) and density testing while the geochemistry sampling will include samples for mineralogy, PH, and adsorption test.

The simulation experiment is being conducted jointly by Sandia National Laboratories which is coordinating the thermal and geochemical analysis; Applied Physics Laboratories at the University of Washington

coordinating instrumentation design and fabrication; and the Marine Geomechanics Laboratory at the University of Rhode Island coordinating tank design and fabrication; sediment preparation, geotechnical analysis, and serving as project coordinator.

The current schedule calls for a trial sediment sample to be consolidated and evaluated at URI/MGL in Spring 1981. Consolidation of the actual sediment sample is scheduled to begin at NSRDC in mid July 1981 leading to the simulation experiment commencing in mid October or November 1981.

4.3.3 Summary

A scale model experiment is being planned to simulate the In Situ Heat Transfer Experiment in a carefully controlled laboratory environment. An electrical heater will be used in a reconstituted, reconsolidated sample of Pacific illite, 1.0 meter diameter by 1.0 meter high, and the sediment response will be monitored with thermocouples, pore pressure probes, vane shear tests and thermal conductivity measurements. The 30 day experiment will be run at high pressure, to simulate 5800 meter water depth, in the large pressure vessel at the Naval Ship Research and Development Center, Annapolis, Md. The main purpose of the experiment is to compare the thermal field to computer model predictions. In addition, an evaluation will be made of temperature effects on geotechnical and geochemical properties of the sediments. The results of this experiment will be very useful for final design of ISHTE and should provide valuable data to the overall SDP.

ISHT E SIMULATION

TANK CONFIGURATION

CONSOLIDATION PHASE

SJC URI/MGL
1/23/81

FIGURE 4.3-1

SCALE
50 cm

ISHTE SIMULATION TEST CONFIGURATION

FIGURE 4.3-2

SJC URI/MGL
1/23/81

4.4 GEOTECHNICAL ANALYSIS AND DESIGN (S. Jordan, A. Silva)

Introduction

A revised analysis for sizing the support pads and determining the total settlement (based on one year deployment time), of the ISHE platform has been completed. The pads are sized according to the allowable bearing capacity of the supporting sediment and geometry of the pads. The total settlement calculation includes the elastic deformation, primary consolidation and secondary compression (plastic deformation) of the supporting sediment. This analysis incorporates the latest data from the cores of the RAMA-1 cruise as well as previously reported data within the MPG-I area (Silva and Calnan, 1980).

Pad Size

The computation of ultimate load for a long rectangular foundation on an incompressible soil uses the bearing capacity equation (Buisman, 1940; Terzaghi, 1943)

$$q_0 = cN_c + qN_q + 1/2 \gamma BN_\gamma \quad \text{Eq. 1}$$

where q_0 = maximum unit load,
 c = cohesive strength.
 q = surcharge due to surrounding overburden,
 γ = effective unit weight of soil,
 B = footing width and
 N_γ, N_c, N_q = bearing capacity factors.

For the application of equation 1 to sea floor sediments (saturated clays), it is assumed that $\phi = 0^\circ$. Under this assumption $N_\gamma = 0$ and $N_q = 1$, equation 1 reduces to

$$q_0 = cN_c + q \quad \text{Eq. 2}$$

In order to account for various foundation shapes, the effect of shear resistance in the overburden and the compressibility of the supporting soil, dimensionless parameters or other factors are used. Under a $\phi = 0^\circ$ analysis, equation 2 becomes

$$q_0 = cN_c \zeta_c \zeta_{cd} \zeta_{cc} + q \quad \text{Eq. 3}$$

where ζ_c = shape factor (Vesic, 1970)
 ζ_{cs} = depth factor (Skempton, 1951; Hansen, 1961) and
 ζ_{cc} = compressibility factor (Vesic, 1970).

According to Vesic, the shape factor ζ_c is

$$1 + (B/L) (N_q/N_c) \text{ for rectangular footings and} \quad \text{Eq. 4a}$$

$$1 + N_q/N_c \text{ for circular and square footings.} \quad \text{Eq. 4b}$$

When a condition $D/B \leq 1$ is satisfied, the depth factor ζ_{cd} is

$$\zeta_{cd} = 1 + 0.4 D/B \text{ (Hansen, 1970)} \quad \text{Eq. 5}$$

where D = depth of the footing and
 B = width of the footing.

The compressibility factor ζ_{cc} is dependent on the rigidity of the supporting soil and geometry of the footing. According to Vesic

$$\zeta_{cc} = .32 + .12 B/L + .6 \log_{10} I_r \quad \text{Eq. 6}$$

where L = length of the footing,
 $I_r = G/c$, rigidity index and
 G = shear modulus.

Eq. 7a

Vesic also formulated a critical rigidity index $(I_r)_{crit.}$ which is a guide for dividing a soil between one that is either incompressible or compressible. For $\phi = 0^\circ$

$$(I_r)_{crit.} = 1/2 \exp (3.30 - .45 B/L) \quad \text{Eq. 7b}$$

The shear modulus in equation 7a can be determined from an initial tangent modulus E_i and poisson ratio ν ; $G = E_i/2(1+\nu)$. For saturated clays $\nu = .5$ and E_i can be calculated from Janbu's relationship which accounts for the variation of initial tangent modulus with confining pressure. Here

$$E_i = K p_a \left(\frac{\sigma_3}{p_a} \right)^n \quad (\text{Janbu, 1963}) \quad \text{Eq. 8a}$$

where K = pure modulus number,

$\sigma_3 = K_0 d \gamma_b$, effective confining stress,

Eq. 8b

n = controls the variance of E_i and σ_3 ,

p_a = atmospheric pressure in same units as E_i

γ_b = buoyant unit weight and

K_0 = coefficient of lateral earth pressure at rest.

Data from the GC-04 core of the MARA-02 cruise was used to find E_i at a simulated average depth d of 60 cm (Silva and Calnan, 1980). This data was obtained from a series of isotropically consolidated triaxial tests; it would be safe to assume that the in situ modulus E_{i0} is approximately $1/2 E_i$.

Table 4.4-1 shows the values used for each parameter in the previous equations. Here the rigidity index for the supporting sediment is less than Vesic's critical, and therefore, the soil is considered as compressible.

Assuming plastic failure initiates at 15 cm below the seafloor (since the skirt is 15 cm depth) and the pad has a circular or square shape ($B = L$), the factors in equation 3 with $B = 100$ cm and $N_c = 5.14$ are

$$\zeta_c = 1.2,$$

$$\zeta_{cd} = 1.04 \text{ and}$$

$$\zeta_{cc} = .08.$$

The cohesive strength c is taken from section 4.1.2 which has a 20% increase as in situ factor to account for sample disturbance in cores. The maximum bearing capacity of the supporting sediment with $c = 4.60$ kPa and $q = 0.65$ kPa is

$$q_0 = 24.0 \text{ kPa}$$

With a recommended safety factor of 3, the allowable bearing capacity, q_a , is

$$q_a = q_0/3 = 8.0 \text{ kPa}$$

Since the shape of the footing influences the allowable bearing capacity, a calculation for a rectangular pad where $B = 2/3L$ and $D/B = .11$ yields

$$\zeta_c = 1.13$$

$$\zeta_{cc} = .76$$

Here

$$q_a = 7.2 \text{ kPa}$$

The buoyant weight of the ISHTE platform has not been determined, although it is estimated to be between 2700 kgf (26.5 kN) and 3600 kgf (35.3 kN) with the total load distributed equally to 3 pads. Using these values, Table 4.4-2 shows the minimum area and size of a circular, square and rectangular ($B = 2/3 L$) pad.

Table 4.4-2 Minimum area and size for various pad shapes

Shape	<u>Structure Weight</u>			
	<u>26.5 kN</u>		<u>35.3 kN</u>	
	<u>Area (m²)</u>	<u>Size (m)</u>	<u>Area (m²)</u>	<u>Size (m)</u>
Circular	1.10	$d=1.2$	1.47	$d=1.37$
Square	1.10	1.1×1.1	1.47	1.2×1.2
Rectangular	1.23	$.9 \times 1.4$	1.63	1.1×1.5

Settlement

The calculation of total settlement of the ISHTE platform involves the summation of three pases; initial compression, primary consolidation and secondary compression.

The initial settlement (elastic deformation) can be determined for a uniform stress perpendicular to the surface of a deep stratum as (Winterkorn and Fang, 1975)

$$S_d = C_d P B \left(\frac{1 - \nu^2}{E} \right) \quad \text{Eq. 9}$$

where S_d = initial settlement at a point (for this case, centroid of pad),

C_d = shape factor; circle $C_d = 1$
 square $C_d = 1.2$
 rectangle $C_d = 1.36$

p = applied uniform stress,

E = elastic modulus and

B = diameter of circle or width of square or rectangle.

A numerical value for E can be calculated from equations 8a and 8b where $dY_b = p$ at the base of the skirt. In order to check the variation of modulus E with depth, a typical point where the stress increase is 50% of the applied was selected. Using the Boussinesq stress distribution, at the base of the skirt and at a point of 50% stress increase $E = 569$ kPa (circular) and $E = 687$ kPa (square). Here, it can be seen that the change in modulus E with depth is not significant enough to justify an examination of initial settlement vs. depth.

Using the modulus E at the base of the skirt, the initial settlement (equation 9) for various pad shapes is

Shape	S_d (cm)
Circular	1.1
Square	1.2
Rectangular	1.0

A calculation for estimating the settlement due to primary consolidation has been described in detail in the previous analysis (Silva and Calnan, 1980). As indicated in previous reports, the upper few meters of the MPG-I sediments exhibit appreciable amounts of apparent overconsolidation due to high interparticle bonding and/or cementation. Therefore, for the ISHE platform pads, the zone of stress influence is within the overconsolidated region and compression due to consolidation will occur entirely along the reload region of the consolidation curve. For this situation, the settlement can be calculated with the following equation

$$S_c = \sum_{i=1}^n \frac{H_i}{1+e_{oi}} C_{si} \log \left(\frac{\sigma'_0 + \Delta \sigma'_i}{\sigma'_0} \right) \quad \text{Eq. 10}$$

where S_c = settlement due to consolidation,
 n = number of i layers,
 H_i = thickness of i -th layer,
 e_{oi} = initial void ratio of i -th layer,
 C_{si} = swelling index of i -th layer and

Layers of sediment are solved (to account for changes in properties) to a depth where a 10% or less increase in effective stress is realized. Below this depth, insignificant settlement due to primary consolidation can be expected (Hough, 1969).

Employing a Boussinesq stress distribution for a square foundation on a semi-infinite elastic solid and assuming a complete dissipation of

excess pore water pressure, 10% of the applied load occurs at a depth of approximately 2 meters. Since this 2 meter depth is within the area of apparent overconsolidation found in all MPG-I cores, the swelling index C_s is used instead of the virgin compression index in equation 10. However, it is noted here that it would be highly desirable to conduct an in situ plate bearing test to confirm these assumptions and calculations.

To date, consolidation data from the RAMA-01 cruise is available for the top 50 cm (Table 2.4.1-2). Data from the MARA cruises is used for the remaining depth (Silva and Calnan, 1980). Solving for nine layers of sediment using $q_a = 8$ kPa yields approximately .8 cm of settlement due to primary consolidation.

Deep sea sediments within the MPG-I area have displayed additional deformation after reaching 100 percent consolidation. This settlement is designated as secondary compression and is determined from the following equation

$$S_s = \frac{HC_\alpha}{1+e} \log (t/t_0) \quad \text{Eq. 11}$$

where S_s = settlement due to secondary compression,
 H = thickness of layer after primary consolidation,
 C_α = coefficient of secondary compression,
 e = void ratio at time t_0 ,
 t_0 = time of completion of primary compression and
 t = life of structure or time over which secondary compression is significant.

Secondary compression data from the RAMA-01 cruise is not yet available, but a calculation based on MARA cruise data was reported in a previous report (Silva and Calnan, 1980). Based on $t_0 = .72$ years (at 95% primary consolidation) and $t = 1$ year, the total settlement due to secondary compression was reported to be 0.2 cm.

A summary of the settlement calculations for the ISHTE platform using a rectangular pad is

Initial compression (S_d)	1.0 cm
Primary consolidation (S_c)	0.8 cm
Secondary compression (S_s)	<u>0.2 cm</u>
Total	2.0 cm

Discussion and Conclusion

Undrained shear strength data from the RAMA-01 cores (where deployment of the ISHTE platform will occur) showed a significant increase with respect to values obtained from other cruises (MARA-02) and 12, VEMA-32 and LL-44) in the MPG-I area. This has necessitated a revision to the original pad design and settlement calculations of the platform. Using a

revised undrained shear strength value of 4.6 kPa (as opposed to 3.5 kPa) which includes a 20% in situ factor (see Section 4.1.2) the required area of a square or circular pad decreased by 45%.

Revised settlement calculations have been performed using the new allowable bearing capacity of the sediment as the applied load for three types of footings, circular, square and rectangular. A rectangular configuration is recommended. A summary of the computations using a rectangular pad ($B=2/3 L$) revealed an estimated total settlement of 2.0 cm with 50% occurring immediately after platform landing. It must be remembered however, that effects from impact and eccentric (uneven landing) loads are assumed negligible. Fifty percent (50%) of the total settlement occurring directly after set down is not unusual because of the geotechnical nature of the soft sediment near the surface.

Future Work

Additional calculations must be made to investigate the penetration of the skirts into the soft upper sediments (if the resistance due to adhesion and bearing exceeds the structure weight then the platform will be supported only by the skirt resulting in an unstable condition). An estimate of the average undrained shear strength for the upper 15 cm (skirt is 15 cm deep) and determination of the type of material used for the skirt is required to study this behavior. Box core samples will be used to determine the necessary parameters.

Also, a venting system is required within the pad to allow the water and suspended sediment to escape during seating of the platform. A conceptual design has been completed with a final design due to be finished by mid 1981.

It should be remembered that the total settlement calculation is a reliable estimate. Depending on the limits of accuracy in predicting the total settlement during implementation of the platform, a numerical (computer) solution may be required. At this time the effects of the upper 5-15 cm of softer sediment on settlement estimates is not fully known. The calculations will be reviewed when additional consolidation data is obtained from the RAMA-1 samples.

It is strongly recommended that an in situ, long-term settlement test be conducted at the proposed ISHTE site. A conceptional design has been prepared for this experiment and presented to the ISHTE working group.

Summary

A revised analysis to determine the required pad sizes for the ISHTE platform and estimate the total settlement based on one year deployment time has been completed. The data used to obtain the necessary parameters for computations was taken from the recent RAMA-1 cruise as well as previous cruises in the MPG-I area.

With a recommended safety factor of 3, the allowable bearing capacity of the sediment was calculated to be 8 kPa for a circular or square pad and 7.2 kPa for a rectangular pad. Using these values with the applied load, Table 4.4-2 (shown within the text) shows the minimum required area

and size for three pad shapes. The rectangular shaped pad is recommended, and the total estimated settlement (one year deployment) for this configuration is 2.0 cm neglecting effects from impact, uneven landing, lateral stresses, and the upper 15 cm of sediment.

It is strongly recommended that an in situ, long-term settlement test be conducted at the proposed ISHTE site to further refine or possible modify this design.

Table 4.4-1

Parameters Used For Determining Pad Size

<u>Parameter</u>	<u>Symbol</u>	<u>Equation</u>	<u>Value</u>
Buoyant Unit Weight	γ_b	8b	4.32 kN/m ³
Coefficient of Lateral Earth Pressure at Rest	K_o	8b	.51
Pure Modulus	K	8a	345
Exponent	n	8a	1.25
Atmospheric Pressure	P _a	8a	101.4 kPa
In Situ Modulus	E_{i_o}	--	77.0 kPa
Shear Modulus	G	7a	25.6 kPa
Rigidity Index	I_r	6	5.6
Critical Rigidity Index	$(I_r)_{crit.}$	7b	8.6

4.5 IN SITU VANE SHEAR DEVICE (J. Babb, A. Silva)

Introduction

The University of Rhode Island Marine Geomechanics Laboratory is currently designing a self-contained, self-powered vane shear device for in situ measurements of soil properties in deep sea sediments. Two instruments will be deployed on the ISHTE platform during the year long heat transfer experiment in MPG-I.

The objective is to determine changes in stress-strain properties due to the heat source. Therefore, one set of measurements will be taken in the far field at the beginning of the experiment, and another set near the heater at the end of the experiment.

Geotechnical Design Considerations

Flaate (1966) determined that the total vane diametral area (blades and shaft) must be less than 15% of the area sheared to prevent disturbance during penetration. This corresponds to a 0.476 cm vane shaft diameter for the 4 bladed, 2 cm diameter, 3 cm high shear vane.

Flaate, in the same paper, developed an equation for rotational torque of the shear vane in soil, for an assumption of no progressive failure at the ends of the vane. Here

$$T = \pi/2 H D^2 S_v + \pi/6 D^3 S_h \quad \text{Eq. 1}$$

where T = total resisting torque at failure,
 H = vane height,
 D = vane diameter,
 S_v = shear strength in the vertical direction and
 S_h = shear strength in the horizontal direction.

Assuming that S_v and S_h are equal, then the above equation can be solved for the undrained shear strength, S_u

$$S_u = \frac{6T}{\pi D^2 (3H+D)} \quad \text{Eq. 2}$$

This equation will be used to calculate the undrained shear strength, remolded shear strength, and the residual shear strength from the experimental measurements of torque required to rotate the miniature vane.

Table 4.5-1 lists the parameters that the two shear vanes will measure in their respective test zones. The Bingham parameters may be obtained from a Bingham model plot similar to Figure 4.5-1. The Bingham yield stress (τ_u) and Bingham viscosity (μ_u) are related in the following equation (Gularte, 1978)

$$T = \pi^2 D^2 \frac{(3H+D)}{90} \mu_u \dot{\epsilon} + \pi^2 D^2 \frac{(3H+D)}{6} \tau_u \quad \text{Eq. 3}$$

where T = torque,
 D = vane diameter,
 H = vane height and
 $\dot{\epsilon}$ = strain rate.

The shear modulus, G , will be determined from the following equation, assuming cylindrical failure during rotation (Cadling and Odenstad, 1950)

$$G = S_u / 2\omega \quad \text{Eq. 4}$$

where S_u = undrained shear strength and
 ω = angle of rotation of vane for the corresponding value of S_u .

Sensitivity, S_t , will be determined by the ratio of the undrained shear strength, S_u , to the remolded shear strength, S_r (Wu, 1976)

$$S_t = S_u / S_r \quad \text{Eq. 5}$$

Measurements of soil properties will take place in the unheated sediments, at the rear of the lander, and in the heated sediments, near the heat source at the front of the lander, by two separate shear vane devices (See Figure 4.5-2). Figure 4.5-3 shows the test intervals to be used during penetration.

The shear vane test series in the unheated sediments will be run before placement of the heat source into the sediments. Rotation of the shear vane housing allows access to 7 separate test sites, assuming that the influence zone is 3 vane diameters, with a resulting center to center spacing of 6 cm. The plan is to run the entire vertical sequence of each site at different rates of rotation ranging from 60°/minute to 100 rpm. A Bingham plot, similar to Figure 4.5-1, will be constructed for each test depth from the corresponding shear stress versus strain rate.

The device in the heated sediment will only measure sediment shear strength after completion of the heat transfer experiment, but before removal of the heated implant. This test series will be conducted so that the full range of temperature regimes will be tested.

The anticipated average shear strength in the unheated zone is 70 g/cm². This was derived from the upper 2 meters of cores from the RAMA-1 cruise, using a 50% increase factor to account for sample disturbance due to coring.

In 1978, some high temperature, high pressure tests were conducted on sediment samples at Battelle Columbus Laboratories. Shear strength measurements were taken before the experiment. During the experiment the samples were brought to a temperature of 420°C and a pore pressure of 600 bars. After the samples were cooled and depressurized shear strength measurements were again taken. In the two tests the shear strength increased, on the average by factors of 6 and 10 over the original value (Silva and Calnan, 1980). A precipitate coating, which effectively cemented some of the clay, and sample contraction account for some of the increase in shear strength. It is not known if this increase is the result of the heating or the cooling afterwards. Tests to be performed during the ISHTe simulation should resolve these questions.

The 10 fold increase in shear strength will be used for design calculations in the heated zones as this produces a conservative estimate. A shear strength distribution in Figure 4.5-4 was derived from the inter-

sections of the vane shaft and the calculated isotherms. This will be used for determining design parameters in the heated zone.

Mechanical Design Considerations

An extensive design process is being used to develop a state-of-the-art instrument. In addition to A.J. Silva, the main design team consists of John Babb, S.J. Criscenzo, two U.E. Technicians, and Dr. P. Datseris who acts as a general overseer to the design. Many ideas, for improving the vane design, have been discussed, investigated, and analyzed during 1980. Tables 4.5-2, 3 and 4 show some important design criteria and calculations from the design process. The following discussion describes the status of the design as of Jan. 1981.

One of the most important design elements is strain gage placement for measurement of torque. The strain gages will be mounted in pairs at 45° to horizontal to form a torque transducer. Orientation of the gages in this arrangement will automatically cancel out any displacements in the vane shaft not due to torque on the shaft.

It is planned to mount the torque transducer above the miniature vane, but below the bearings and seals so that the torque produced by bearings and seals are not a problem. Mounting the transducer inside of the vane shaft will protect the gages from sea water corrosion. It is anticipated that this design will simplify calibration of the apparatus (See Figure 4.5-5).

The shear vane rotation can be accomplished by coupling a low speed motor and high speed motor through a differential and operating them at separate times. Although this set-up is acceptable, current investigation involves a motor capable of handling the complete rotation rate range, while maintaining a high degree of precision. Incorporation of this idea could simplify the mechanical design and reduce motor control problems.

The vane shear device is currently designed for operation at a depth of 6000 meters. A pressure compensated housing filled with instrument grade hydraulic oil will contain the instruments and mechanical parts. Use of pressure compensation simplifies the design since the shafts and seals need not resist a pressure differential.

The vane shear device will be self-controlled and self-powered. A microprocessor will control the vane operation and record the data (See Figure 4.5-6). A hard wire from the ISHTE control system, on the main platform, to the vane microprocessor enables an on-station ship to collect stored data or to turn on the instrument. Data stored on a magnetic tape in analog form in the microprocessor will be converted to digital form for transference to the ISHTE system. Self-powering the vane shear device lessens the power needs of the ISHTE system and allows use of the apparatus independently of the ISHTE platform.

Completion of the ISHTE shear vane is expected for the summer of 1981. Most of the remaining work involves specifying and testing components, although some design and reevaluation remains. The plan is to use the device in the ISHTE simulation experiment in Fall, 1981.

Summary

The design phase for the ISHTE In Situ Vane Shear Device is reaching completion. Two different vanes will be used during the year long heat transfer experiment to measure shear strengths in the heated and unheated regions. Several selected measurements will be taken in the unheated region to determine various soil properties. One shear vane will be used in the simulation experiment in Fall 1981 to measure the change in shear strength caused by a heat source.

The vane shear device will be self-controlled and self-powered and the primary system will be housed in a pressure compensated chamber. Construction and testing of the apparatus will be finished during 1981 with subsequent deep water tests in 1982.

Table 4.5-1

IN SITU SOIL PROPERTIES WHICH CAN BE
DETERMINED WITH THE SHEAR VANE TEST
PROGRAM

	<u>UNHEATED</u>	<u>HEATED</u>
UNDRAINED SHEAR STRENGTH	X	X
RESIDUAL SHEAR STRENGTH	X	X
REMOLDED SHEAR STRENGTH	X	X
SHEAR MODULUS	X	X
SENSITIVITY	X	X
BINGHAM YIELD	X	
BINGHAM VISCOSITY	X	

Table 4.5-2

MECHANICAL DESIGN CRITERIA

OPERATION DEPTH:	6000 m (18,000 ft)
EXPERIMENT DURATION:	12 months
POWER SUPPLY:	Self-contained, batteries
CONTROL:	Independent, can be triggered by ISHTE control system
TYPE OF DRIVE:	Motorized lead screw
TYPE OF MOTORS:	DC low voltage PM stepper motors
MATERIAL:	Inconel and Hastelloy at exposed areas

Table 4.5-3

GEOTECHNICAL DESIGN CRITERIA

PENETRATION DEPTH:	1.5 m (5.0 ft)
SHEAR STRENGTH, UNHEATED:	6867 kPa (70 g/cm ²)
SHEAR STRENGTH, HEATED:	See Figure 4.5-4
VANE DIMENSIONS:	D=2 cm (0.8 in) H=3 cm (1.2 in)
SHEAR STRENGTH ROTATION RATE:	60° /min
VISCOSITY ROTATION RATE:	up to 100 rpm
PENETRATION RATE:	1 cm/sec (0.4 in/sec)
PENETRATION INTERVALS:	See Figure 4.5-3
LOCATION ON PLATFORM:	See Figure 4.5-2
SHAFT DIAMETER: (Area ratio 15% to prevent disturbance)	4.76 mm (3/16 in)
ACCOUNT FOR SHAFT FRICTION:	Sleeve

Table 4.5-4

Summary of Calculated Design Values

Vane Shaft Diameter :	Outside	4.76 mm	0.1875 in
	Inside	3.34 mm	0.1315 in
Protective Sleeve Diameter :	Outside	9.52 mm	0.375 in
	Inside	8.10 mm	0.319 in

	<u>UNHEATED</u>		<u>HEATED</u>	
Max Torque to Rotate : (Includes all factors)	0.173 N-m	(1.53 lb-in)	1.63 N-m	(14.4 lb-in)
Max Force to Penetrate :	162.0 N	(36.4 lb)	1154.0 N	(259.0 lb)
Max Strain in vane Shaft :	47.9 μ strains		479 μ strains

Figure 4.5-1

SHEAR VANE PLACEMENT ON THE ISHTE
PLATFORM

Figure 4.5-2

ISHTE IN SITU VANE TESTING SEQUENCE

Figure 4.5-3

COMPARISON OF SHEAR STRENGTH DISTRIBUTION IN THE HEATED ZONE

Figure 4.5-4

STRAIN GAGE PLACEMENT

Figure 4.5-5

ISHTE IN SITU VANE

SIMPLIFIED FLOW DIAGRAM

Figure 4.5-6

5. SUMMARY

5.1 Introduction

The geotechnical program at the University of Rhode Island, Marine Geomechanics Laboratory (URI/MGL) is in its eighth year in support of the Subseabed Disposal Program. The continuing emphasis of this research effort has been in the determination and evaluation of the engineering properties of deep sea sediments as they relate to the specific problems encountered in subseabed disposal of radioactive wastes. The results of much of the experimental work at URI/MGL are essential input parameters for numerical models under development by the Subseabed Disposal Program as well as in determination of general sediment behavior for each study site as related to site selection. Two technical reports on completed work were published in FY 80 and two additional reports will be completed in spring (1981).

5.2 Sediment Characterization

Sediment characterization studies are an ongoing and essential effort related to site evaluation, including engineering property comparison and overall analysis in support of the SDP. In the MPG-I area, classification tests on samples from the MARA-02 and MARA-12 cores are essentially complete and tests are in the early stages on the RAMA cores. All data, points to relative homogeneity of properties laterally. Specific gravities in this area ranging between 2.6 and 2.9 are typical for illitic clay with traces of heavy metals being responsible for samples trending towards the upper end of this range. Buoyant unit weights average 454 kg/m^3 for the upper 2 meters and water content profiles are relatively consistent between cores.

Preliminary results from the Abyssal Plain region of MPG-III N have indicated that the area where the cores were taken has some disadvantages, from a geotechnical point of view, as a waste disposal site. The permeability of the upper several meters of the very soft sediments is probably low but the sandy layer that appeared in the piston cores below about 900 cm presents problems of high penetration resistance and higher permeability. However, the characteristics of deeper zones are not known and it is possible that this coarser layer is of very limited thickness. The sediment seems quite stratified in nature as indicated by the profiles of water content and shear strength. Classification work on these cores started in FY 80 and will be continued in FY 81 to further aid in characterizing this site.

The work on MPG-IV area samples was also started in FY 80 and the VEMA-36-12 cores will be under detailed investigation in FY 81 (M.S. Thesis - G. Walker). Buoyant unit weights determined so far yield an average of 280 kg/m^3 for the area. This is significantly lower than MPG-I and the water contents are correspondingly higher. Many of the designated sub-areas in MPG-IV seem to have significant variations in index properties between themselves. Further classification work will involve filling in of the data base for all three areas; especially grain size analysis, Atterberg Limits, permeability and compressibility.

5.3 Triaxial Testing

The URI/MGL involvement with triaxial testing of deep sea sediments has been of great value to the many stress-strain conditions that are under examination in the sub-seabed disposal problem. Triaxial testing in the past has centered around conventional isotropically consolidated undrained testing (CIU) and anisotropically consolidated (K_0) undrained tests (CAU). These studies are continuing during FY 81. Programs that are presently getting underway are high pressure CIU triaxial series in coordination with efforts at Waterways Experiment Station and a study examining the effects of stress path on stress-strain behavior.

The majority of CIU testing on deep sea illite and smectite is complete and published as a technical report (Akers and Silva, 1980). It was found that the Mohr-Coulomb failure parameters of effective cohesion (c) and angle of internal friction (ϕ) are comparable with other published values for marine illites and smectites. Undisturbed smectite samples had friction angles slightly greater than the undisturbed illite and in general, smectite had the larger undrained strength as well. On the other hand, much larger differences in friction angle are seen between remolded smectite and illite with smectite being 32 percent larger. This sensitivity of Pacific illite to remolding (30% reduction in ϕ) coupled with lower undrained shear strengths is an important consideration to canister emplacement. Hyperbolic stress-strain analysis seems to work well as a predictor of stress-strain behavior prior to failure; however, post-failure behavior, which could be important to canister emplacement, cannot be modelled this way. Measurements of undrained shear strength with depth in a core by miniature vane and values calculated from triaxial results correlate very well. This indicates that the Giant Poston Corer takes a high quality undisturbed sample and that the vane shear device gives good undrained shear strength. Current CIU work involves continuation of testing of undisturbed illites to resolve inconsistencies between parameters obtained at higher consolidation stresses (sec. 2.2.2) than those of this study.

A related study of the effects of anisotropic stress conditions on deep-sea sediments was performed by consolidating the sample under conditions of no lateral strain (K_0 consolidation). This first phase of CAU testing has been completed and published in a technical report (Schwartz and Silva, 1980). The averaged experimental K_0 values at the end of consolidation are 0.52 for undisturbed illite and 0.48 for remolded smectite. These vary slightly from those predicted by Jaky's formulation (1948). As K_0 is a function of stress history we feel the no lateral strain condition for anisotropic consolidation is the most advantageous for simulating the in situ conditions. CAU results for undisturbed illite and remolded smectite show that normalized shear strength is about 15 percent less than for CIU tests, while normalized pore pressure is significantly higher than CIU. As expected, CAU samples failed at axial strains approximately three times less than CIU tests. Also these preliminary results indicate some strain softening behavior for CAU tests on undisturbed illite. In summary, it appears that anisotropic consolidation has a significant effect on material parameters and general sediment behavior and further CAU studies at URI/MGL will define these effects.

Tests to study the effect of stress-path on stress-strain behavior were begun in early 1981. The first tests will examine the differences between conventional CIU triaxial compression and reduced triaxial extension tests. Preliminary results indicate that strains at failure appear to be significantly less for illite samples in extension compared to compression tests on the same material. Further tests of this kind as well as other various combinations of stress conditions are planned.

Other programs just getting underway (FY 81) involve a series of CIU triaxial tests examining sediment response at high consolidation pressures and a CIU series that will examine the effects of varying doses of gamma radiation on sediment strength.

5.4 Creep Testing

Creep studies at URI/MGL have concentrated mostly on stress-strain-time behavior of deep sea sediments under drained loading conditions. An extensive series of room-temperature creep tests has been completed and the results will be published as a technical report (Moran and Silva, 1981). The first phase of the creep program studying the effects of high temperature has been completed including a detailed analysis being conducted by J. Wildman as part of her M.S. Thesis.

The results of the room-temperature creep series provide essential input parameters for computer modelling studies of the long term sediment behavior around the canister. This is essentially the first experimental data of this type of behavior for deep sea sediments. It was found that these sediments exhibit larger strains than published data for terrestrial and "bay" material tested at the same stress levels. This behavior appears to be a function of the high in situ water contents though other factors such as mineralogy surely contribute. New phenomenological equations are presented for the illite and smectite materials of MPG-I that predict the deformational behavior of these deep sea clays for the long term (i.e. drained) condition. Since these materials exhibit nonlinear decreases of strain rate with time under long term conditions, generalized equations that assume linearity are less accurate. Another interesting phenomena observed in the stress-strain-time behavior of these materials were the occurrence of "jumps" or "instabilities" in the stress-strain plots. These are believed to be caused by a reorientation of the sediment structure under constant stress conditions. A long term (1 year) test at room temperature has been set-up to more accurately define these microstructural observations.

In the variable temperature creep program similar instabilities were noted in almost all temperature tests (40°, 200°, 750° and 1500°). In this preliminary series a trend of increasing resistance of illites to creep failure with increasing temperature is indicated and further tests at intermediate temperatures are planned. It appears that heating may substantially alter the physio-chemical properties of the sediment and that rate process theory may not be sufficient in evaluating the creep behavior of these deep sea sediments.

A single undisturbed illite specimen was tested under conditions of undrained constant load. Here instabilities occurred on a larger scale

than the drained test and appear to be a direct consequence of the build-up of excess pore pressures. It appears that undrained creep behavior is totally different than drained sediment response and further studies are essential to define these differences.

5.5 Compressibility Studies

Compressibility studies are an ongoing program at URI/MGL. These results are used to examine stress history in SDP sites as part of the site characterization work and for settlement computations of the ISHE platform. The compressibility studies of SDP site MPG-I are essentially complete. Results show the upper 2 meters of the site to be "apparently" overconsolidated. This phenomenon is believed to be due to high inter-particle bonding and/or cementation. This upper 2 meters must be considered in any settlement analysis for this site. As previously reported, the remainder of the sediment column is normally consolidated.

The same phenomenon of "apparent" overconsolidation in the surficial sediments also appears in the MPG-III N area. However, the overconsolidation ratios obtained in this region are significantly lower than those reported in MPG-I at comparable sub-bottom depths.

Only three consolidation tests have been completed on samples from the MPG-IV area. Again, "apparent" overconsolidation is indicated in the surficial layers. A detailed analysis of site E₂ is underway with a more general assessment of sites B₁ and C₁.

5.6 Permeability Studies

There are three aspects to permeability studies at URI/MGL. The standard permeability program provides baseline data for site characterization and water migration studies relevant to canister emplacement and the two test programs are designed to study the effects of high temperature permeability properties. The coefficient of permeability is determined directly from constant head permeameter readings and theoretically from standard consolidation tests. Values of the coefficient of permeability in the MPG-I form a fairly consistent pattern with depth. The average for the upper two meters average approximately 3×10^{-6} cm/sec. While below these surficial sediments the average decreases to an essentially constant average of 5×10^{-7} cm/sec. These changes with depth may be due to mineralogical changes. Preliminary data from MPG-III N indicates it to be similar in permeability characteristics to MPG-I. In the new area, MPG-IV, values range from 6×10^{-7} to 1×10^{-6} cm/sec. Further tests in MPG-III N and MPG-IV (concentrating on E₂) are planned to develop more extensive permeability profiles.

The second research area in permeability examines the effects of elevated temperatures using a modified back-pressure system at moderate pressure. An initial series of direct constant head measurements of the coefficient of permeability at temperatures up to 150°C suggest that there is no change in permeability due to changing sediment character. The measured increase in the coefficient of permeability with increasing temperature is due entirely to the decrease in the viscosity of water.

The third test program involves simulation of in-situ pressures (up to 700 bars) with measurement of permeability and thermal conductivity under changes in temperature (up to 220°C) and pressure. Preliminary data (at room temperature), points to no significant dependence of permeability on high hydrostatic pressure for the illite sample tested. Thermal conductivity during these room temperature tests, also show no noticeable change. Additional pressure variation tests will be conducted on smectite and then the effects of variable temperature will be studied.

5.7 IN SITU HEAT TRANSFER EXPERIMENT (ISHTe)

a. ISHTe Site Selection and Sediment Characterization

A 10 km square area in MPG-I was selected by the SDP as prime ISHTe study area as a result of the RAMA-01 cruise of April 1980. URI/MGL personnel were responsible for box core and gravity core recovery, handling, and testing. All gravity cores have been extruded, subsampled and tested for vane shear strength and water content. Box cores of the upper 50 cm of seafloor exhibit water contents averaging 135% within the upper 15 cm and decreasing to 115% for the remainder of the section. As a consequence of the data obtained from this cruise, revised sediment strength parameters for the ISHTe platform design were calculated. For the pad design the recommended design shear strength is 4.5 kPa while for the penetration force analysis the design shear strength is 6.8 kPa.

b) Sediment Structure Interaction Testing (SSIT)

The SSIT program involves controlled laboratory testing of actual components and scale models of the ISHTe platform. Tests conducted to study variation of surface finish of the Inconel implant rod on penetration and pullout forces indicate that roughness has virtually no effect. However there was a very significant effect on adhesion characteristics with the roughest finish having the largest amount of sediment adhering after pullout. Tests to determine the penetration force and penetration speed for the ISHTe thermal probe have been made using full scale thermal probe casings in both undisturbed and remolded illite. A core penetration study was conducted to determine the driving force for a slowly driven (10 cm/sec.) core that would be taken at the completion of the ISHTe. The results indicate the penetration force for the corer will be about 350 kg in the unheated zone and 3000 kg in the heated zone (assuming a ten-fold increase in sediment strength due to heating). The SSIT Program will be continued in FY 81.

c. Simulation Experiment

A scale model experiment is being planned that would simulate the In Situ Heat Transfer Experiment in a carefully controlled laboratory environment. The main purpose of the experiment is to compare the measured thermal field to that predicted by computer models. An electrical heater will be used in a reconstituted-reconsolidated tank of Pacific illite. This and all measurement devices will be left for 30 days in the large Naval Ship Research Development Center pressure vessel at pressures simulating 5800 m water depth. Sediment response will be monitored by thermocouples, piezometers, thermal conductivity probes and

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vane shear testing. The URI/MGL group has been designated project coordinator for this experiment which will be conducted in early FY 82.

d. Geotechnical Analysis and Design

A revised calculation of configuration and total settlement for the ISHTE platform pads has been completed based on new data from recent RAMA-01 cruise. Using a safety factor of 3, the allowable bearing capacity of the sediment was calculated to be 8 kPa for circular or square pads and 7.2 kPa for rectangular pads. Using these values with the estimated applied load, minimum required areas and sizes were determined for the three pad shapes. This analysis suggests that the rectangular shaped pad would be desirable. The total estimated settlement due to compression of sediment below the 15 cm skirt at the end of one year would be 2.0 cm for this configuration. It must be noted that this is an estimate and does not take into account effects of impact and uneven landing.

e. In Situ Vane Shear Device

The design phase for the ISHTE In Situ Vane Shear Device is nearing completion. Fabrication and testing will be finished during 1981 with subsequent deep water tests planned for 1982. A modified configuration of the shear vane will be used in the simulation experiment to measure the change in shear strength due to a heat source. It was decided that two shear vanes will be used during the year long heat transfer experiment to measure strengths inside and outside the heat region. The vane shear device will be self-controlled and self-powered with its components housed in a pressure compensated chamber. The vane device will be capable of determining a number of sediment stress-strain parameters in both temperature regimes.

REFERENCES

- Akers, S.A. and Silva, A.J., Stress-Strain and Strength Properties of Marine Sediments from the North Pacific, URI Tech. Report., June 1980.
- Banford, S.R. and Silva, A.J., Hole Closure Behavior of Marine Sediments Following Projectile Penetration, URI Tech. Report, June 1980.
- Beverly, B.E., Consolidation Characteristics of Deep-Sea Sediments Recovered with a Giant Piston Corer: Blake Bahama Outer Ridge Area, M.S. Thesis, Worcester Polytechnic Institute, Worcester, Massachusetts, 1975.
- Bishop, A.W. and Lovenbury, H.T., Creep Characteristics of Two Undisturbed Clays, Proceedings of the Seventh International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, pp. 29-37, 1969.
- Bryant, W.R., Deflache, A.P. and Trabant, P.K., Consolidation of Marine Clays and Carbonates, Deep-Sea Sediments, Marine Science 2, Plenum Press, New York, 1974.
- Buisman, A.S.K., Grondmechanica, Waltman, Delft, pp. 190, 1940.
- Cadling, L. and Odenstad, S., The Vane Corer, Royal Swedish Geotechnical Institute Proceedings, No. 2, Stockholm, pp. 37-39, 1950.
- Campanells, R.G. and Vaid, Y.P., Influence of Stress Path on the Plane Strain Behavior of a Sensitive Clay, Soil Mechanics Series No. 19, Dept. of Civil Engr., The University of British Columbia, Vancouver, CA., April 1972.
- Duncan, J.M. and Seed, H.E., Errors in Strength Tests and Recommended Corrections, Report No. TE-65-4, Dept. of Civil Eng., Univ. of California, Berkeley, 1965.
- Flaate, K., Factors Influencing the Results Vane Test, Canadian Geotechnical Journal, Vol. 3, No. 1, pp. 18-31, Feb. 1966.
- Garfield, G.M., Apparent Overconsolidation of Deep Sea Clay, URI Course Project, 1979.
- Gularte, R.C., Erosion of Cohesive Marine Sediment as a Rate Process, Ph.D. Dissertation on O.E., URI, 1978.
- Hadley, G.R., McVey, D.F. and Morin, R., Thermophysical Properties of Deep Ocean Sediments, Sixteenth Annual Conf., 1980.
- Hansen, B. and Christensen, N.H., Discussion on theoretical bearing capacity of very shallow footings, Proceedings ASCE Journal of the Soil Mech. and Found. Division, 95, No. SM-6, pp. 1568-72, 1969.
- Hough, B.K., "Basic Soils Engineering," Second Edition, The Ronald Press, N.Y., 1969.

- Jaeger, J.C., The Measurement of Thermal Conductivity and Diffusivity with Cylindrical Probes, Trans. American Geophysical Union, 39, 1958.
- Jaky, J., Pressure in Silos, Proc. Sec. Intern. Conf. on Soil Mech. and Found. Eng., Rotterdam, Vol. 1, pp. 103, 1948.
- Janbu, N., Soil Compressibility as Determined by Oedometer and Triaxial Test, European Conf. on Soil Mech. and Foundation Engr., Wissbaden, Germany, Vol. 1, pp. 19-25, 1963.
- Ladd, C.C., Stress-Strain Behavior of Anisotropically Consolidated Clays During Undrained Shear, Proc. Sixth Intern. Conf. on Soil Mech. and Found. Eng., Montreal, Vol. 1, pp. 282-286, 1965.
- Lambe, T.W., and Whitman, R.V., "Soil Mechanics," John Wiley & Sons, Inc., New York, 1969.
- Lang, W.J., The Influence of Pressure on the Electrical Resistivity of Clay Water Systems, Proc. of the Fifteenth Conference on Clays and Clay Minerals, Clay Minerals Society, 1969.
- Lee, H.J., "The Role of Laboratory Testing in the Determination of Deep-Sea Sediment Engineering Properties," ed. by A.L. Inderbitzen, Plenum Press, 1974.
- Leinen, Margaret and Heath, G. Ross, "Paleochemical Signatures in Cenozoic Sediments from the Central North Pacific," *Geochimica et Cosmochimica Acta*, 1980.
- Lo, K.Y., The Pore Pressure-Strain Relationship of Normally Consolidated Undisturbed Clays, Part I and Part II, Canadian Geotechnical Journal, Vol. 6, pp. 383-412, 1969.
- Mitchell, J.K., "Fundamentals of Soil Behavior," John Wiley and Sons, Inc., 1976.
- Moran, K., Atlantic/Abyssal Plain-HUDSON Cruise, URI Geotechnical Report, 1980.
- Moran, K., Drained Creep of Deep Sea Sediments, M.S. Thesis, URI, 1981.
- Nickerson, C.R., Consolidation and Permeability Characteristics of Deep-Sea Sediments: North Central Pacific Ocean, M.S. Thesis, Worcester, Polytechnic Institute, Worcester, MA, Jan., 1978.
- Pusch, R., A Physical Creep Model and Its Mathematical Analogy, Proceedings of the Third International Conference on Numerical Models in Geomechanics, Aachen, edited by W. Wittke, pp. 485-492, 1979.
- Schwartz, S., Undrained Stress-Strain Behavior of Anisotropically Consolidated Deep-Sea Clays, M.S. Thesis, URI, 1980.
- Schwartz, S. and Silva, A.J., Undrained Stress-Strain Behavior of Anisotropically Consolidated Deep Sea Clays, URI Tech. Report, 1981.

- Silva, A.J. and Calnan, D.I., "Geotechnical Aspects of Subsurface Seabed Disposal of High Level Radioactive Wastes," Annual Progress Report No. 4, DOE/SLA Contract No. 05-7899, May 1978.
- Silva, A.J. and Calnan, D.I., "Geotechnical Aspects of Subsurface Seabed Disposal of High Level Radioactive Wastes," Annual Progress Report No. 5, Contr. No. 05-7899 and 13-2561, 1979.
- Silva, A.J. and Calnan, D.I., "Geotechnical Aspects of Sub-seabed Disposal of High Level Radioactive Wastes," Annual Progress Report No. 6, DOE/SLA Contr. No. 13-2561 and 13-9927, May, 1980.
- Singh, A. and Mitchel, J.K., General Stress-Strain-Time Function of Soils, Journal of the Soil Mechanics and Foundations Division, ASCE, No. SM1, pp. 21-46, 1968.
- Skempton, A.W., The bearing capacity of clays, Proceedings, Building Research Congress, Longdon, pp. 180-189, 1951.
- Ter-Stepanon, G., Creep of a Clay During Shear and its Rheological Model, Geotechnique, Vol. 25, No. 2, pp. 299-320, 1975.
- Terzaghi, K., "Theoretical Soil Mechanics," J. Wiley & Sons, New York, 1943.
- Terzaghi, K. and Peck, R.B., "Soil Mechanics in Engineering Practice," New York (J. Wiley), Second edition, 1967.
- Trollope, D.H. and Chan, C.K., Soil Structure and the Step-Strain Phenomenon, Journal of the Soil Mechanics and Foundations Division, ASCE, No. 6, SM2, pp. 1-39, 1960.
- Vesic, A.S., Research on Bearing Capacity of Soils (unpublished), 1970.
- Von Herzen, R. and Maxwell, A.E., The Measurement of Thermal Conductivity of Deep-Sea Sediments by a Needle-Probe Method, J. of Geophysical Research, 64, 1959.
- Winterkorn, H.F. and Fang, H.Y., "Foundation Engineering Handbook," Van Nostrand Reinhold Co., New York, 1975.
- Wong, K.S. and Duncan, J.M., Hyperbolic Stress-Strain Parameters for Nonlinear Finite Element Analyses of Stresses and Movements in Soil Masses, Report No. TE-74-3 to NSF, Univ. of Calif., Berkeley, 1974.
- Wu, Tien Hsing, "Soil Mechanics," Allyn and Bacon, Inc., Boston, pp. 8, 1976.

Appendix L

Constitutive Properties and Material Model Development
for Marine Sediments in Support of the Subseabed Disposal Program

G. Y. Baladi and S. A. Akers

CONSTITUTIVE PROPERTIES AND MATERIAL MODEL DEVELOPMENT FOR
MARINE SEDIMENTS IN SUPPORT OF THE SUBSEABED DISPOSAL PROGRAM

by

George Y. Baladi and Stephen A. Akers

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Structures Laboratory
Vicksburg, Mississippi

PREFACE

This report documents the results of research conducted for Sandia National Laboratories by personnel of the Geomechanics Division (GD), Structures Laboratory (SL), U. S. Army Engineer Waterways Experiment Station (WES), in support of the Subseabed Disposal Program (SDP), Activity D, Emplacement of Wastes in Sediments, under Purchase Order No. 46-3861, dated November 1979.

The investigation was conducted during the period November 1979 - December 1980 under the general direction of Mr. Bryant Mather, Chief, SL; Dr. J. G. Jackson, Jr., Chief, GD; and Mr. J. Q. Ehgott, Acting Chief, Operations Group, GD. The principal investigator at WES for SDP was Dr. Behzad Rohani. SDP at WES is divided into two areas--theoretical and experimental. Dr. G. Y. Baladi was responsible for the theoretical program and Mr. S. A. Akers was responsible for the experimental program. Dr. J. S. Zelasko provided SDP with detached peer review. This report was written by Dr. Baladi and Mr. Akers.

COL Nelson P. Conover, CE, was the Commander and Director of WES during this investigation. Mr. F. R. Brown was the Technical Director.

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CONSTITUTIVE PROPERTIES AND MATERIAL MODEL DEVELOPMENT FOR
MARINE SEDIMENTS IN SUPPORT OF THE SUBSEABED DISPOSAL PROGRAM

INTRODUCTION

BACKGROUND

In support of the Subseabed Disposal Program (SDP), Activity D, Emplacement of Wastes in Sediments, the Geomechanics Division, Structures Laboratory, of the U. S. Army Engineer Waterways Experiment Station (WES) was tasked by Sandia National Laboratories (SNL) in June 1979 under Purchase Order No. 13-7177 to develop and submit a program plan to conduct research on the dynamic high-pressure mechanical properties of seabed sediments and to participate in the formulation of a mathematical constitutive model for such materials using effective-stress concepts. As a result of this task, a program plan was developed and submitted to SNL in the form of a work statement in October 1979. The work statement was approved by SNL, and WES was funded in November 1979 under Purchase Order No. 46-3861 to conduct the proposed work. The proposed work consisted of two tasks; Task I - a theoretical investigation and Task II - an experimental program. The purpose of the theoretical investigation was to develop an appropriate elastic-plastic effective-stress constitutive model and the necessary numerical algorithms for seabed sediments for use in computer code simulations of both early-time dynamic penetration of waste canisters and late-time hole closure. The purpose of the experimental program was to provide high-pressure dynamic stress-strain and strength properties for seabed sediments of interest, which in conjunction with data provided by the University of Rhode Island (URI), could be used to guide the development and verification of a constitutive model for such materials.

The status of the work conducted under Purchase Order No. 46-3861 as of 31 December 1979 was communicated to SNL in the form of a letter report entitled "Constitutive Properties and Model Development for Marine Sediments in Support of the Subseabed Waste Disposal Program," dated January 1980. That letter report contained only a very brief description of a proposed effective-stress model for seabed sediments. Since the submission of that report, however, the SDP at WES has been considerably advanced. The development of the effective-stress model has been completed. The model has been implemented into a numerical algorithm. In order to simulate the behavior of the constitutive model in a variety of conventional laboratory test conditions such as triaxial compression, uniaxial strain and hydrostatic stress, a computer "driver" has been developed and coupled with the numerical algorithm of the model under the name SANDR. Using SANDR and the available experimental data, numerical values of the various material constants contained in the constitutive model were determined for Pacific illite. Moreover, the constitutive model was furnished to SNL personnel who successfully incorporated it into two-dimensional wave codes for dynamic penetration calculations and hole closure simulations.

In the experimental area a large number of tests were conducted at WES on both undisturbed and remolded samples of Pacific illite and the results quantified to provide information on the stress-strain and strength properties of seabed sediments under high-pressure static and dynamic loading conditions.

The purpose of this report is to document in detail the findings of the WES SDP for the period November 1979 - December 1980.

SCOPE

This report is divided into four independent parts. Each part contains its own references, figures, equations, and chapters.

The results of the theoretical program are documented in Part I, which contains four chapters. The fundamental basis of elastic-plastic constitutive models is presented in Chapter 1. The numerical implementation of the elastic-plastic models is discussed in Chapter 2. The development of the effective-stress constitutive model for seabed sediments is presented in Chapter 3. The behavior of this effective-stress model under hydrostatic and triaxial compression test conditions is illustrated in Chapter 4.

Part II deals with the experimental program and includes five chapters. Chapter 1 deals with background geotechnical information regarding the physical properties of seabed sediments and presents the scope of the experimental program. Testing equipment and specimen preparation are described in Chapter 2. Chapter 3 outlines test procedures and techniques. Test results are presented in Chapter 4. Representative constitutive properties for Pacific illite are given in Chapter 5.

Comparison of the final effective-stress constitutive model fits with laboratory test data are presented in Part III. The numerical values of the material model constants for Pacific illite are also summarized therein.

Part IV contains a summary and recommendations for future work.

This report also contains seven addenda that appear in the order in which they are first referenced in the main text.

PART I: DEVELOPMENT OF AN ELASTIC-PLASTIC EFFECTIVE-STRESS CONSTITUTIVE
MODEL AND ASSOCIATED NUMERICAL ALGORITHMS FOR SEABED SEDIMENTS

CHAPTER 1

FUNDAMENTAL BASIS OF ELASTIC-PLASTIC CONSTITUTIVE MODELS

1.1 BASIC CONCEPTS FROM CONTINUUM MECHANICS

From a microscopic point of view, physical bodies are composed of discrete molecules interconnected by internal forces of mutual attraction and repulsion. The concept of stress within a body requires that boundary distances and/or loaded areas be large in comparison with distances between molecules and/or the sizes of the individual molecules. This, in effect, transforms a conglomerate of discrete molecules into a statistically macroscopic equivalent body amenable to mathematical analysis. Since most engineering problems deal with macroscopic phenomena and involve very large boundary distances and loaded areas compared with individual molecules, it appears reasonable (and is certainly convenient) to invoke the mechanics of continua as the basis for analytical consideration of these problems.

The theory of continuous media is built upon two strong foundations: basic balance and conservation laws and a constitutive theory. The basic balance and conservation laws of any continuum are

1. Conservation of mass
2. Conservation of energy
3. Balance of linear momentum
4. Balance of angular momentum
5. Inadmissibility of decreasing entropy

When thermal effects are neglected and symmetry of the stress tensor is assumed, these basic axioms of continuum mechanics lead to the following continuity equation:*

$$\frac{\partial \rho}{\partial t} + (v_i)_{,i} = 0 \quad (1.1)$$

and the equations of motion:

$$\sigma_{ij,j} + F_i - \rho a_i = 0 \quad (1.2)$$

* Indices take on a value of 1, 2, or 3. A repeated index is to be summed over its range. A comma between subscripts represents a derivative. Quantities are referred to rectangular Cartesian coordinates X_i .

where ρ = mass density

t = time

v_i = components of velocity vector

$\sigma_{ij} = \sigma_{ji}$ = symmetrical stress tensor

F_i = components of body force

a_i = components of acceleration vector

Equations 1.1 and 1.2 are called field equations. They constitute four equations that involve ten unknown functions of time and space. Therefore, the system resulting from Equations 1.1 and 1.2 is indeterminate. These unknown functions are the mass density ρ , the three velocity components v_i , and the six independent stress components σ_{ij} . The body force components F_i are known quantities, and the acceleration components a_i are expressible in terms of the velocity components v_i . To overcome the indeterminacy and make the system complete, six additional expressions relating the ten unknown variables are required. In continuum mechanics such relations are stated by constitutive equations (or material models), which relate stresses to deformations and the history of deformation. The difference between constitutive equations and field equations (Equations 1.1 and 1.2) is that the latter are applicable to all materials whereas the former represent the intrinsic response of a particular material or class of materials and, as such, are a mathematical idealization of the mechanical behavior of real materials.

The general form of a constitutive equation may be expressed by the following functional form:

$$H_{ij}(D_{mn}, \Omega_{qp}, \epsilon_{rs}, \sigma_{kl}, \rho) = 0 \quad (1.3)$$

where D_{mn} is the deformation-rate tensor, and Ω_{qp} is the spin tensor, both of which are related to the components of the velocity vector v_i by

$$D_{mn} = \frac{1}{2} (v_{m,n} + v_{n,m}) \quad (1.4)$$

and

$$\Omega_{qp} = \frac{1}{2} (v_{q,p} - v_{p,q}) \quad (1.5)$$

σ_{kl} is the stress tensor, and ϵ_{rs} is the infinitesimal strain tensor which is related to the components of the displacement vector u_i by

$$\epsilon_{rs} = \frac{1}{2} (u_{r,s} + u_{s,r}) \quad (1.6)$$

Equations 1.1 through 1.3 constitute ten equations involving ten unknown variables. These equations lead, in conjunction with the kinematic relations given by Equations 1.4 through 1.6 and the appropriate boundary condition prescriptions, to a complete description for the solution of a given boundary-value problem.

Materials having the same mass and geometry generally respond differently when subjected to identical external effects. Therefore, a variety of constitutive theories have emerged, each of which describes only a limited number of physical phenomena. In the following sections the constitutive theory of isotropic elastic-plastic solids is presented.

1.2 GENERAL DESCRIPTION OF ELASTIC-PLASTIC CONSTITUTIVE MODELS

The basic premise of elastic-plastic constitutive models is the assumption that certain materials are capable of undergoing small plastic (permanent) as well as elastic (recoverable) strains at each loading increment. Mathematically, the total strain increment is assumed to be the sum of the elastic and plastic strain increments; i.e.,

$$d\epsilon_{ij} = d\epsilon_{ij}^E + d\epsilon_{ij}^P \quad (1.7)$$

where $d\epsilon_{ij}$ = components of the total strain increment tensor

$d\epsilon_{ij}^E$ = components of the elastic strain increment tensor

$d\epsilon_{ij}^P$ = components of the plastic strain increment tensor

1.2.1 The Elastic Strain Increment Tensor

Within the elastic range, the behavior of the material can be described by an elastic constitutive relation of the type

$$d\epsilon_{ij}^E = C_{ijkl}(\sigma_{mn}) d\sigma_{kl} \quad (1.8)$$

where C_{ijkl} = material response function

$d\sigma_{kl}$ = components of stress increment tensor

For isotropic materials, the simplest form of the elastic constitutive relation (Equation 1.8) is given by

$$d\epsilon_{ij}^E = \frac{dJ_1}{9K} \delta_{ij} + \frac{1}{2G} dS_{ij} \quad (1.9)$$

where K = elastic bulk modulus

G = elastic shear modulus

$dJ_1 = d\sigma_{nn}$ = first invariant of the stress increment tensor

$dS_{ij} = d\sigma_{ij} - (dJ_1/3)\delta_{ij}$ = stress deviation increment tensor

δ_{ij} = Kronecker delta = $\begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}$

It can be seen from Equation 1.9 that the elastic behavior of an isotropic material is governed by the response function K and G which may take the following forms:

$$K = K(J_1, \bar{J}_2, \bar{J}_3, I_1^P, I_2^P, I_3^P) \quad (1.10)$$

and

$$G = G(J_1, \bar{J}_2, \bar{J}_3, I_1^P, I_2^P, I_3^P) \quad (1.11)$$

where $J_1 = \sigma_{nn}$ = first invariant of the stress tensor

$\bar{J}_2 = \frac{1}{2} S_{ij} S_{ij}$ = second invariant of the stress deviation tensor

$\bar{J}_3 = \frac{1}{3} S_{ik} S_{km} S_{mi}$ = third invariant of the stress deviation tensor

I_1^P = first invariant of the plastic strain tensor

I_2^P = second invariant of the plastic strain tensor

I_3^P = third invariant of the plastic strain tensor

For K and G constants, Equation 1.9 expresses the familiar Hook's law. In order not to generate energy or hysteresis within the elastic range, the elastic behavior of the material must be path independent. The path independence can be guaranteed if and only if the bulk and shear moduli have the following forms (see References 1 through 3):

$$K = K(J_1, I_1^P, I_2^P, I_3^P) \quad (1.12)$$

and

$$G = G(\bar{J}_2, I_1^P, I_2^P, I_3^P) \quad (1.13)$$

Equation 1.9 can be expressed in terms of the hydrostatic (or spherical) and deviatoric components of the strain and stress increment tensors; i.e.,

$$d\epsilon_{kk}^E = \frac{1}{3K(J_1, I_1^P, I_2^P, I_3^P)} dJ_1 \quad (1.14)$$

$$d\epsilon_{ij}^E = \frac{1}{2C(\bar{J}_2, I_1^P, I_2^P, I_3^P)} dS_{ij} \quad (1.15)$$

where $d\epsilon_{kk}^E$ = increment of elastic volumetric strain

$d\epsilon_{kk}^E$ = elastic strain deviation increment tensor

1.2.2 The Plastic Potential Function and the Plastic Strain Increment Tensor

The idealized behavior of a material in the plastic range can be described within the framework of the generalized incremental theory of plasticity. The mathematical basis of the theory was established by Drucker (Reference 4), who introduced the concept of material stability, which has the following implications:

1. The yield surface (loading function) should be convex in stress space.
2. The yield surface and plastic potential should coincide (which results in an "associated" flow rule).
3. Work "softening" should not occur.

These three conditions can be summarized mathematically by the following inequality

$$d\sigma_{ij} d\epsilon_{ij}^P \geq 0 \quad (1.16)$$

These conditions allow considerable flexibility in the choice of the form of the loading function f for the model, which serves as both a yield surface and the plastic potential. In general the loading function may be expressed as

$$f(\sigma_{ij}, \kappa) = 0 \quad (1.17)$$

while for isotropic materials it may be expressed, for example, as

$$f(J_1, \sqrt{\bar{J}_2}, \kappa) = 0 \quad (1.18)$$

where κ = a hardening parameter

For our purposes, we consider a loading function that consists of two parts: an ultimate failure envelope (or surface) which serves to limit the maximum shear stresses in the material and a strain-hardening surface or "cap" (Figure 1.1). This type of representation is usually referred to as cap-type models. The failure envelope portion of the loading function is denoted by

$$\phi = h(J_1, \sqrt{J_2}) = \sqrt{J_2} - f(J_1) = 0 \quad \text{for } J_1 < L(\kappa) \quad (1.19)$$

and the strain-hardening surface by

$$\phi = H(J_1, \sqrt{J_2}, \kappa) = \sqrt{J_2} - F(J_1, \kappa) = 0 \quad \text{for } \begin{cases} X(\kappa) \geq J_1 \geq L(\kappa) \\ \text{or } J_1 > X(\kappa) \end{cases} \quad (1.20)$$

Note in Figure 1.1 that $L(\kappa)$ and $X(\kappa)$ define the intersections of the hardening surface with the failure envelope, $h(J_1, \sqrt{J_2})$ and the J_1 axis, respectively.

In general, the hardening parameter κ is a function of the history of plastic volumetric strain ϵ_{kk}^P and is chosen so that

$$L(\kappa) = \begin{cases} \kappa & \text{if } \kappa > 0 \\ 0 & \text{if } \kappa \leq 0 \end{cases} \quad (1.21)$$

For our purposes, κ can be one of the following functions

$$\kappa = g_1(\epsilon_{kk}^P) \quad (1.22)$$

or

$$\kappa = g_2[(\epsilon_{kk}^P)_{\max}] \quad (1.23)$$

Both Equations 1.22 and 1.23 produce hysteresis in the hydrostatic load-unload cycle. The use of Equation 1.22, however, permits the hardening surface to move back toward the origin (Figure 1.1) when a point on the failure envelope, h , is reached, thus allowing a certain amount of control over the dilatancy the model will exhibit in shear. The use of Equation 1.23, on the other hand, only permits the hardening surface to move away from the origin, thus allowing full dilatancy in shear.

The plastic loading criteria for the function ϕ are given by

$$\frac{\partial \phi}{\partial \sigma_{ij}} d\sigma_{ij} \begin{cases} > 0 \text{ loading} \\ = 0 \text{ neutral loading} \\ < 0 \text{ unloading} \end{cases} \quad (1.24)$$

Plastic strain will occur only when $d\phi$ is positive and $\phi = 0$. During unloading or neutral loading, as well as for $\phi < 0$, the material will behave elastically. The prescription that neutral loading produces no plastic strain is called the continuity condition. Its satisfaction leads to coincidence of elastic and plastic constitutive laws during neutral loading (References 4 and 5).

Based on Equation 1.16 the plastic strain increments in the model can be defined through what is called the associated plastic flow rule; i.e.,

$$d\epsilon_{ij}^P = \begin{cases} d\lambda \frac{\partial \phi}{\partial \sigma_{ij}} & \text{if } \phi = 0 \\ 0 & \text{if } \phi < 0 \end{cases} \quad (1.25)$$

where ϕ is defined by either Equation 1.19 or Equation 1.20 and $d\lambda$ is a positive factor of proportionality which is nonzero only when plastic deformation occurs.

Like the elastic behavior, the plastic stress-strain flow rule can be expressed in terms of the hydrostatic and deviatoric components of strain. Applying the chain rule of differentiation to the right-hand side of Equation 1.25 yields

$$d\epsilon_{ij}^P = d\lambda \left(\frac{\partial \phi}{\partial J_1} \frac{\partial J_1}{\partial \sigma_{ij}} + \frac{\partial \phi}{\partial \sqrt{J_2}} \frac{\partial \sqrt{J_2}}{\partial \sigma_{ij}} \right) \quad (1.26)$$

or

$$d\epsilon_{ij}^P = d\lambda \left(\frac{\partial \phi}{\partial J_1} \delta_{ij} + \frac{1}{2\sqrt{J_2}} \frac{\partial \phi}{\partial \sqrt{J_2}} S_{ij} \right) \quad (1.27)$$

Multiplying both sides of Equation 1.27 by δ_{ij} results in

$$d\epsilon_{kk}^P = 3 d\lambda \frac{\partial \phi}{\partial J_1} \quad (1.28)$$

The deviatoric component of the plastic strain increment tensor $d\epsilon_{ij}^P$ can be written as

$$de_{ij}^P = d\epsilon_{ij}^P - \frac{1}{3} d\epsilon_{kk}^P \delta_{ij} \quad (1.29)$$

Substitution of Equations 1.27 and 1.28 into Equation 1.29 yields

$$de_{ij}^P = \frac{d\lambda}{2\sqrt{J_2}} \frac{\partial \phi}{\partial \sqrt{J_2}} S_{ij} \quad (1.30)$$

In order to use Equation 1.27 or Equations 1.28 and 1.30, the proportionality factor $d\lambda$ must be determined. This can be accomplished in the following manner. From Equations 1.18 and 1.22 or 1.23 the total derivative of δ becomes

$$d\delta = \frac{\partial \delta}{\partial J_1} dJ_1 + \frac{1}{2\sqrt{J_2}} \frac{\partial \delta}{\partial \sqrt{J_2}} S_{ij} dS_{ij} + \frac{\partial \delta}{\partial \kappa} \frac{\partial \kappa}{\partial \epsilon_{kk}^P} d\epsilon_{kk}^P = 0 \quad (1.31)$$

In view of Equations 1.14, 1.15, and 1.28, Equation 1.31 becomes

$$3K d\epsilon_{kk}^E \frac{\partial \delta}{\partial J_1} + \frac{G de_{ij}^E}{\sqrt{J_2}} \frac{\partial \delta}{\partial \sqrt{J_2}} S_{ij} + 3 d\lambda \frac{\partial \delta}{\partial J_1} \frac{\partial \delta}{\partial \kappa} \frac{\partial \kappa}{\partial \epsilon_{kk}^P} = 0 \quad (1.32)$$

Substituting Equation 1.7 into Equation 1.32 results in

$$3K(d\epsilon_{kk} - d\epsilon_{kk}^P) \frac{\partial \delta}{\partial J_1} + \frac{G}{\sqrt{J_2}} (de_{ij} - de_{ij}^P) \frac{\partial \delta}{\partial \sqrt{J_2}} S_{ij} = -3 d\lambda \frac{\partial \delta}{\partial J_1} \frac{\partial \delta}{\partial \kappa} \frac{\partial \kappa}{\partial \epsilon_{kk}^P} \quad (1.33)$$

or

$$3K d\epsilon_{kk} \frac{\partial \delta}{\partial J_1} + \frac{G}{\sqrt{J_2}} \frac{\partial \delta}{\partial \sqrt{J_2}} S_{ij} de_{ij} = 3K d\epsilon_{kk}^P \frac{\partial \delta}{\partial J_1} + \frac{G}{\sqrt{J_2}} \frac{\partial \delta}{\partial \sqrt{J_2}} S_{ij} de_{ij}^P - 3 d\lambda \frac{\partial \delta}{\partial J_1} \frac{\partial \delta}{\partial \kappa} \frac{\partial \kappa}{\partial \epsilon_{kk}^P} \quad (1.34)$$

Substituting the values of $d\epsilon_{kk}^P$ and de_{ij}^P from Equations 1.28 and 1.30, respectively, into Equation 1.34 yields

$$3K d\epsilon_{kk} \frac{\partial \delta}{\partial J_1} + \frac{G}{\sqrt{J_2}} \frac{\partial \delta}{\partial \sqrt{J_2}} S_{ij} de_{ij} = 9K d\lambda \left(\frac{\partial \delta}{\partial J_1} \right)^2 + G d\lambda \left(\frac{\partial \delta}{\partial \sqrt{J_2}} \right)^2 - 3 d\lambda \frac{\partial \delta}{\partial J_1} \frac{\partial \delta}{\partial \kappa} \frac{\partial \kappa}{\partial \epsilon_{kk}^P} \quad (1.35)$$

Solving for $d\lambda$ gives

$$d\lambda = \frac{3K \frac{\partial \delta}{\partial J_1} d\epsilon_{kk} + \frac{G}{\sqrt{J_2}} \frac{\partial \delta}{\partial \sqrt{J_2}} S_{ij} de_{ij}}{9K \left(\frac{\partial \delta}{\partial J_1} \right)^2 + G \left(\frac{\partial \delta}{\partial \sqrt{J_2}} \right)^2 - 3 \frac{\partial \delta}{\partial J_1} \frac{\partial \delta}{\partial \kappa} \frac{\partial \kappa}{\partial \epsilon_{kk}^P}} \quad (1.36)$$

1.3 TOTAL STRAIN INCREMENT TENSOR

The total strain increment tensor can be obtained by combining Equations 1.7, 1.9, 1.27, and 1.36

$$d\epsilon_{ij} = \frac{dJ_1}{9K} \delta_{ij} + \frac{dS_{ij}}{2G} + \left[\frac{3K \frac{\partial f}{\partial J_1} d\epsilon_{kk} + \frac{G}{\sqrt{J_2}} \frac{\partial f}{\partial \sqrt{J_2}} S_{mn} de_{mn}}{9K \left(\frac{\partial f}{\partial J_1} \right)^2 + G \left(\frac{\partial f}{\partial \sqrt{J_2}} \right)^2 - 3 \frac{\partial f}{\partial J_1} \frac{\partial f}{\partial \kappa} \frac{\partial \kappa}{\partial \epsilon_{kk}^P}} \right] \left(\frac{\partial f}{\partial J_1} \delta_{ij} + \frac{1}{2\sqrt{J_2}} \frac{\partial f}{\partial \sqrt{J_2}} S_{ij} \right) \quad (1.37)$$

Similarly, the stress increment tensor can be written as

$$d\sigma_{ij} = K d\epsilon_{kk} \delta_{ij} + 2G de_{ij} - \left[\frac{3K \frac{\partial f}{\partial J_1} d\epsilon_{kk} + \frac{G}{\sqrt{J_2}} \frac{\partial f}{\partial \sqrt{J_2}} S_{mn} de_{mn}}{9K \left(\frac{\partial f}{\partial J_1} \right)^2 + G \left(\frac{\partial f}{\partial \sqrt{J_2}} \right)^2 - 3 \frac{\partial f}{\partial J_1} \frac{\partial f}{\partial \kappa} \frac{\partial \kappa}{\partial \epsilon_{kk}^P}} \right] \left(3K \frac{\partial f}{\partial J_1} \delta_{ij} + G \frac{\partial f}{\partial \sqrt{J_2}} \frac{S_{ij}}{\sqrt{J_2}} \right) \quad (1.38)$$

Equation 1.37 or Equation 1.38 is the general constitutive equation for an elastic-plastic isotropic material. To use either of these equations it is necessary only to specify the functional forms of K , G , κ , and f and, of course, to determine experimentally the numerical values of the coefficients in these functions.

1.4 PROCEDURE FOR FITTING ELASTIC-PLASTIC MODELS TO A GIVEN SET OF MATERIAL PROPERTIES

The procedure for obtaining the functional forms and parameters used in elastic-plastic models constructed for use in boundary-value/initial-value problems is based on the quantities and types of data obtained from laboratory tests on representative samples of the material of interest.

The data generally consist of stress-strain and strength properties from uniaxial strain and triaxial compression tests. Sometimes, hydrostatic, proportional loading, direct shear, and/or other laboratory test data are also available. The first step in the fitting procedure is to use the unloading portions of the available stress-strain data to determine the appropriate elastic behavior of the model, since the strain hardening model generally behaves elastically during initial unloading in these various tests. For example, as long as the model behaves elastically, unloading behavior in hydrostatic tests indicates the form of the bulk modulus K , while the form

of the shear modulus G can be ascertained from triaxial stress test unloading data. Moreover, the combination $K + 4/3 G$ can be deduced from uniaxial strain test unloading data. Other tests, if available, may also be used to check or adjust the overall fit of the elastic portion of the model.

The next step in the fitting procedure is to establish the failure envelope, i.e., that portion of the yield surface which limits the shearing stresses that the material can withstand. The failure envelope is generally obtained by fitting failure data from triaxial stress and proportional loading tests. These data are fit by a function of the stresses, and are usually assumed to involve only the first stress invariant and the second invariant of the stress deviator tensor.

The remaining step in the fitting procedure is the most difficult. The hardening surface portion of the model is obtained by a trial-and-error procedure in which a cap shape and a hardening rule are assumed and the loading stress-strain behavior of this assumed model is computed and compared to the representative material property data. If the fit requires improvement, a new set of parameters is tried and the procedure is repeated.

Obviously, the success of such a trial-and-error procedure and the rapidity with which it converges are strongly dependent on the experience of the modeler. Knowledge of the effects on the model behavior of changes in its parameters is important for rapidly obtaining satisfactory fits. For example, the fitting procedure is greatly simplified by the knowledge that the hardening rule strongly affects the stress-strain curves for uniaxial strain and hydrostatic loading paths, whereas the shape of the hardening surface strongly influences the stress-strain behavior for triaxial stress situations and the stress path for the uniaxial strain condition. In addition, an adequate hardening rule has often been obtained in the past from analyzing only the plastic volumetric strain occurring during cyclic hydrostatic tests.

Figure 1.1 Typical yield surface for an elastic-plastic strain-hardening model.

CHAPTER 2

NUMERICAL IMPLEMENTATION OF THE MODEL

Various methods exist for incorporating the model discussed in Chapter 1 into computer programs (Reference 6). The method presented here is appropriate for both finite-difference and finite-element codes and is applicable for solving static as well as dynamic problems. This method makes use of Equation 1.38; i.e., the input quantities are the stress components σ_{ij}^n and the hardening parameter κ^n obtained at the end of the n th loading increment and the components of the new strain increments $d\epsilon_{ij}^{n+1}$ which are obtained from the field equations. The output quantities are the new values of the stress components σ_{ij}^{n+1} .

The first step of the numerical algorithm is to determine the possible stress path resulting from the given strain increments $d\epsilon_{ij}^{n+1}$ (Figures 2.1 and 2.2). To accomplish this, a set of elastic trial stresses σ_{ij}^E is computed by means of Equations 1.14 and 1.15; i.e.,

$$J_1^E = J_1^n + 3Kd\epsilon_{kk}^{n+1} \quad (2.1)$$

$$S_{ij}^E = S_{ij}^n + 2Gd\epsilon_{ij}^{n+1} \quad (2.2)$$

where

$$K = K[J_1^n, (I_1^P)^n, (I_2^P)^n, (I_3^P)^n] \quad (2.3)$$

and

$$G = G[\sqrt{J_2}^n, (I_1^P)^n, (I_2^P)^n, (I_3^P)^n] \quad (2.4)$$

These trial stresses are then tested, first with respect to the failure envelope $h(J_1^E, \sqrt{J_2}^E)$, and second with respect to the hardening surface $H(J_1^E, \sqrt{J_2}^E, \kappa^n)$. If these trial stresses do not violate either loading function, the behavior of the material is truly elastic, the hardening parameter κ^n remains unchanged, and the final stresses at the end of the $n+1$ loading increment are (Figure 2.2, stress path 1):

$$J_1^{n+1} = J_1^E \quad (2.5)$$

$$S_{ij}^{n+1} = S_{ij}^E \quad (2.6)$$

Note that K and G given in Equations 2.3 and 2.4 represent the values of the elastic moduli at the end of the n th loading increment; i.e., they are assumed to be constant during the $n+1$ loading increment. The effect of this assumption on the accuracy of the computations is negligible if the

given strain increments de_{ij}^{n+1} are relatively small. For relatively large strain increments, on the other hand, accuracy will suffer accordingly. This problem can be overcome, however, by splitting the given strain increment into m equal increments and sequentially going through the numerical algorithm m times, using updated values of K and G each time.

If the failure envelope is violated by the elastic trial stresses, i.e.,

$$J_1^E \leq L(\kappa^n) \quad (2.7)$$

$$\sqrt{J_2}^E \geq \min \{ f(J_1^E), F[L(\kappa^n), \kappa^n] \} \quad (2.8)$$

and

$$h(J_1^E, \sqrt{J_2}^E) \geq 0 \quad (2.9)$$

then the trial stresses have to be corrected such that the final stresses at the end of the $n+1$ loading increment satisfy the following relation (Figure 2.3, stress path 2)

$$h(J_1^{n+1}, \sqrt{J_2}^{n+1}) = 0 \quad (2.10)$$

Mathematically, the statement that the final stress point must be on the failure surface is given by Equation 1.24; thus

$$dh = \frac{\partial h}{\partial \sigma_{ij}} d\sigma_{ij} = 0 \quad (2.11)$$

For small strain increments, Equation 2.11 can be approximated numerically by

$$dh = \sqrt{J_2}^E - \sqrt{J_2}^{n+1} - f(J_1^E) + f(J_1^{n+1}) \quad (2.12)$$

but since

$$\sqrt{J_2}^{n+1} - f(J_1^{n+1}) = 0 \quad (2.13)$$

we have

$$dh = \sqrt{J_2}^E - f(J_1^E) \quad (2.14)$$

which, when substituted into Equation 2.11, leads to

$$\begin{aligned}
\sqrt{J_2^E} - f(J_1^E) &= \frac{\partial h}{\partial J_1} dJ_1^E + \frac{1}{2\sqrt{J_2^E}} \frac{\partial h}{\partial \sqrt{J_2}} s_{ij}^E ds_{ij}^E \\
&= 3K \frac{\partial h}{\partial J_1} de_{kk}^{n+1} + \frac{G}{\sqrt{J_2^E}} \frac{\partial h}{\partial \sqrt{J_2}} s_{ij}^E de_{ij}^{n+1}
\end{aligned} \tag{2.15}$$

Then, substituting Equation 2.15 into Equation 1.36 results in, after recognizing that $\partial h / \partial \kappa = 0$,

$$d\lambda = \frac{\sqrt{J_2^E} - f(J_1^E)}{9K \left(\frac{\partial f}{\partial J_1} \right)^2 + G} \tag{2.16}$$

Moreover, substitution of Equations 2.16 and 1.19 into Equation 1.28 leads to

$$de_{kk}^P = -3 \left[\frac{\sqrt{J_2^E} - f(J_1^E)}{9K \left(\frac{\partial f}{\partial J_1} \right)^2 + G} \right] \frac{df}{dJ_1} \tag{2.17}$$

Hence the final value of J_1 at the end of the $n+1$ loading increment is

$$J_1^{n+1} = J_1^E - 3K de_{kk}^P \tag{2.18}$$

Our work is not yet done, however, for the hardening parameter κ^n , which is a function of ϵ_{kk}^P , must also be updated; i.e., the hardening surface must intersect the failure envelope (thereby creating a corner) at this new value of J_1^{n+1} . We therefore test the tentative J_1^{n+1} value against $L(\kappa^n)$ and if $J_1^{n+1} > L(\kappa^n)$, "corner coding" is triggered (Figure 2.4).

The treatment of "corner coding" depends on the form of the hardening function. If Equation 1.22 is used, i.e., if the hardening surface is permitted to move back toward the origin, then Equations 1.21 holds. Moreover, Equation 2.18 also holds. Hence

$$J_1^E - 3K de_{kk}^P = J_1^{n+1} = L(\kappa^{n+1}) = \kappa^{n+1} = \kappa^n + \left. \frac{\partial \kappa}{\partial \epsilon_{kk}^P} \right|_{\kappa^n} de_{kk}^P \tag{2.19}$$

Eliminating de_{kk}^P from Equation 2.19 and solving for $J_1^{n+1} = \kappa^{n+1}$ leads to the final corner value of κ , i.e.,

$$\kappa^{n+1} = J_1^{n+1} = \frac{\left(\frac{\partial \kappa}{\partial \epsilon_{kk}^p} \bigg|_{\kappa^n} J_1^E + 3K \kappa^n \right)}{\left(\frac{\partial \kappa}{\partial \epsilon_{kk}^p} \bigg|_{\kappa^n} + 3K \right)} \quad (2.20)$$

If Equation 1.23 is used as the functional form for κ , i.e., the hardening surface is not permitted to reverse itself, then the corner coding simply consists of setting

$$J_1^{n+1} = \kappa^n \quad (2.21)$$

Having now determined the final "spherical" stress and strain states J_1^{n+1} and κ^{n+1} , the final values of the deviatoric stresses S_{ij}^{n+1} can be easily determined by simple proportional reductions in the trial (elastic) deviatoric stresses (Figures 2.3 and 2.4). This completes the correction process for stress states violating the failure envelope.

We now proceed to examine the case where the failure envelope is not violated but the hardening surface is (Figure 2.5). The elastic trial stresses are tested against the hardening surface; i.e., if

$$H(J_1^E, \sqrt{J_2^E}, \kappa^n) > 0 \quad (2.22)$$

and

$$J_1^E > X(\kappa^n) \quad (2.23)$$

or

$$J_1^E \geq L(\kappa^n) \quad (2.24)$$

then the hardening surface computations are performed.

Since both the plastic potential and the elastic potential are implicit functions of their arguments, an iterative scheme must be used. First, a trial value of $d\kappa$ is assumed in order to compute $\kappa^t = \kappa^n + d\kappa$. Then the corresponding values of $L(\kappa^t)$, $X(\kappa^t)$, and $d\epsilon_{kk}^p$ are computed. Third, a trial value of J_1 , i.e., J_1^t , corresponding to κ^t is computed in a manner similar to Equation 2.18; i.e.,

$$J_1^t = J_1^E - 3K d\epsilon_{kk}^p \quad (2.25)$$

If $J_1^t \geq X(\kappa^t)$, a larger value of $d\kappa$ is tried, while if $J_1^t \leq L(\kappa^t)$, a smaller value of $d\kappa$ is tried, and the process is repeated until the condition: $L(\kappa^t) \leq J_1^t < X(\kappa^t)$ is met. Then, the quantity

$$H(J_1^t, \sqrt{J_2}, \kappa^t) = \sqrt{J_2} - F(J_1^t, \kappa^t) \quad (2.26)$$

is computed together with the derivative

$$a = - \frac{\partial F}{\partial J_1} \bigg|_{J_1^t, \kappa^t} \quad (2.27)$$

As will be shown subsequently, the desired final value for κ is the one for which the equation

$$\sqrt{J_2} + G \, d\epsilon_{kk}^P / 3a = \sqrt{J_2}^E \quad (2.28)$$

is satisfied within some specified accuracy. Note that for convenience sake we omitted the subscript $n+1$ in Equation 2.28 and hereafter.

Equation 2.28 may be derived by noting that the elastic trial and final stress deviators are related by

$$S_{ij} + 2G d\epsilon_{ij}^P = S_{ij}^E \quad (2.29)$$

where $d\epsilon_{ij}^P$ are the final plastic deviatoric strain increments. The yield condition

$$H(J_1, \sqrt{J_2}, \kappa) = 0 \quad (2.30)$$

in conjunction with the flow rule

$$d\epsilon_{ij}^P = d\lambda \frac{\partial H}{\partial \sigma_{ij}} = d\lambda \left(\frac{S_{ij}}{2\sqrt{J_2}} + a \delta_{ij} \right) \quad (2.31)$$

implies that

$$d\epsilon_{ij}^P = S_{ij} d\epsilon_{kk}^P / 6a \sqrt{J_2} \quad (2.32)$$

Substitution of Equation 2.32 into Equation 2.29 gives

$$S_{ij} \left(1 + G d\epsilon_{kk}^P / 3a \sqrt{J_2} \right) = S_{ij}^E \quad (2.33)$$

which, when each side is multiplied by itself, leads to Equation 2.28.

The choice of iteration values for κ to converge to a value that approximately satisfies Equation 2.28 is facilitated by defining the dimensionless function $P(\kappa)$ as

$$P(\kappa) = \begin{cases} \frac{\kappa - J_1}{\kappa - X(\kappa)} & \text{if } J_1 \geq X(\kappa) \\ \frac{\sqrt{J_2^E} - b}{\sqrt{J_2^E} + b} & \text{if } X(\kappa) > J_1 > L(\kappa) \\ \frac{X(\kappa) - J_1}{L(\kappa) - X(\kappa)} & \text{if } J_1 \leq L(\kappa) \end{cases} \quad (2.34)$$

in which

$$b = \sqrt{J_2^E} + Gd\epsilon_{kk}^P/3a \quad (2.35)$$

Because $L(\kappa) \leq J_1 < J_1^E$, Equation 2.8 implies that the true value of κ lies in the range $J_1^E > \kappa > \kappa^n$. In that range $P(\kappa)$ can be shown to be bounded and monotonic in the strict sense, so that the solution of the equation $P(\kappa) = 0$, which is equivalent to that of Equation 2.28, is unique and can always be found to any desired degree of accuracy. This is accomplished by means of the modified Regula Falsi method (Reference 7) with the tolerated error being given approximately by

$$|\sqrt{J_2^E} - b| < Q f[X(\kappa)] \quad (2.36)$$

Based on experience with the model, a value of the tolerance Q on the order of 10^{-3} is small enough for most applications.

After the final values for κ and hence J_1 and $\sqrt{J_2}$ have been determined, the final shear stresses are computed from the proportionality relation

$$s_{ij} = \frac{\sqrt{J_2^E}}{\sqrt{J_2^E}} s_{ij}^E \quad (2.37)$$

The numerical implementation of the work hardening model is illustrated in Figure 2.2 (stress path 3).

Equations 2.1 through 2.37 have been implemented into a computer program. In order to use this program to simulate the behavior of a given material under specified stress or strain paths, a driver has been developed together with a plotting software package. A listing of the program without the plotting package is given in Addendum A.

(a) ELASTIC PATH

(b) ELASTIC PERFECTLY PLASTIC PATH

(c) ELASTIC WORK HARDENING PATH

(d) ELASTIC PERFECTLY PLASTIC PATH WITH A CORNER

Figure 2.1 Possible stress paths resulting from a strain increment $d\epsilon_{ij}^{n+1}$.

Figure 2.2 Flow diagram of the algorithm of the model.

Figure 2.3 Flow diagram showing the correction procedure for a stress path violating the failure envelope without corner correction.

Figure 2.4 Flow diagram showing the correction procedure for a stress path violating the failure envelope with corner correction.

Figure 2.5 Flow diagram showing the correction procedure for a stress path violating the hardening surface.

CHAPTER 3

EFFECTIVE-STRESS CONSTITUTIVE MODEL FOR SEABED SEDIMENTS

3.1 BASIC CONCEPTS

The soil model described in this chapter is based on the basic theory of elastic-plastic constitutive models presented in detail in Chapter 1 and patterned on the concept of effective stress. This means that two types of response functions are required to formulate the model. The first type characterizes the effective-stress response of the soil of interest, and the other characterizes the total bulk response, as determined by appropriate laboratory tests. The combination of these two types of response functions form the effective-stress model. This can be accomplished by imposing two constraints: (a) compatibility of total volumetric strain increments, and (b) compatibility of individual effective and total deviatoric stress increments ($dS'_{ij} = dS_{ij}$). The first constraint leads to

$$\frac{J_1}{3} = \frac{J'_1}{3} + u \quad (3.1)$$

and the second leads to

$$\sigma_{ij} = \sigma'_{ij} + u\delta_{ij} \quad (3.2)$$

where J'_1 = the first invariant of the effective stress tensor

u = pore pressure

σ'_{ij} = effective stress tensor

$$S'_{ij} = \sigma'_{ij} - \frac{J'_1}{3} \delta_{ij} = \text{effective stress deviation tensor}$$

The model is thus able to predict deformation, total and effective stresses, and pore pressure for real two-phase media.

Technically speaking then, modeling the behavior of two-phase soil systems requires two separate sets of material constants. The first set must reflect the effective-stress properties of the soil (i.e., the properties of the soil measured under drained laboratory tests). The second set must reflect the total stress properties under undrained laboratory tests.

Formulation of the model is based on the total applied stress; i.e., the strain tensor is taken to be zero for an assumed hydrostatic overburden pressure. For sign convention purposes compression is considered positive. In the following paragraphs the various response functions of the model are described.

The elastic behavior of the model is defined by Equations 1.9 through 1.15. The plastic behavior is described by Equations 1.19 through 1.36. The complete elastic-plastic description is expressed by Equation 1.37 or Equation 1.38. These equations are used herein, with selected mathematical forms of the various response functions contained in the model, to describe the specific soil responses of seabed sediment under both drained and undrained loading conditions. According to Equations 3.1 and 3.2, however, only the isotropic compression test results are needed to describe the behavior of the model under undrained conditions.

3.2 BEHAVIOR OF THE DRAINED PORTION OF THE MODEL

3.2.1 Elastic Behavior

The behavior of the model in the elastic range is governed by the elastic bulk and shear moduli (Equations 1.12 and 1.13). The elastic bulk modulus describes the unloading stress-strain response of an isotropic consolidation test (Figure 3.1). The elastic bulk modulus is taken to be a function only of the first invariant of the effective-stress tensor J'_1 . The following expression is chosen:

$$K_s = \frac{K_{1s}}{1 - K_{1s}} \left\{ 1 - K_{1s} \exp[-K_{2s}(J'_1 - 3G'_r)] \right\} \quad (3.3)$$

with the following conditions

$$\begin{aligned} K_{2s} &\leq -\frac{1}{3G'_r} \ln K_{1s} && \text{if } 0 < K_{1s} < 1 \\ &-\infty < K_{2s} < \infty && \text{if } K_{1s} \leq 0 \end{aligned} \quad (3.4)$$

where K_{1s} = initial elastic bulk modulus (evaluated at $J'_1 = 3G'_r$)

K_{1s} and K_{2s} = material constants

G'_r = submerged (effective) overburden stress due to gravity

Equation 3.3 is illustrated in Figure 3.2. The material constants in Equation 3.3 can be readily determined experimentally from the unloading isotropic consolidation test results, as illustrated in Figure 3.1.

The elastic shear modulus must account for the curvature observed in unloading stress difference-strain difference data obtained from triaxial compression tests (Figure 3.3). In this model, the elastic shear modulus is assumed to be a function of the second invariant of the effective-stress deviation tensor $\bar{J}'_2$. The following expression is chosen:

$$G = \frac{G_1}{1 - G_1} \left[1 - G_1 \exp(-G_2 \sqrt{\bar{J}'_2}) \right] \quad (3.5)$$

with the following condition

$$G_1 < 1 \quad (3.6)$$

where G_1 = initial elastic shear modulus

G_1 and G_2 = material constants

Equation 3.5 is illustrated in Figure 3.4. The material constants in Equation 3.5 can be readily determined from the slopes of experimental unloading stress-strain curves obtained from drained triaxial shear tests.

3.2.2 Plastic Behavior

For the plastic behavior, the failure envelope (Equation 1.19) is assumed to be of the Prager-Drucker type (Figure 3.5) and is mathematically described by

$$h(J_1', \sqrt{J_2'}) = \sqrt{J_2'} - f(J_1') = \sqrt{J_2'} - \alpha J_1' - C = 0 \quad (3.7)$$

and the strain-hardening yield surface (Equation 1.20) is described by an ellipse (Figure 3.5)

$$\begin{aligned} H(J_1', \sqrt{J_2'}, \kappa) &= \sqrt{J_2'} - F(J_1', \kappa) \\ &= \sqrt{J_2'} - \frac{1}{R} \left\{ [X(\kappa) - L(\kappa)]^2 - [J_1' - L(\kappa)]^2 \right\}^{0.5} = 0 \end{aligned} \quad (3.8)$$

where α and C are material constants representing the "frictional" and "cohesive" strengths of the material, respectively, and the parameter R is the ratio of the major to minor axes of the elliptic yield surface. The hardening parameter κ is taken to be a function of plastic volumetric strain in the following relation

$$X(\kappa) = \kappa + R[\alpha\kappa + C] = -\frac{1}{D} \ln \left(1 - \frac{\epsilon_{kk}^p}{W} \right) + 3 G_r' \quad (3.9)$$

where the parameters D and W are material constants. Equation 3.9 implies that whenever

$$X(\kappa) \geq 3 G_r' \quad (3.10)$$

then

$$\kappa = \frac{X - CR}{1 + \alpha R} \quad (3.11)$$

This indicates that the tangent to the hardening surface at its intersection with the failure envelope is always horizontal. Note that Equation 3.9, in

conjunction with Equation 3.8, allows the elliptic hardening surface to expand and contract as well as to translate relative to the origin of the $J_1', \sqrt{J_2}$ axes.

3.3 BEHAVIOR OF THE UNDRAINED PORTION OF THE MODEL

As mentioned in Section 3.1, the deviatoric components of the stress increment tensor are constrained to be the same under drained and undrained conditions (i.e., $dS_{ij} = dS_{ij}'$). Therefore, the undrained portion of the overall model can be completely specified by adding only a description of the spherical portion of the undrained behavior to the equations developed in Section 3.2. This is obtained by the following selected bulk modulus:

$$K_m = \frac{K_{im}}{1 - K_{1m}} \left\{ 1 - K_{1m} \exp[-K_{2m}(J_1 - 3 G_r)] \right\} \quad (3.12)$$

with the following conditions

$$\begin{aligned} K_{2m} &\leq -\frac{1}{3G_r} \ln K_{1m} \quad \text{if } 0 < K_{1m} < 1 \\ -\infty < K_{2m} < \infty \quad \text{if } K_{1m} \leq 0 \end{aligned} \quad (3.13)$$

$$K_m \geq K_s$$

where K_{im} = initial bulk modulus measured under undrained isotropic compression test (evaluated at $J_1 = 3 G_r$)

K_{1m} and K_{2m} = material constants

G_r = "total" overburden stress due to gravity

Equation 3.12 is illustrated in Figure 3.6.

Figure 3.1 Proposed elastic relationship for isotropic consolidation test.

Figure 3.2 Elastic bulk modulus versus first invariant of the effective-stress tensor.

Figure 3.3 Proposed elastic relationship for drained triaxial shear test.

Figure 3.4 Elastic shear modulus versus second invariant of the stress deviation tensor.

Figure 3.5 Proposed yield surfaces for the elastic-plastic, strain-hardening model.

Figure 3.6 Proposed total (undrained or bulk) response of the material.

CHAPTER 4

BEHAVIOR OF THE SEABED SEDIMENT MODEL UNDER LABORATORY TRIAXIAL TEST CONDITIONS

4.1 INTRODUCTION

The ability of the effective-stress model to simulate the response of two-phase (fully saturated) soil systems can be more clearly understood if the model is examined under familiar laboratory test boundary conditions. Since most of the mechanical testing of soils for engineering purposes is performed with the triaxial test (TX) apparatus, it is appropriate to investigate the model under both drained and undrained TX conditions. Adopting the z-axis of a cylindrical coordinate system (z , r , and θ) as the axis of symmetry of the test sample, the total and effective stress tensors and the total strain tensor associated with this configuration become, respectively,

$$\sigma_{ij} = \begin{bmatrix} \sigma_z & 0 & 0 \\ 0 & \sigma_r & 0 \\ 0 & 0 & \sigma_r \end{bmatrix} \quad (4.1)$$

$$\sigma'_{ij} = \begin{bmatrix} \sigma'_z & 0 & 0 \\ 0 & \sigma'_r & 0 \\ 0 & 0 & \sigma'_r \end{bmatrix} \quad (4.2)$$

$$\epsilon_{ij} = \begin{bmatrix} \epsilon_z & 0 & 0 \\ 0 & \epsilon_r & 0 \\ 0 & 0 & \epsilon_r \end{bmatrix} \quad (4.3)$$

where ϵ_z and ϵ_r are the accumulated vertical and radial strains, respectively. Equations 4.1 and 4.2 imply homogeneity of stress ($\sigma_\theta = \sigma_r$), and Equation 4.3 implies homogeneity of deformation (tangential strain $\epsilon_\theta = \epsilon_r$). The variables $P' = J'_1/3$ (effective mean normal stress), $P = J_1/3$ (total mean normal stress), J'_2 (the second invariant of the effective stress deviation tensor), J_2 (the second invariant of the total stress deviation tensor), and $\epsilon_{kk}/3$ (mean volumetric strain) associated with the above stress and strain tensors take the following forms

$$P' = J'_1/3 = \frac{\sigma'_z + 2\sigma'_r}{3} \quad (4.4)$$

$$P = J_1/3 = \frac{\sigma_z + 2\sigma_r}{3} \quad (4.5)$$

$$\bar{J}_2' = \frac{(\sigma_z' - \sigma_r')^2}{3} = \bar{J}_2 = \frac{(\sigma_z - \sigma_r)^2}{3} \quad (4.6)$$

$$\epsilon_{kk} = \epsilon_z + 2\epsilon_r \quad (4.7)$$

The TX test is generally conducted in two phases: a hydrostatic phase and a shear phase. Both phases can be conducted either drained or undrained. They are discussed below.

4.2 HYDROSTATIC PHASE

4.2.1 Drained Condition

During the drained hydrostatic phase of a TX test, the pore pressure is always zero, and the behavior of the soil skeleton alone (i.e., the effective-stress behavior) is examined. The following conditions are applicable:

$$\sigma_z' = \sigma_r' = \sigma_\theta' \quad (4.8)$$

$$\epsilon_z = \epsilon_r = \epsilon_\theta = \frac{\epsilon_{kk}}{3} \quad (4.9)$$

The relation between the increment of the first invariant of effective stress and the elastic volumetric strain increment is given as (see Equation 1.14 of Chapter 1)

$$dJ_1' = 3K_s d\epsilon_{kk}^E \quad (4.10)$$

where the response function K_s is given by Equation 3.3. Equation 3.3 is substituted into Equation 4.10, and the resulting expression is integrated to provide the following relation between the elastic volumetric strain ϵ_{kk}^E and J_1'

$$\epsilon_{kk}^E = \frac{1 - K_{1s}}{3K_{2s} K_{1s}} \ln \left\{ \frac{\exp[K_{2s}(J_1' - 3G_r')] - K_{1s}}{1 - K_{1s}} \right\} \quad (4.11)$$

The relation between the plastic volumetric strain ϵ_{kk}^P and J_1' is given by Equation 3.9, where $X(\kappa)$ is J_1' ; thus

$$\epsilon_{kk}^P = W \{1 - \exp[-D(J_1' - 3G_r')]\} \quad (4.12)$$

In view of Equations 4.11 and 4.12, the total volumetric strain takes the following form

$$\epsilon_{kk} = \frac{1 - K_{1s}}{3K_{2s} K_{is}} \ln \left\{ \frac{\exp[K_{2s}(J'_1 - 3G'_r)] - K_{1s}}{1 - K_{1s}} \right\} + W \{1 - \exp[-D(J'_1 - 3G'_r)]\} \quad (4.13)$$

Equations 4.11 through 4.13 provide a complete specification for the deformation response of the soil skeleton subjected to a drained hydrostatic test (i.e., isotropic consolidation).

The qualitative behavior of the model during a drained hydrostatic test is shown in Figure 4.1. If a sample is first isotropically consolidated (from point 1 to point 2 in Figure 4.1), then unloaded (point 2 to point 3), and then reloaded (point 3 to point 2), the model dictates that the unloading-reloading behavior is purely elastic. The slope of the $J'_1 - \epsilon_{kk}$ curve during virgin loading can be obtained from Equation 4.13 with the help of Equations 4.12 and 3.3:

$$\frac{dJ'_1}{d\epsilon_{kk}} = \frac{3K_s}{1 + 3K_s D(W - \epsilon_{kk}^p)} = 3\tilde{K}_s \quad (4.14)$$

Here, K_s and $\tilde{K}_s$ are, respectively, the elastic (Equation 3.3) and the apparent bulk moduli of the soil skeleton under drained hydrostatic loading. The second term in the denominator of Equation 4.14 produces a softening of the apparent bulk modulus due to plastic volumetric compaction. At high pressures, the softening term goes to zero; i.e., as $\epsilon_{kk}^p \rightarrow W$ or $\exp[-D(J'_1 - 3G'_r)] \rightarrow 0$, the apparent modulus $\tilde{K}_s$ approaches the elastic bulk modulus K_s .

4.2.2 Undrained Condition

During an undrained hydrostatic test, the effective stresses and the pore pressure are generally not zero. The stress-strain relations for this condition can be obtained in a manner similar to that used to derive Equation 4.11, except that this new expression will involve the total stresses (Equation 4.5) instead of the effective stresses; thus

$$\epsilon_{kk} = \frac{1 - K_{1m}}{3K_{2m} K_{im}} \ln \left\{ \frac{\exp[K_{2m}(J_1 - 3G_r)] - K_{1m}}{1 - K_{1m}} \right\} \quad (4.15)$$

The pore pressures and the resulting effective stresses generated during undrained hydrostatic tests can be computed using the assumption that the volumetric strains from Equations 4.13 and 4.15 are equal; thus

$$\begin{aligned} & \frac{1 - K_{1s}}{3K_{2s} K_{is}} \ln \left\{ \frac{\exp[K_{2s}(J'_1 - 3G'_r)] - K_{1s}}{1 - K_{1s}} \right\} + W \{1 - \exp[-D(J'_1 - 3G'_r)]\} \\ & = \frac{1 - K_{1m}}{3K_{2m} K_{im}} \ln \left\{ \frac{\exp[K_{2m}(J_1 - 3G_r)] - K_{1m}}{1 - K_{1m}} \right\} \end{aligned} \quad (4.16)$$

from which J_1' can be obtained as a function of J_1 using a bit of algebra. The pore pressure u and the effective stresses then become (see Equations 3.1 and 3.2)

$$\sigma_z' = \sigma_r' = \frac{J_1'}{3} \quad (4.17)$$

$$u = \frac{(J_1 - J_1')}{3} \quad (4.18)$$

Note that if the mixture is assumed to be incompressible ($K_m = \infty$), $\epsilon_{kk} = 0$ and the right-hand sides of Equations 4.15 or 4.16 become zero. As a result, Equation 4.16 can be satisfied if and only if J_1' is equal to $3 G_r'$. This means that all of the applied stress is carried by the water and none by the skeleton. Consequently, J_1' is independent of J_1 .

4.3 SHEAR PHASE

During the shear phase of a conventional TX test, the cell pressure is held constant while the axial stress is changed, i.e.,

$$\sigma_r = \text{constant} = P_c \quad (4.19)$$

and

$$d\sigma_r = 0 \quad (4.20)$$

where P_c is the total confining pressure at the end of the hydrostatic compression phase. If the hydrostatic compression phase preceding shear was drained, the confining pressure P_c is also the effective confining pressure P_c' .

4.3.1 Drained Condition

During a drained shear test, the effective and total stresses are equal; i.e., the effective stress path is known and is identical with the total stress path. The response of the soil skeleton is modeled using Equation 1.37 of Chapter 1 and Equations 3.3, 3.5, and 3.7 through 3.9 of Chapter 3. Thus

$$d\epsilon_{ij} = \frac{dJ_1'}{9K_s} \delta_{ij} + \frac{dS_{ij}'}{2G} + d\lambda \left[\frac{\partial f}{\partial J_1'} \delta_{ij} + \frac{1}{2\sqrt{J_2'}} \frac{\partial f}{\partial \sqrt{J_2'}} S_{ij}' \right] \quad (4.21)$$

where $d\epsilon_{ij}$ = component of the total strain increment tensor

$$\sqrt{J_2'} = \sqrt{J_2}$$

$$\delta = \begin{cases} H(J'_1, \sqrt{J'_2}, \kappa) & \text{on the hardening surface} \\ h(J'_1, \sqrt{J'_2}) & \text{on the failure envelope} \end{cases}$$

In view of Equations 1.15 and 1.30 of Chapter 1, the deviatoric components of the total strain increment tensor are

$$de_{ij} = de_{ij}^E + de_{ij}^P = \frac{dS'_{ij}}{2G} + \frac{d\lambda}{2\sqrt{J'_2}} \frac{\partial \delta}{\partial \sqrt{J'_2}} S'_{ij} \quad (4.22)$$

and according to Equation 1.30, the value of $d\lambda$ can be written as

$$d\lambda = \frac{2\sqrt{dI_2^P}}{\frac{\partial \delta}{\partial \sqrt{J'_2}}} \quad (4.23)$$

where $dI_2^P = \frac{1}{2} de_{ij}^P de_{ij}^P$ = second invariant of the plastic strain increment deviation tensor

Substitution of Equation 4.23 into Equation 4.22 leads to

$$dS'_{ij} = 2G \left[de_{ij} - \sqrt{dI_2^P} \frac{S'_{ij}}{\sqrt{J'_2}} \right] \quad (4.24)$$

For TX test conditions, Equation 4.24 can be written as

$$\frac{d(\sigma'_z - \sigma'_r)}{d(\epsilon'_z - \epsilon'_r)} = 2G \left[1 - \frac{d(\epsilon_z^P - \epsilon_r^P)}{d(\epsilon_z - \epsilon_r)} \right] = 2\tilde{G} \quad (4.25)$$

where $\tilde{G}$ is the apparent shear modulus of the material under drained triaxial loading conditions. The second term on the right side of Equation 4.25 produces a softening of the apparent loading shear modulus due to plastic flow. Within the yield surface (i.e., in the elastic range), the plastic strain increments are zero and the apparent shear modulus equals the elastic shear modulus G .

The volumetric strain increment can be obtained by multiplying both sides of Equation 4.21 by the Kronecker delta δ_{ij} and then using Equations 3.7, 3.9, and 4.23; thus

$$d\epsilon_{kk} = \frac{dJ'_1}{3K_s} - 6\alpha \sqrt{dI_2^P} \quad \text{on the failure envelope} \quad (4.26)$$

$$d\epsilon_{kk} = \frac{dJ_1'}{3K_s} + D(W - \epsilon_{kk}^P) dX(\kappa) \quad \text{on the hardening surface} \quad (4.27)$$

Typical (qualitative) results predicted by this model for two types of drained TX shear tests are shown in Figure 4.2.

4.3.2 Undrained Conditions

During an undrained shear test (following isotropic consolidation),* only the total stresses and, consequently, the total stress path are known for the skeleton-water mixture. The volumetric response for this test can be written either in terms of total stresses or effective stresses. Using Equations 4.13, 4.15, and 4.21, the volumetric strain in terms of total stresses becomes

$$\begin{aligned} \epsilon_{kk} = & \frac{1 - K_{1s}}{3K_{2s} K_{is}} \ln \left\{ \frac{\exp[3K_{2s}(P'_c - G'_r)] - K_{1s}}{1 - K_{1s}} \right\} + W \{1 - \exp[-3D(P'_c - G'_r)]\} \\ & + \frac{1 - K_{1m}}{3K_{2m} K_{im}} \ln \left\{ \frac{\exp[K_{2m}(J_1' - 3P'_c - 3G'_r)] - K_{1m}}{1 - K_{1m}} \right\} \end{aligned} \quad (4.28)$$

Using the same equations, the volumetric strain in terms of effective stresses can be expressed as

$$\begin{aligned} \epsilon_{kk} = & \frac{1 - K_{1s}}{3K_{2s} K_{is}} \ln \left\{ \frac{\exp[K_{2s}(J_1' - 3G'_r)] - K_{1s}}{1 - K_{1s}} \right\} \\ & + W \{1 - \exp[-D(X - 3G'_r)]\} \end{aligned} \quad (4.29)$$

From Equation 4.24 the deviatoric components of strain are given as (note; $S'_{ij} = S_{ij}$)

$$de_{ij} = \frac{dS_{ij}}{2G} + \sqrt{\frac{dI_2^P}{J_2}} \frac{S_{ij}}{\sqrt{J_2}} \quad (4.30)$$

For TX test conditions, Equation 4.30 can be written as

$$\frac{d(\sigma_z - \sigma_r)}{d(\epsilon_z - \epsilon_r)} = \frac{d(\sigma'_z - \sigma'_r)}{d(\epsilon'_z - \epsilon'_r)} = 2G \left[1 - \frac{d(\epsilon_z^P - \epsilon_r^P)}{d(\epsilon_z - \epsilon_r)} \right] = 2\tilde{G} \quad (4.31)$$

Note that Equations 4.25 and 4.31 are identical. These two identities are a direct outcome of the constraints originally imposed on the model in Chapter 3, which led to Equations 3.1 and 3.2.

* The isotropic compression phase preceding shear could either be drained or undrained. In this example, however, it was chosen to be drained.

The effective stresses and the pore pressure at the end of each applied total stress loading increment can be computed from the following Equations which are based on Equations 3.8, 4.28, and 4.29; thus

$$\sqrt{J'_2} = \frac{1}{R} \left\{ \left[\frac{R\alpha X + RC}{1 + R\alpha} \right]^2 - \left[J'_1 - \frac{X - CR}{1 + \alpha R} \right]^2 \right\}^{0.5} \quad (4.32)$$

where

$$X = -\frac{1}{D} \ln \left(1 - \frac{n}{W} \right) + 3G'_r \quad (4.33)$$

and

$$\begin{aligned} \eta = & \frac{1 - K_{1s}}{3K_{2s} K_{is}} \ln \left\{ \frac{\exp[3K_{2s}(P'_c - G'_r)] - K_{1s}}{1 - K_{1s}} \right\} \\ & + W \{ 1 - \exp[-3D(P'_c - G'_r)] \} \\ & + \frac{1 - K_{1m}}{3K_{2m} K_{im}} \ln \left\{ \frac{\exp[K_{2m}(J'_1 - 3P'_c - 3G'_r)] - K_{1m}}{1 - K_{1m}} \right\} \\ & - \frac{1 - K_{1s}}{3K_{2s} K_{is}} \ln \left\{ \frac{\exp[K_{2s}(J'_1 - 3G'_r)] - K_{1s}}{1 - K_{1s}} \right\} \end{aligned} \quad (4.34)$$

Knowing the total stress path for this test (i.e., $\sqrt{3} \bar{J}_2 = J'_1 - 3P'_c$) Equation 4.32 gives an expression for the effective stress path (i.e., $\sigma'_z - \sigma'_r = \sqrt{3J'_2}$ versus J'_1) for the undrained condition. Having determined J'_1 and J'_1 the pore water pressure can be obtained from Equation 4.18 and the individual effective stresses from Equation 3.2 (of Chapter 3) as

$$u = \frac{J'_1 - J'_1}{3} \quad (4.35)$$

$$\sigma'_z = \sigma_z - u \quad (4.36)$$

and

$$\sigma'_r = \sigma_r - u \quad (4.37)$$

Typical (qualitative) results predicted by this model for undrained TX shear tests are shown in Figure 4.3. Figure 4.3 also depicts qualitatively the effects of the parameter R on the stress-strain and pore pressure responses during a conventional undrained shear test.

When the mixture is assumed to be incompressible ($K_m = \infty$), the third term on the right-hand side of Equation 4.34 becomes zero. Consequently

J_1 is independent of J_1 . This means that the effective stress path is independent of the total stress path applied to the material. Such behavior is demonstrated, for example, by the model reported in Reference 8.

Figure 4.1 Behavior of the model under drained hydrostatic compression (isotropic consolidation).

Figure 4.2 Drained shear behavior predicted by the model for two conventional triaxial tests and a constant mean normal stress test.

Figure 4.3 Undrained shear behavior predicted by the model (after drained isotropic consolidation), showing the influence of the parameter R on the effective-stress path, the shear stress-strain response, and the pore pressure response in a conventional undrained TX test.

REFERENCES

1. Prager, W.; Introduction to Mechanics of Continua, Ginn, 1961.
2. Sandler, I. S., DiMaggio, F. L., and Baladi, G. Y.; "A Generalized Cap Model for Geological Materials"; Journal of the Geotechnical Engineering Division; ASCE, Vol 102, No. GT7, Proc. Paper 12243, July 1976; pp 683-699.
3. Baladi, G. Y. and Rohani, B.; "Liquefaction Potential of Dams and Foundations; Development of an Elastic-Plastic Constitutive Relationship for Saturated Sand"; Research Report S-76-2, Report 3, February 1977; U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS.
4. Drucker, D. C.; "On Uniqueness in the Theory of Plasticity"; Q. Applied Mathematics; Vol 14, 1956.
5. Handelman, G. H., et al; "On the Mechanical Behavior of Metals in the Strain Hardening Range"; Q. Applied Mathematics; Vol 4, 1947; pp 397-407.
6. Sandler, I. and Rubin, D.; "A Modular Subroutine for the Cap Model"; DNA 3875F; Weidlinger Associates, Consulting Engineers; January 1976.
7. Conte, S. D. and de Boor, C.; Elementary Numerical Analysis; McGraw-Hill; 1972.
8. Baladi, G. Y. and Rohani, B.; "Liquefaction Potential of Dams and Foundations; Development of a Constitutive Relation for Simulating the Response of Saturated Cohesionless Soil"; Research Report S-76-2, Report 5, August 1978; U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS.

PART II: EXPERIMENTAL PROGRAM

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The objective of the experimental test program as outlined in the WES work statement of October 1979 was "to provide high-pressure dynamic stress-strain-strength properties of seabed sediments of interest." The work statement outlined three areas of study for FY 80. These consisted of:

- a. Conducting consolidated-undrained, low-pressure triaxial shear tests (1) to ascertain the effects of rate of loading on the shear response of the materials, (2) to determine the effects of various degrees of back-pressure saturation on the response of the materials, (3) to correlate the results with the the URI triaxial test data, and (4) to determine the variability of the data for the subseabed material under similar test conditions.
- b. Conducting several high-pressure uniaxial strain tests (1) to obtain high-pressure compressibility data for the subseabed materials, and (2) to determine the effects of loading rate on their compressibility.
- c. Conducting both drained and undrained high-pressure triaxial shear tests to obtain the static stress-strain-pore pressure response of the materials at high pressure.

The first year of the experimental program was acknowledged to be a period in which to gain experience in working with the seabed materials and to discover problems with existing equipment and test procedures specifically introduced by the ocean sediments. Therefore, tests were conducted on a variety of available specimens of ocean sediment, and no attempt was made to conduct a complete test matrix on specimens of one particular sediment type.

A majority of the presently available geotechnical physical property data for the SDP has previously been generated by URI. They have conducted numerous low pressure (i.e., confining pressures less than 0.69 MPa) consolidated undrained triaxial shear tests on specimens of undisturbed and reconstituted-reconsolidated (i.e., remolded) illite and smectite (References 1-3). However, the entire URI triaxial testing program was conducted at one strain rate; i.e., 10^{-6} /second. The WES experimental program was aimed at supplementing and extending the URI data base by furnishing data (a) at loading rates as fast as 1/second, and (b) at confining pressures up to 69 MPa.

1.2 SCOPE

The seabed material tested in the WES FY 80 experimental program consisted of both undisturbed and reconstituted-reconsolidated specimens of North Pacific MPG-I (Mid-Plate/Mid-Gyre, Site I) illite. Undisturbed specimens were furnished by SNL from MARA cruise 12, gravity core number 19 (MA-12 GC-19). These were tested in the WES pore pressure uniaxial strain (PPUX) test device. Remolded illite specimens were prepared and furnished by URI and were tested in the low- and high-pressure triaxial test devices. The remolded specimens were subsamples extracted from two large consolidation tanks at URI and have been identified as specimen groups PI 4.5-1 and PI 5-8. The designation PI 4.5-1 denotes the specimen as a North Pacific illite material with a simulated in situ depth of 4.5 meters, originating from tank No. 1. This designation was retained as a prefix to our test specimen numbering system. Communications from URI stated (Reference 4) that the material in tank No. 1 (specimen group PI 4.5-1) did not fully consolidate under the applied loads. As a result, these specimens exhibited numerous cavities. Specimens originating from tank No. 8 (specimen group PI 5-8), however, appeared to be of good quality with no observable cavities.

In the WES FY 80 experimental program a total of 51 tests were attempted; 32 low-pressure triaxial shear tests, 10 high-pressure shear tests, and 9 pore pressure uniaxial strain tests. The results of these tests are presented in Chapter 4.

CHAPTER 2

TEST EQUIPMENT AND SPECIMEN PREPARATION

2.1 TEST EQUIPMENT

All the basic pieces of laboratory equipment used in the experimental program had been developed and were in existence before the SDP was initiated at WES. However, various equipment (valves, fluid lines, etc.) was modified, where necessary, to negate the corrosive effects of the saltwater pore fluid. In addition, in order to measure the low effective pressures and low loads associated with SDP (i.e., low relative to the pressures and loads that the various apparatuses were originally designed for), new pressure transducers, load cells, etc., were fabricated. In addition, several new duplicate control systems were fabricated so as to permit long-term testing of several specimens.

The low-pressure triaxial shear (LPTX) test apparatus includes several main components. The first of these, the test chamber, is shown in Figure 2.1 and is typical of most commercial triaxial cells (Reference 5). The cell base contains parts which allow for both top and bottom drainage of the specimen. Three pressure transducers have been affixed around the cell base plate to measure the chamber fluid pressure, the pore fluid pressure, and the differential pressure between the chamber and pore fluids, as shown in Figure 2.1. Interchangeable bottom pedestals are available to allow both 3.68- and 4.95-cm-diameter samples to be tested. Top and bottom porous stones and side filter strips are utilized to improve drainage and pore pressure equilibration. The cell top plate holds the loading piston assembly and a film pot to measure vertical piston displacement. The piston load during shear is measured inside the chamber with a strain gage-type load cell. A Plexiglas chamber wall is used for tests with chamber fluid pressures less than 0.69 MPa, and an aluminum chamber wall is used for pressures between 0.69 and 1.72 MPa.

Figure 2.2 shows a schematic of the loading frame and hydraulic support devices which permit tests to be conducted at various loading rates (from "static" to "dynamic"). Typical rise times to peak load for "static" tests are 1-2 hours; for "dynamic" tests 12-15 msec. The loading frame is driven by a hydraulic piston located at the bottom of the test device (see Figure 2.2). After the hydraulic system is pressurized, the solenoid valve is triggered, allowing the fluid below the piston to empty into the fluid reservoir, thus forcing the piston to descend. For dynamic tests the rate of descent is controlled (within limits) by an adjustable orifice that meters the flow. For static tests, a micrometering flow control valve was put in line with the solenoid valve to greatly reduce the rate of fluid flow. Five electrical transducers are used to record the pressures, loads, and deformations that occur during the test. The electronic output from these transducers is amplified and recorded on light-sensitive paper with a light-beam galvanometer oscillograph. Timing marks are automatically placed on the record during dynamic tests. Data reduction and analysis will be discussed in Chapter 3 and Addendum B.

A simplified representation of the back-pressure saturation control boards and pressure control systems used with the LPTX, high-pressure triaxial shear (HPTX), and PPUX test programs is illustrated in Figure 2.3. All of the three systems utilize house air to generate pressures up to 0.69 MPa. For the LPTX, bottled nitrogen is used to generate pressures in excess of 0.69 MPa and up to 14 MPa. For the HPTX and PPUX tests, however, house air and a hydraulic pump are used to generate pressures greater than 0.69 and up to 69 MPa. For all the devices, a back pressure was applied to the pore fluid through the volume change burette. A booster regulator was sometimes used in the LPTX tests to automatically hold the initial pressure differential between the chamber fluid and pore fluid.

The HPTX test chamber, shown in Figure 2.4, has a maximum working pressure of 69 MPa. The drainage line in the base of the test device allows the specimen to consolidate and back-pressure saturate. One lateral and two vertical deformeters are used to measure specimen height and diameter changes during hydrostatic and shear loadings. The lateral deformeter is constructed from four cantilever spring-steel "arms" mounted on a rigid support ring. Two resistance-type foil strain gages epoxied to the center of each arm are electrically tied so that they give an averaged diameter change output. The lateral deformeter is calibrated as a unit using a stepped aluminum frustrum with known diameters. The four arms of the gage are capable of measuring both expansion and contraction of the specimen over a limited range. The two vertical deformeters each consist of a linear variable differential transducer (LVDT) independently mounted on a rigid support ring. The LVDT cores rest on supports extending out from the sample top cap. The vertical and lateral deformeter support rings are suspended around the specimen on vertical rods which are attached to the base of the chamber. Because hydraulic oil is used as the confining fluid in the HPTX device and because it is electrically nonconductive, the LVDT's and strain gages can be simply placed in the oil without electrical protection (which would be required if water were used as a chamber fluid).

Vertical load in the HPTX device is measured inside the chamber with a WES-built strain-gaged load cell attached to the bottom of the vertical piston. Piston displacement is measured with a film pot located outside the chamber. The film pot provides a check on the vertical deformeters during shear. Chamber fluid pressure and pore fluid pressure are measured in the hydraulic lines outside the chamber. During a test the output from seven transducers is amplified and recorded with a Hewlett-Packard data acquisition system. Data reduction details and data analysis are described in Chapter 3 and Addendum B. In addition, during drained hydrostatic loading, independent volume change measurements are made using a volume change burette system.

The PPUX test device, illustrated in Figure 2.5, was used to conduct high-pressure, effective-stress uniaxial strain tests. A pressure transducer in the fluid chamber is used to measure the applied vertical pressure. A hyperdermic needle transmits pore fluid pressure at the midheight of the test specimen to a pore pressure transducer. The drainage line to the bottom of the specimen chamber permits consolidation and back-pressure saturation of the test specimen. A valve inside the device, in close proximity to the bottom of the specimen, minimizes the volume of water in this drainage line that is subjected to compression at high pressures. Vertical displacement of the top surface of the specimen is measured with an LVDT system. With the

static loading piston fixed in place, static tests are conducted by applying a regulated pressure to the chamber fluid. Chamber fluid and pore fluid pressures less than 0.69 MPa are applied through an air-controlled back-pressure saturation control panel; pressures between 0.69 and 69 MPa are generated with a high-pressure hydraulic pump (Figure 2.3). During static loading, the output of three transducers, i.e., the chamber and pore fluid pressures and the vertical displacement, are amplified and recorded on the Hewlett-Packard data acquisition system. Under drained conditions specimen volume changes are also measured with a volume change burette system which provides a check on the axial displacement measurements.* Dynamic tests were conducted using the WES/SECO 100-kip ram loader (Reference 6). For these tests, a sliding loading piston was placed into the device. For these tests, the outputs of the three transducers were simultaneously recorded on both magnetic tape and a light-beam galvanometer oscillograph. Data reduction and analysis is discussed in Chapter 3 and Addendum B.

2.2 SPECIMEN PREPARATION

All sealed ocean sediment samples received by WES, whether undisturbed or reconstituted-reconsolidated, were immediately cataloged in terms of an identification number and the size and type of sample, and then stored in seawater (35 ppt salt content) at 4°C. As each specimen was tested, its identifying number and the date it was removed from storage and prepared for testing were logged into the record book of the appropriate test device.

All of the reconstituted specimens received from URI were intended for the LPTX and HPTX programs. These specimens were contained in stainless steel tubes of varying lengths with inside diameters of 4.95 and 3.68 cm. These tubes were all capped, labeled, and sealed with wax. The sample tubes provided specimens of identical pretest diameters requiring only that specimen length be adjusted prior to testing. Specimens of 4.95 and 3.68 cm diameter were tested in the LPTX test device; these specimens were trimmed to lengths of approximately 10.16 and 7.62 cm, respectively. The material trimmed from the ends of each of these specimens was used to determine their pretest water contents. The wet unit weight of the trimmed specimens was also determined prior to testing. Only 4.95-cm-diameter by 10.16-cm-long specimens were tested in the HPTX test device.

Specimens for the PPUX test program were obtained from two 10.2-cm-diameter sections of undisturbed gravity core (MA-12 GC-19). The PPUX test device accepts a specimen that is 9.14 cm in diameter and 2.29 cm high. Specimens of this diameter were obtained by pushing a 2.29-cm-high specimen ring and cutter into the source material. The ring- and cutter-encased specimen was removed, the excess material above and below the specimen ring was trimmed, and the trimmed faces were covered with Plexiglas plates. The specimens were then labeled and sealed with wax. Water contents were determined from the trimmed material taken from above and below each specimen. The specimens were identified by number (e.g., MA-12 GC-19 Sample #1) rather than by depth. The specimen number, however, was logged, and its exact location within the core was documented.

* Since $\epsilon_r = 0$ in a UX test, then $\Delta V/V_0 = \epsilon_a$, where ϵ_r = radial strain and ϵ_a = axial strain.

Figure 2.1 A Sketch of the WES Low Pressure Triaxial Test Device.

Figure 2.2 The Loading System for the Low Pressure Triaxial Test Device.

Figure 2.3 A Schematic of the Back Pressure Saturation Control Board and Pressure Control System used in the Experimental Test Program.

Figure 2.4 A Schematic of the WES High Pressure Triaxial Test Device.

Figure 2.5 The WES Pore Pressure Uniaxial Strain Test Device.

CHAPTER 3

TEST PROCEDURES

3.1 TEST PROCEDURES FOR LPTX

The tests performed in the LPTX program followed procedures outlined by Bishop and Henkel (Reference 5) for consolidated-undrained triaxial shear tests. The procedures included (a) pretest saturation of all drainage and pore fluid lines, (b) specimen setup, (c) consolidation-back pressure saturation, and (d) undrained hydrostatic and shear loading. To insure complete saturation of all drainage and pore fluid lines, deaired seawater was allowed to flow from the volume change burette to the top and bottom specimen pedestals. In addition, vents in each of the three pressure transducers allowed air to be purged from the transducer's fluid cavity. All porous stones and filter strips were saturated before each test.

As discussed in Chapter 2, specimens were received in sealed sample tubes. Each tube was opened (the wax removed, etc.) and weighed (for future use in determining the wet unit weight of the specimen). The specimen was extruded from the tube, trimmed to the desired length, positioned on the bottom porous stone with filter paper, and then placed on the cell bottom pedestal. The top filter paper, top porous stone, top cap, and side filter strips were next placed on the specimen. The specimen was then enclosed in a flexible 0.31-mm-thick rubber membrane which was sealed to the top and bottom pedestals with stretched elastic bands. The top cap drainage line was connected to the drainage port in the base of the cell. When hydraulic oil was used as the confining fluid, the rubber membrane was coated with a synthetic rubber coating (manufactured by Micromeritics, Inc.; trade name: Gagekote #2). This coating prevented the chemical breakdown of the natural rubber membrane by the hydraulic oil. No coating is required if water is used as the chamber fluid. The cell was then assembled and filled with the chamber fluid, the piston was brought into contact with the top cap, and the initial readings of the five transducers were obtained.

The specimen was then consolidated-back pressure saturated. In this process a constant differential pressure is maintained between the confining fluid and the pore fluid while the back pressure is increased incrementally. The specimen is free to reach equilibrium under the imposed stress difference; i.e., the specimen can consolidate. This process is stopped at a predetermined stress level and the specimen saturation is checked. The pore pressure response of the specimen was determined using the method outlined by Bishop and Henkel (Reference 5); i.e., closing the drainage line, increasing the confining pressure, and measuring the subsequent increase in pore pressure. A criterion of 95 percent response in three minutes (ratio of change in pore pressures to change in confining pressure) was used to satisfy that the specimen was saturated. When an inadequate response is determined, the original confining pressure and back pressure are reestablished and the consolidation-back pressure technique continued to higher pressures.

All shear tests were conducted under undrained conditions with a live undrained hydrostatic load applied prior to shear. Static tests were

conducted at a deformation rate of 0.046 mm per minute. This rate was obtained by using the regulated pressure source detailed in Figure 2.2 and a micrometering valve (not shown in Figure 2.2) placed in line with the solenoid valve. After a minimum axial strain of 15 percent had been achieved, each test was concluded by unloading the specimen.

After each test the specimen weight, water content, and physical dimensions were obtained and photographs were taken. After the water content sample had been taken, specimen remnants were bagged, labeled, and stored for possible future use.

The five channels of analog data obtained from each test were recorded using a light-beam galvanometer oscillograph. From the oscillograph record, a technician measured the departure distance from a reference line to each channel trace at numerous key points throughout the test. These data were then entered into a data reduction program (see Addendum B) from which the calculated stresses and strains were obtained. All strains calculated in the experimental program are engineering strains; i.e., axial strain is defined as the change in length ΔL divided by the original length L_0 . To account for the changes in specimen cross-sectional area A that occurred during undrained shear, a "corrected" area was calculated as $A_0/1-\epsilon$, where A_0 is the preshear area and ϵ is the axial strain during shear (Reference 7). The principal stress difference was calculated as P/A where P is the measured (load cell) vertical load applied to the specimen. No corrections were made to account for the effects of the membrane or filter strips. Excess pore pressure u was defined as the pore pressure generated by the application of shear loads.

For the dynamic shear tests, it was assumed that the pore pressure transducer was too remote from the specimen to give a true indication of the effective-stress conditions within the specimen. The dynamic pore pressure data were therefore ignored and the analysis of all dynamic test data was based on total-stress concepts. For the static shear tests, however, the pore fluid pressure was assumed to be uniform throughout the specimen and the principle of effective-stress was therefore applied to the analysis of the data.

3.2 TEST PROCEDURES FOR HPTX

Specimen preparation procedures for the HPTX tests were essentially identical to those for the LPTX tests. The only significant difference was that the HPTX apparatus did not have provisions for drainage through the specimen top cap. With the specimen in place and the rubber membrane coated with synthetic rubber coating, the lateral and vertical deformer rings were positioned and secured to their support bars around and above the sample, respectively. The lateral deformers were positioned so that they would monitor radial deformations at essentially the midheight of the specimen. To distribute the point loads of the lateral deformer tips, a small piece of aluminum foil was placed between each deformer tip and the specimen membrane. The two LVDT vertical deformers were then adjusted so as to allow use of their maximum available range. After the cell chamber had been assembled and filled with fluid and the loading piston brought into contact with the top cap, the initial pretest transducer outputs were recorded.

During the consolidation-back pressure saturation phase, specimen deformations were monitored with the deformaters from which volume changes could be deduced and subsequently compared with the direct volume change measurements read from the volume change burette. Volumetric strain was calculated from the deformer measurements using two computational methods (Reference 7). The first method assumes that uniform lateral deformation occurs over the entire length of the specimen, i.e., that the specimen deforms as a uniform cylinder. This volumetric strain is closely approximated by the expression $\epsilon_a + 2\epsilon_r$, where ϵ_a is the axial strain and ϵ_r is the radial strain. The second method assumes that the specimen deforms a maximum amount at the midheight and zero at the top and bottom, with a uniform variation between; i.e., the assumed deformed shape is that of two truncated cones. This volumetric strain turns out to be closely approximated by the expression $\epsilon_a + \epsilon_r$. Volumetric strains derived from the volume-change burette measurements are computed as $\Delta V/V_0$, where ΔV is the change in volume (determined from the volume of water expelled) and V_0 is the original (pretest) specimen volume. Comparisons among these three methods are shown and discussed in Addendum C.

During the imposition of live undrained hydrostatic loadings prior to shear, the drainage valve was closed and the chamber fluid pressure was manually increased to the desired level over a period of approximately 5 minutes. This pressure was then decreased and increased again to produce an unloading and reloading cycle prior to shear. During this phase of the HPTX tests, volumetric strains were calculated using the deformer measurements only.

The undrained shear phase was initiated next. Specimens were axially loaded at a deformation rate of 0.030 mm per minute until an axial strain of more than 15 percent was achieved and then unloaded. The changes in cross-sectional area of the specimen during shear were calculated from the lateral deformer measurements. Posttest water contents, specimen weights, physical dimensions, and photographs were obtained for each specimen.

3.3 TEST PROCEDURES FOR PPUX

In the PPUX test device, a uniform vertical stress is applied to a test specimen 9.14 cm in diameter and 2.29 cm high. The procedures followed to conduct a test in this device are similar to those previously described for the triaxial tests and include (a) pretest saturation of the pore fluid and drainage lines, (b) specimen placement into the device, (c) consolidation-back pressure saturation of the specimen, and (d) static or dynamic loading. To insure proper transmission of the pore fluid pressure to the face of the pore pressure transducer, the hyperdermic needle and the line from the bottom of the specimen chamber to the transducer were filled with a silicon gel. The hyperdermic needle was then epoxied into place for the test duration. Prior to placing the specimens, a porous stone (9.65-cm-diameter by 0.32-cm-high) and filter paper were positioned in the bottom of the specimen chamber to help promote uniform specimen consolidation. All drainage lines were saturated by allowing seawater to flow from the volume change burette up through the porous stone into the specimen chamber. With the specimen chamber completely filled with water, the specimen encased in the specimen ring was slowly pushed into place, forcing the water back through the burette

system. A flexible rubber membrane was then placed over the specimen and secured with a retaining ring. The membrane was coated with the synthetic rubber coating to protect it from the hydraulic oil. After the device was assembled and the fluid chamber filled, the static or dynamic loading piston was put in place.

In the static PPUX tests, the consolidation-back pressure saturation process was initiated by applying a differential pressure to the chamber fluid and the pore fluid and then increasing the back pressure incrementally. The specimen volume change was monitored with both the volume change burette and the vertical displacement LVDT. After the specimen had reached equilibrium under the applied stresses, the specimen was subjected to the desired loading, i.e., either static undrained loading or static drained loading. Static undrained loading was initiated by manually increasing the chamber fluid pressure up to the desired level over a period of approximately 5 minutes and then decreasing it back to the initial vertical pressure, thus producing a complete load-unload cycle. Static drained tests were conducted by applying successive increments of vertical pressure to the specimen and allowing the specimen to come to equilibrium. As a minimum criterion, the specimen was allowed to reach t_{90} (90 percent consolidation; Reference 8) before the next increment of pressure was applied. The calculation of 90 percent consolidation is dependent upon the initial stages of specimen consolidation and only requires measurements up to the time t_{90} , whereas the calculation of 100 percent consolidation requires measurements past t_{100} . For this reason, t_{90} was chosen as a minimum time for specimen consolidation during each load increment.

Due to equipment constraints, static consolidation-back pressure saturation could not be applied to the PPUX test specimens before dynamic loading.* A static seating pressure of 0.41 MPa was therefore applied under undrained conditions immediately prior to dynamic loading for the three dynamic PPUX tests documented in this report.

Static PPUX data were recorded and processed with a Hewlett-Packard data acquisition system. Data generated during dynamic tests were recorded by two methods--oscillograph paper and magnetic tape. The oscillograph record was hand-reduced by a technician whereas the analog tape was digitized and processed by computer. The vertical strain was calculated as an engineering strain, i.e., $\Delta H/H_0$, where ΔH is the change in specimen height and H_0 is the pretest specimen height. Volumetric strains from the burette measurements were calculated as $\Delta V/V_0$, where ΔV is the measured volume change and V_0 is the pretest specimen volume.

* The test device has since been modified for the FY 81 experimental program to allow consolidation-back pressure saturation before dynamic loading.

CHAPTER 4

TEST RESULTS

4.1 LPTX TEST RESULTS

In the FY 80 experimental program 32 tests were conducted in the LPTX device on reconstituted-reconsolidated specimens of North Pacific illite from MPG-1. As discussed previously, two groups of specimens were obtained from URI, each having specimen diameters of 4.95 and 3.68 cm. Specimens identified by the prefix PI 4.5-1 were to represent a simulated in situ depth of 4.5 meters and have been identified as originating from tank No. 1. Specimens with the prefix PI 5-8 represent a simulated depth of 5 meters and originated from tank No. 8. Communications from URI personnel indicated that tank No. 1 (PI 4.5-1 specimens) did not fully consolidate under the imposed stress, and the specimens from this tank appeared to be of questionable quality. However, due to specimen and time constraints, tests were conducted on the tank No. 1 specimens as well as those from tank No. 8.

Table 4.1 lists pretest composition data; i.e., water content w , wet density γ , dry density γ_d , volumes of air V_a , water V_w , and solids V_s , type of test, and posttest water content for all specimens tested from tank No. 1. Similarly, Table 4.2 presents composition data for all of the tank No. 8 specimens. The mean pretest water content and bulk density for tanks No. 1 and 8 specimens are 100.6 percent, 1.474 g/cc and 86.6 percent, 1.535 g/cc, respectively. Addendum D discusses the procedures and assumptions used to calculate the composition properties.

For each successful static and dynamic shear test, Tables 4.3 and 4.4 list the final back pressure saturation stresses; the stresses at the end of the live undrained hydrostatic loading (i.e., just prior to shear); the principal stress difference at failure $(\sigma_1 - \sigma_3)_f$; the pore pressure at failure u_f ; the effective mean normal stress at failure $(J_1/3)_f$; the pretest water content and bulk density; and the posttest water content. For the dynamic tests, the pore pressure at failure (and, hence, the effective mean normal stress at failure) was not measured. For each static test listed in Tables 4.3 and 4.4, plots of principal stress difference versus axial strain and pore pressure versus axial strain have been generated. For the dynamic tests, only plots of principal stress difference versus axial strain have been generated. For purposes of comparison axial strains have been referenced to changes in specimen height from the beginning of the shear phase and all individual shear test figures have been drawn to identical scales. Figures 4.1 through 4.20 present these plots for the static and dynamic tests on the PI 4.5-1 specimens. Figures 4.21 through 4.33 present the plots of the individual shear test results from the PI 5-8 specimens. Figure 4.34 is a plot of principal stress difference versus effective mean normal stress, i.e., the effective-stress paths during shear, for three selected PI 4.5-1 tests. Figure 4.35 shows the total stress paths for four static and five dynamic PI 5-8 tests where the solid and dashed lines represent the static and dynamic total stress paths, respectively. Figure 4.36 presents the effective-stress paths for four PI 5-8 static tests.

Due to difficulties in saturating the poor quality PI 4.5-1 specimens, consistent (from specimen to specimen) back-pressure saturation stress states could not be achieved. Consequently, the initial conditions of the specimens varied, more or less randomly, thus complicating attempts to make definitive statements concerning the effects of loading rate on strength. As an attempt to offset this factor, the values of principal stress difference at failure were normalized for each test by dividing by the respective effective mean normal stress prior to shear. These normalized strengths are listed in Table 4.5. The average normalized static and dynamic strengths were 0.8077 and 1.9814, respectively, indicating that the dynamic (10-msec rise time) strength is 2.45 times the static (1- to 2-hour rise time) strength.

To obtain the effective failure envelope, three tests (PI 4.5-1B 43-53 cm, PI 4.5-1B 28-38 cm, and PI 4.5-1F 28-38 cm) were chosen from the PI 4.5-1 static shear test series. Linear and nonlinear failure envelopes (Figure 4.34) have been drawn through the failure points. These data, if replotted in a Mohr stress space and fitted with a linear Mohr-Coulomb envelope, would yield an effective internal friction angle ϕ of 20.4 degrees and an effective cohesion intercept $\bar{c}$ of 0.0065 MPa. A nonlinear envelope could be fit to the same data, in which case the envelope would be approximated by a polynomial of n degrees. However, an intercept must be assumed or derived from test data (presently not available) at lower effective mean normal stresses.

All of the PI 5-8 specimens were consolidated-back pressure saturated to approximately the same stress conditions; i.e., an average effective mean normal stress of 0.034 MPa with an average back pressure of 0.38 MPa. Additional live undrained hydrostatic loads ranging between 0 and 0.28 MPa were then applied to these specimens before they were sheared. Only 9 of the 12 tests conducted on these specimens (four of these were static and five were dynamic) produced acceptable results (see Addendum E).

The total stress paths in Figure 4.35 illustrate the effects of strain rate on the shearing strength of the PI 5-8 sediments. For both the static and dynamic tests, the principal stress difference at failure appears to be independent of the total mean normal stress; therefore, horizontal failure envelopes result. For these tests the mean dynamic principal stress difference at failure was 0.0659 MPa versus 0.0394 MPa for the static tests, an increase of 67 percent (see Figure 4.35). The effective-stress paths for the four static tests are presented in Figure 4.36. These stress paths all have similar shapes which are qualitatively typical of normally consolidated soils. A comparison of the WES and URI static consolidated-undrained triaxial shear test data is presented in Addendum F.

One of the objectives of the LPTX experimental program was to determine the variability of test results under essentially similar initial conditions. The poor quality of the PI 4.5-1 test specimens and the variations in the initial stress conditions under which they were tested preclude any meaningful variability analysis of these data. However, the PI 5-8 specimens were of similar consistency and were tested under nearly identical initial conditions. The table below indicates the statistical variability present in the values of static and dynamic principal stress difference at failure for these test specimens.

	<u>Static</u>	<u>Dynamic</u>
Number of samples	4	5
Mean $(\sigma_1 - \sigma_3)_f$ MPa	0.0394	0.0659
Standard deviation	0.0028	0.0035
Coefficient of variation	7.1%	5.3%

4.2 DRAINED AND UNDRAINED HYDROSTATIC LOADING TESTS

Eight drained hydrostatic load tests were performed in both the LPTX (four tests) and HPTX (four tests) experimental programs to determine the consolidation response of the tanks No. 1 and 8 materials. Table 4.6 presents the composition property data for these eight tests. Figure 4.37 presents the drained response of four PI 5-8 specimens tested in the LPTX device (peak effective mean normal stresses were less than 0.60 MPa). Figures 4.38 through 4.41 present the drained response of the high-pressure tests on specimens from tanks No. 1 and 8. The volumetric strains plotted in these figures were calculated from volume change burette measurements.

From the four low-pressure tests (Figure 4.37) the desired unloading data was only obtained from one specimen, PI 5-8#40 40-50 cm. The remaining three tests were terminated prior to or during the unloading process due to volume change measurements which indicated membrane leakage had occurred. The four loading curves illustrate the influence of pretest water content and wet density on the consolidation response of the PI 5-8 material; i.e., the two specimens with the higher densities and lower water contents exhibited less strain at a given pressure than the lower density specimens.

A major problem in completing the high-pressure hydrostatic tests has been the failure of the natural rubber membrane which seals the specimen. As discussed in Section 3.1 the membranes slowly dissolve when in contact with hydraulic oil. Though protected with a synthetic rubber coating, the large volumetric strains and long test durations aggravate this problem. Test procedures will be reviewed prior to the start of the FY 81 experimental program in an attempt to overcome this problem.

During loading, the four HPTX tests produced large volumetric strains (30 to 40 percent) at low stress levels consistent with the LPTX tests. Under an effective stress of 0.69 MPa, specimen PI 4.5-1A 75-85 cm reached a volumetric strain of 34.6 percent prior to membrane leakage. Specimen PI 5-8#98 40-50 cm (Figure 4.38) was also terminated due to a leak in the specimen membrane. Specimen PI 4.5-1A 43-53 cm (Figure 4.39) exhibited a volumetric strain of 61 percent at 48.3 MPa before a fitting in the test chamber failed. A final volumetric strain calculated for this test from the posttest water content was 60.8 percent. For this test PI 4.5-1A 43-53 cm, plots of volume change versus square root of time, for all of the loading increments, are presented in Addendum G. Loading and unloading data were successfully obtained from test number PI 5-8#88 40-50 cm (Figure 4.40). This test was programmed as a special test to obtain loading and unloading consolidation data as well as undrained shear data. Hence, larger loading increments were used to reduce the test duration. Conceivably, this also

mitigated the membrane deterioration problem. When terminated, this test had a final volumetric strain of 60 percent. The volumetric strain calculated from the posttest water content was 57.7 percent. Tests PI 4.5-1A 43-53 cm and PI 5-8#88 40-50 cm exhibited nearly identical loading responses, as shown in Figure 4.41.

In addition to the above tests, six specimens were hydrostatically loaded, with no drainage permitted, in the HPTX device. Two of these specimens were subsequently sheared to failure (see Section 4.3). Table 4.7 presents the composition properties of these six tests. Tests PI 4.5-1D 28-38 cm and PI 4.5-1E 75-85 cm were the pioneer high-pressure undrained hydrostatic loading tests performed on this material. The loading rates and stress increments used for these two tests approximated those applied in the drained hydrostatic tests. In general, each load increment was maintained for a period of 24 hours. However, the high-pressure hydraulic supply was unable to maintain a constant chamber pressure over a 24-hour period, resulting in fluctuations of the chamber pressure and therefore erratic variations in volumetric strain. Both tests were terminated after partial specimen drainage occurred. Due to the questionable character of the data obtained, the results are not presented herein; however, the data are presented in Addendum E. The results of test PI 5-8#97 40-50 cm are also presented in Addendum E.

Figures 4.42 through 4.44 present the data from the three remaining (better quality) undrained hydrostatic tests, all on PI 5-8 specimens. These three tests were fully loaded in approximately 5 minutes. Tests PI 5-8#99 40-50 cm (Figure 4.42) and PI 5-8#93 40-50 cm (Figure 4.43) qualitatively appear to be excellent tests. Test PI 5-8#89 40-50 cm (Figure 4.44) after reaching a live stress of 21.45 MPa leaked, resulting in an accumulated volumetric strain of 1.2 percent. For each undrained hydrostatic test, two deformed specimen shapes were assumed in calculating volumetric strains. The two calculational methods (Addendum C) indicate the possible range of uncertainty in the actual volumetric strains (and hence the actual bulk modulus) associated with these tests.

4.3 HPTX TEST RESULTS

Ten static HPTX tests were brought to various stages of completion under several different applied loading conditions in this test program. Eight of the ten tests were terminated either during the hydrostatic phase or prior to completion of shear loading. The hydrostatic data from these HPTX tests have been discussed previously in Section 4.2.

Figures 4.45 and 4.46 present plots of principal stress difference versus principal strain difference for the two successful high-pressure shear tests. It should be acknowledged that the pore pressure measurements in the HPTX were not of sufficient resolution to define the effective-stress response of the specimens undergoing shear loading; hence, no pore pressure plots are shown. The two specimens PI 5-8#89 40-50 cm (Figure 4.45) and PI 5-8#93 40-50 cm (Figure 4.46) were sheared undrained at chamber pressures of 33.79 and 54.48 MPa, respectively, to axial strains in excess of 15 percent. These two specimens were consolidated-back pressure saturated to the same effective-stress conditions as the four previously presented PI 5-8

LPTX tests. Figure 4.47 shows the total stress paths for these four LPTX and the two HPTX tests. The principal stress differences at failure for the two HPTX shear tests fall within the scatter of the static PI 5-8 LPTX failure stresses. From this limited data it appears that the total stress failure envelope is unaffected by confining pressure and that a $\sigma = 0$ total stress failure envelope is maintained to pressures as high as 55 MPa.

4.4 PPUX TEST RESULTS

Nine PPUX tests were conducted on undisturbed sediment specimens from the gravity core MARA-12 GC-19 of which six were undrained tests and three were drained tests. Table 4.8 presents composition data for all nine specimens and identifies the type of test conducted on each specimen. For the undrained tests, Table 4.9 presents values of the undrained constrained modulus, pretest and posttest water contents, rise time, and the stresses imposed during consolidation-back pressure saturation.

Static test S#1 unexpectedly partially drained during loading; hence, the test results were considered questionable and are therefore reported in Addendum E. Figures 4.48 through 4.51 present the results of static tests S#2 and S#3 in terms of plots of vertical stress versus vertical strain and vertical stress versus pore pressure. Tests S#2 and S#3 had similar values of undrained constrained modulus (2455 and 2425 MPa, respectively; Table 4.9). Both tests exhibited reversible stress-strain and pore pressure responses as expected from a saturated undrained material of very low strength.

Figures 4.52 through 4.57 present similar plots for three dynamically loaded undrained PPUX tests (S#4, S#5, and S#6). These tests were loaded at three different rates (123, 24, and 6 msec, respectively, Table 4.9). As discussed in Section 3.3 these specimens were not consolidated prior to dynamic loading. The apparent decrease in constrained modulus of the dynamic test specimens as rise time decreased is, in general, contrary to expected material behavior. The composition properties for these three specimens were essentially the same as the static tests (even after consolidation); therefore, the dynamic constrained moduli were expected to be close to those of the static tests. At the present time we cannot explain the apparent contradiction to the expected trend. It is presumed that tests S#4 and S#5 are of good quality, whereas test S#6 may have undergone partial drainage or seating movement, as it underwent approximately 1 percent permanent deformation.

Pore pressure measurements were made at the midheight of the specimens for both static and dynamic tests. However, a lag time of 1.5 msec between peak vertical stress and pore pressure was found to be inherent in the measuring system, independent of rise time. Although this lag time is not important for the slower tests, it prevents the acquisition of meaningful pore pressure response for rise times less than 25 msec. For this reason the pore pressure response of test S#6 (Figure 4.57), which was loaded in 6 msec, should be neglected when comparing data. There exists a one-to-one relationship between vertical stress and pore pressure for the other tests, as expected for these saturated materials.

Three high-pressure drained uniaxial strain tests were conducted on specimens MA-12 GC-19 S#7, S#8, and S#9. The results of these tests are plotted in Figures 4.58 through 4.63. Each test was cycled once at low stress levels (less than 1 MPa) and then loaded up to the desired peak stress prior to unloading. Test S#9 was consolidated to a volumetric strain of 43 percent (burette calculation), unloaded, and reloaded to a vertical stress of 0.2 MPa (Figure 4.62). At this point, the drainage valve was closed and the specimen loaded under undrained conditions. During this loading, an O-ring seal leaked, causing partial specimen drainage. The "undrained" results are therefore reported in Addendum E. However, the consolidation response of this test is reported herein.

Specimen S#7 (Figure 4.58) exhibited 63 percent volumetric strain at 5.5 MPa as computed from the burette, compared to 55 percent volumetric strain as computed from the axial strain measured with the LVDT. The volumetric strain at 41.4 MPa (Figure 4.59) was 74.8 percent as measured by the burette (the axial measurement was out of range at this point). Posttest volumetric strains determined for test S#7 from (a) the volume change burette, (b) the posttest water content, and (c) posttest specimen physical measurements yielded values of 73.7, 61.8, and 62.7 percent, respectively. Therefore, the final burette volumetric strain of 73.7 percent appears to be suspect (too high) in comparison to the posttest measurements.

Figures 4.60 and 4.61 are plots of effective vertical stress versus volumetric strain for test S#8. The vertical deformer (LVDT) was not operational during this test; therefore only burette measurements are indicated. Figure 4.60 presents both the loading and unloading response of the specimen at stresses less than 1.0 MPa. Figure 4.61 indicates that a maximum volumetric strain of 64 percent was achieved at 66 MPa. Posttest volumetric strains calculated from the final burette measurement and posttest water content were in good agreement, i.e., 53.7 and 55.4 percent, respectively. Plots of volume change versus the square root of time for each of the applied loading increments are presented in Addendum G.

The drained loading and unloading response of specimen S#9 is presented in Figure 4.62. As observed in test S#7 (Figure 4.58), there is a difference between the strains calculated from the LVDT and the volume change burette measurements. Factors which may have contributed to the differences are (a) possible expansion of the drainage lines under pressure, and/or (b) the presence of entrapped air in the drainage lines. It is the burette measurements which are most in question for the PPUX device.

Figure 4.63 compares the low stress level drained response of specimens S#8 and S#9 in terms of their burette volumetric strains. The response of the two specimens is nearly identical, indicating that although the burette measurements may tend to be in error, the error is consistent.

The results obtained from this series of nine PPUX tests give reasonable indications of the response of undisturbed illite to high-pressure uniaxial strain loadings. The two static undrained tests (S#2 and S#3) yielded essentially identical values of constrained modulus. These tests had the same initial effective-stress conditions, but were back-pressure saturated to different initial total stress conditions. In the undrained tests, the pore

pressure response under static and dynamic loadings was as expected for a saturated soil; i.e., the changes in pore pressure were directly related to changes in the applied vertical stress. The dynamic tests (S#4, S#5, and S#6), unfortunately, were not back-pressure saturated (the equipment used in the FY 80 program contained no provision for this). However, the test device has since been modified and the effects of back-pressure saturation and rise time will be reexamined in the FY 81 experimental program. The lack of control over the initial effective-stress conditions in tests S#4, S#5, and S#6 is assumed to be a factor in the unexpected finding that the dynamic constrained modulus decreased (significantly) as the loading rise time was decreased.

The pore pressure measurements obtained during the testing program indicated that the PPUX test device can make meaningful and accurate measurements of pore pressure under loading rise times as fast as 50 msec. The three drained uniaxial strain tests provided excellent loading and unloading data with greater success than the drained high-pressure hydrostatic tests. However, either an improved burette measuring system or a longer range LVDT system needs to be incorporated into the PPUX device before completely satisfactory volume change measurements can be expected. The FY 81 experimental program will concentrate heavily on obtaining improved uniaxial strain test data.

Table 4.1 Composition Properties for Tank No. 1 Low Pressure Triaxial Shear Test Specimens

Test No.	Pretest						Type of Test	Posttest
	w* %	γ g/cc	γ_d^* g/cc	V_a^* %	V_s^* %	V_w^* %		w* %
PI 4.5-1A 28-38 cm	101.4	1.481	0.735	0.8	27.2	72.0	Static	91.8
PI 4.5-1B 28-38 cm	100.9	1.461	0.727	2.2	26.9	70.9	Static	78.6
PI 4.5-1B 43-53 cm	97.5	1.462	0.740	2.9	27.4	69.7	Static	82.1
PI 4.5-1C 43-53 cm	103.5	1.456	0.715	1.9	26.5	71.6	Dynamic	86.3
PI 4.5-1C 28-38 cm	99.4	1.483	0.744	1.1	27.5	71.4	Dynamic	91.8
PI 4.5-1D 43-53 cm	108.9	1.464	0.701	0.3	26.0	73.7	Dynamic	81.0
PI 4.5-1E 28-38 cm	98.2	1.463	0.738	2.7	27.3	70.0	Dynamic	83.9
PI 4.5-1B 75-85 cm	101.3	1.474	0.732	1.2	27.1	71.7	Dynamic	92.0
PI 4.5-1C 75-85 cm	99.3	1.480	0.743	1.2	27.5	71.3	Dynamic**	88.1
PI 4.5-1E 43-53 cm	101.5	1.485	0.737	0.4	27.3	72.3	Dynamic	93.5
PI 4.5-1F 43-53 cm	96.2	1.470	0.749	2.6	27.8	69.6	Dynamic	79.4
PI 4.5-1D 75-85 cm	99.1	1.482	0.744	1.1	27.6	71.3	Dynamic	90.5
PI 4.5-1F 75-85 cm	99.0	1.492	0.750	0.5	27.8	71.7	Static	90.8
PI 4.5-1G 43-53 cm	104.5	1.482	0.725	0.0	26.8	73.2	Static**	89.4
PI 4.5-1F 28-38 cm	99.2	1.479	0.742	1.3	27.5	71.2	Static	89.0
PI 4.5-1H 43-53 cm	100.0	1.466	0.733	2.1	27.1	70.8	Static	82.6

* Corrected for 35 ppt salt content. (Specific Gravity Assumed = 2.70).

** Data lost due to equipment malfunction. (see Addendum E).

Table 4.2 Composition Properties for Tank No. 8 Low Pressure Triaxial Shear Test Specimens

Test No.	Pretest						Type of Test	Posttest
	w* %	γ g/cc	γ_d^* g/cc	V_a^* %	V_s^* %	V_w^* %		w* %
PI 5-8#70 40-50 cm	86.0	1.542	0.829	0.4	30.7	68.9	Dynamic	77.8
PI 5-8#71 40-50 cm	83.4	1.550	0.845	0.6	31.3	68.1	Static	77.1
PI 5-8#76 40-50 cm	92.6	1.511	0.784	0.7	29.1	70.2	Dynamic	78.8
PI 5-8#77 40-50 cm	85.8	1.522	0.819	1.8	30.3	67.9	Dynamic	77.9
PI 5-8#81 40-50 cm	92.7	1.515	0.786	0.5	29.1	70.4	Static**	78.0
PI 5-8#82 40-50 cm	85.8	1.545	0.832	0.3	30.8	68.9	Static	76.7
PI 5-8#84 40-50 cm	83.8	1.548	0.842	0.6	31.2	68.2	Static	76.1
PI 5-8#85 40-50 cm	85.8	1.546	0.832	0.2	30.8	69.0	Static	71.1
PI 5-8#86 40-50 cm	86.4	1.545	0.829	0.1	30.7	69.2	Dynamic	77.1
PI 5-8#69 40-50 cm	88.5	1.541	0.817	0.0	30.1	69.9	Dynamic**	77.9
PI 5-8#74 40-50 cm	92.9	1.514	0.785	0.4	29.1	70.5	Dynamic**	78.4
PI 5-8#80 40-50 cm	86.5	1.539	0.825	0.6	30.5	68.9	Dynamic	77.1

* Corrected for 35 ppt salt content. (Specific Gravity Assumed = 2.70).

** Data lost due to equipment malfunction. (see Addendum E).

Table 4.3 Low Pressure Triaxial Shear Test Data for Tank No. 1 Specimens

Test No.	Type of Test	BPS		Shear		$(\sigma_1 - \sigma_3)_f$ MPa	u_f MPa	$(J_1'/3)_f$ MPa	Pretest		Posttest
		σ_r MPa	u MPa	σ_r MPa	u MPa				w %	γ g/cc	w %
PI 4.5-1A 28-38 cm	Static	0.280	0.255	0.280	0.255	0.0106	0.0105	0.0189	101.4	1.481	91.8
PI 4.5-1F 75-85 cm	Static	0.373	0.347	0.442	0.416	0.0234	0.0197	0.0140	99.0	1.492	90.8
PI 4.5-1F 28-38 cm	Static	0.373	0.347	0.511	0.485	0.0250	0.0191	0.0151	99.2	1.479	89.0
PI 4.5-1B 43-53 cm	Static	0.324	0.281	0.324	0.281	0.0373	0.0279	0.0280	97.5	1.462	82.1
PI 4.5-1H 43-53 cm	Static	0.388	0.345	0.526	0.483	0.0309	0.0310	0.0227	100.0	1.466	82.6
PI 4.5-1B 28-38 cm	Static	0.495	0.408	0.495	0.408	0.0514	0.0558	0.0480	100.9	1.461	78.6
PI 4.5-1B 75-85 cm	Dynamic	0.341	0.332	0.341	0.332	0.0333	NM*	NM	101.3	1.474	92.0
PI 4.5-1E 43-53 cm	Dynamic	0.345	0.331	0.379	0.366	0.0407	NM	NM	101.5	1.485	93.5
PI 4.5-1C 28-38 cm	Dynamic	0.272	0.257	0.272	0.257	0.0410	NM	NM	99.4	1.483	91.8
PI 4.5-1D 75-85 cm	Dynamic	0.362	0.343	0.432	0.413	0.0477	NM	NM	99.1	1.482	90.5
PI 4.5-1C 43-53 cm	Dynamic	0.337	0.302	0.337	0.302	0.0551	NM	NM	103.5	1.456	86.3
PI 4.5-1E 28-38 cm	Dynamic	0.381	0.341	0.519	0.479	0.0645	NM	NM	98.2	1.463	83.9
PI 4.5-1D 43-53 cm	Dynamic	0.423	0.358	0.423	0.358	0.0824	NM	NM	108.9	1.464	81.0
PI 4.5-1F 43-53 cm	Dynamic	0.423	0.358	0.561	0.496	0.0822	NM	NM	96.2	1.470	79.4

* NM: not measured (see text concerning dynamic tests).

Table 4.4 Low Pressure Triaxial Shear Test Data for Tank No. 8 Specimens.

Test No.	Type of Test	BPS		Shear		$(\sigma_1 - \sigma_3)_f$ MPa	u_f MPa	$(J_1'/3)_f$ MPa	Pretest		Posttest
		σ_r MPa	u MPa	σ_r MPa	u MPa				w %	γ g/cc	w %
PI 5-8#82 40-50 cm	Static	0.414	0.379	0.448	0.414	0.0367	0.0260	0.0209	85.8	1.545	76.7
PI 5-8#71 40-50 cm	Static	0.414	0.379	0.483	0.448	0.0415	0.0243	0.0241	83.4	1.550	77.1
PI 5-8#84 40-50 cm	Static	0.413	0.379	0.551	0.517	0.0372	0.0188	0.0279	83.8	1.548	76.1
PI 5-8#85 40-50 cm	Static	0.412	0.377	0.688	0.653	0.0421	0.0308	0.0176	85.8	1.546	71.1
PI 5-8#80 40-50 cm	Dynamic	0.414	0.379	0.414	0.379	0.0671	NM*	NM	86.5	1.539	77.1
PI 5-8#76 40-50 cm	Dynamic	0.412	0.378	0.447	0.412	0.0600	NM	NM	92.6	1.511	78.8
PI 5-8#86 40-50 cm	Dynamic	0.412	0.378	0.481	0.447	0.0691	NM	NM	90.2	1.545	77.1
PI 5-8#70 40-50 cm	Dynamic	0.414	0.380	0.552	0.518	0.0663	NM	NM	86.0	1.542	77.8
PI 5-8#77 40-50 cm	Dynamic	0.416	0.381	0.692	0.656	0.0669	NM	NM	85.8	1.522	77.9

* NM: not measured (see text concerning dynamic tests).

Table 4.5 Normalized Static and Dynamic Strengths
for PI 4.5-1 Specimens.

Test No.	$(\sigma_1 - \sigma_3)_f$ MPa	$J_1'/3$ MPa	$3(\sigma_1 - \sigma_3)_f/J_1'$
<u>Static Tests</u>			
PI 4.5-1F 75-85 cm	0.0234	0.026	0.900
PI 4.5-1F 28-38 cm	0.0250	0.026	0.962
PI 4.5-1B 43-53 cm	0.0373	0.043	0.867
PI 4.5-1H 43-53 cm	0.0309	0.043	0.719
PI 4.5-1B 75-85 cm	0.0514	0.087	<u>0.591</u>
Average:			0.8077
<u>Dynamic Tests</u>			
PI 4.5-1E 43-53 cm	0.0407	0.014	2.907
PI 4.5-1C 28-38 cm	0.0410	0.015	2.733
PI 4.5-1D 75-85 cm	0.0477	0.019	2.511
PI 4.5-1C 43-53 cm	0.0551	0.035	1.574
PI 4.5-1E 28-38 cm	0.0645	0.040	1.613
PI 4.5-1D 43-53 cm	0.0824	0.065	1.268
PI 4.5-1F 43-53 cm	0.0822	0.065	<u>1.265</u>
Average:			1.9814

Note: Specimens PI 4.5-1A 28-38 cm and PI 4.5-1B 75-85 cm not included in above analyses.

Table 4.6 Composition Properties for Drained Hydrostatic Loading Test Specimens.

Test No.	Material	Pretest								Type of Test	Posttest
		w* %	γ g/cc	γ_d^* g/cc	V_a^* %	V_s^* %	V_w^* %	w* %			
PI 5-8#40 28-38 cm	Tank #8	101.1	1.477	0.735	1.1	27.2	71.7	Drained Hydrostat/LPTX	54.7		
PI 5-8#55 28-38 cm	Tank #8	85.3	1.546	0.834	0.3	30.9	68.8	Drained Hydrostat/LPTX	51.5		
PI 5-8#72 40-50 cm	Tank #8	84.9	1.548	0.837	0.3	31.0	68.7	Drained Hydrostat/LPTX	54.5		
PI 5-8#59 28-38 cm	Tank #8	NM*	1.511	--	--	--	--	Drained Hydrostat/LPTX	62.2		
PI 4.5-1A 75-85 cm	Tank #1	101.6	1.487	0.738	0.3	27.3	72.4	Drained Hydrostat/HPTX	47.6		
PI 4.5-1A 43-53 cm	Tank #1	105.2	1.493	0.728	0.0	26.1	73.9	Drained Hydrostat/HPTX	17.1		
PI 5-8#98 40-50 cm	Tank #8	97.1	1.494	0.758	0.8	28.1	71.1	Drained Hydrostat/HPTX	20.5		
PI 5-8#88 40-50 cm	Tank #8	97.3	1.487	0.754	1.2	27.9	70.9	Drained Hydrostat/HPTX	17.7		

* Corrected for 35 ppt salt content. (Specific Gravity Assumed = 2.70).

** NM: not measured.

Table 4.7 Composition Properties for High Pressure Triaxial Shear Test Specimens.

Test No.	Material	Pretest							Type of Test	Posttest
		w* %	γ g/cc	γ_d^* g/cc	V _a * %	V _s * %	V _w * %	w* %		
PI 4.5-1D 28-38 cm	Tank #1	95.3	1.477	0.756	2.4	28.0	69.6	Undrained Hydrostat***,†	20.9	
PI 4.5-1E 75-85 cm	Tank #1	94.1	1.499	0.772	1.2	28.6	70.2	Undrained Hydrostat***,†	90.2	
PI 5-8#99 40-50 cm	Tank #8	93.5	1.510	0.781	0.6	28.9	70.5	Undrained Hydrostat**	81.0	
PI 5-8#93 40-50 cm	Tank #8	96.0	1.481	0.756	1.9	28.0	70.1	Undrained Hydro and Shear	77.7	
PI 5-8#89 40-50 cm	Tank #8	93.2	1.518	0.786	0.1	29.1	70.8	Undrained Hydro and Shear	73.6	
PI 5-8#97 40-50 cm	Tank #8	86.9	1.545	0.827	0.0	30.6	69.4	Terminated†	75.0	

* Corrected for 35 ppt salt content. (Specific Gravity Assumed = 2.70).

** Test terminated before completion of shear phase.

† See Addendum E.

Table 4.8 Composition Properties for Pore Pressure Uniaxial Strain Test Specimens.

Test No.	Material	Pretest						Type of Test	Posttest
		W* %	γ g/cc	γ_d^* g/cc	V_a^* %	V_s^* %	V_w^* %		W* %
MA-12 GC-19 S#1	UPI** Top Bottom	107.3	1.463	0.706	0.7	26.1	73.2	Static Undrained	62.2
		104.9	1.463	0.714	1.1	26.5	72.4		
MA-12 GC-19 S#2	UPI Top Bottom	101.2	1.487	0.739	0.3	27.4	72.3	Static Undrained	86.8
		102.2	1.487	0.735	0.2	27.2	72.6		
MA-12 GC-19 S#3	UPI Top Bottom	99.4	1.504	0.754	0.0	27.6	72.4	Static Undrained	89.8
		98.2	1.504	0.759	0.0	28.0	72.0		
MA-12 GC-19 S#4	UPI Top Bottom	106.9	1.481	0.716	0.0	26.1	73.9	Dynamic Undrained	98.4
		100.4	1.481	0.739	0.9	27.4	71.7		
MA-12 GC-19 S#5	UPI Top Bottom	112.4	1.449	0.682	0.6	25.3	74.1	Dynamic Undrained	110.1
		115.1	1.449	0.674	0.1	25.0	74.9		
MA-12 GC-19 S#6	UPI Top Bottom	113.1	1.446	0.679	0.7	25.1	74.2	Dynamic Undrained	110.9
		101.6	1.446	0.717	3.0	26.6	70.4		
MA-12 GC-19 S#7	UPI Top Bottom	99.2	1.484	0.745	1.0	27.6	71.4	Drained	17.1
		108.0	1.484	0.713	0.0	25.6	74.4		
MA-12 GC-19 S#8	UPI Top Bottom	108.6	1.464	0.702	0.4	26.0	73.6	Drained	34.1
		111.4	1.464	0.692	0.0	25.4	74.6		
MA-12 GC-19 S#9	UPI Top Bottom	109.4	1.460	0.697	0.5	25.8	73.7	Static Undrained	43.4
		112.6	1.460	0.687	0.0	25.3	74.7		

* Corrected for 35 ppt salt content. (Specific Gravity Assumed = 2.70)

** UPI: Undisturbed Pacific Illite.

Table 4.9 Pore Pressure Uniaxial Strain Undrained Constrained Moduli

Test No.	Pretest		Posttest	BPS		Rise Time sec	Modulus MPa
	w* %	γ g/cc		σ MPa	u MPa		
MA-12 GC-19 S#1	106.1	1.463	62.2	0.28	0.26	≈300	---**
MA-12 GC-19 S#2	101.7	1.487	86.8	0.41	0.38	≈300	2455
MA-12 GC-19 S#3	98.8	1.504	89.8	7.31	7.28	≈300	2425
MA-12 GC-19 S#4	103.7	1.481	98.4	0.00	0.00	0.123	2575
MA-12 GC-19 S#5	113.8	1.449	110.1	0.00	0.00	0.024	1725
MA-12 GC-19 S#6	107.4	1.446	110.9	0.00	0.00	0.006	1325

* Average water content from Table 4.8

** Leak occurred during test; data questionable (see Addendum E).

Figure 4.1 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 4.5-1A 28-38 cm

Figure 4.2 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 4.5-1A 28-38 cm

Figure 4.3 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 4.5-1F 75-85 cm

Figure 4.4 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 4.5-1F 75-85 cm

Figure 4.5 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 4.5-1F 28-38 cm

Figure 4.6 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 4.5-1F 28-38 cm

Figure 4.7 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 4.5-1B 43-53 cm

Figure 4.8 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 4.5-1B 43-53 cm

Figure 4.9 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 4.5-1H 43-53 cm

Figure 4.10 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 4.5-1H 43-53 cm

Figure 4.11 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 4.5-1B 28-38 cm

Figure 4.12 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 4.5-1B 28-38 cm

Figure 4.13 BACK PRESSURE SATURATED CONSOLIDATED
DYNAMIC UNDRAINED TRIAXIAL SHEAR.
SPECIMEN PI 4.5-1B 75-85 cm

Figure 4.14 BACK PRESSURE SATURATED CONSOLIDATED
DYNAMIC UNDRAINED TRIAXIAL SHEAR.
SPECIMEN PI 4.5-1E 43-53 cm

Figure 4.15 BACK PRESSURE SATURATED CONSOLIDATED
DYNAMIC UNDRAINED TRIAXIAL SHEAR.
SPECIMEN PI 4.5-1C 28-38 cm

Figure 4.16 BACK PRESSURE SATURATED CONSOLIDATED
DYNAMIC UNDRAINED TRIAXIAL SHEAR.
SPECIMEN PI 4.5-1D 75-85 cm

Figure 4.17 BACK PRESSURE SATURATED CONSOLIDATED
DYNAMIC UNDRAINED TRIAXIAL SHEAR.
SPECIMEN PI 4.5-1C 43-53 cm

Figure 4.18 BACK PRESSURE SATURATED CONSOLIDATED
DYNAMIC UNDRAINED TRIAXIAL SHEAR.
SPECIMEN PI 4.5-1E 28-38 cm

Figure 4.19 BACK PRESSURE SATURATED CONSOLIDATED
DYNAMIC UNDRAINED TRIAXIAL SHEAR,
SPECIMEN PI 4.5-1D 43-53 cm

Figure 4.20 BACK PRESSURE SATURATED CONSOLIDATED
DYNAMIC UNDRAINED TRIAXIAL SHEAR,
SPECIMEN PI 4.5-1F 43-53 cm

Figure 4.21 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 5-8#82 40-50 cm

Figure 4.22 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 5-8#82 40-50 cm

Figure 4.23 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 5-8#71 40-50 cm

Figure 4.24 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 5-8#71 40-50 cm

Figure 4.25 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 5-8#84 40-50 cm

Figure 4.26 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 5-8#84 40-50 cm

Figure 4.27 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 5-8#85 40-50 cm

Figure 4.28 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 5-8#85 40-50 cm

Figure 4.29 BACK PRESSURE SATURATED CONSOLIDATED
DYNAMIC UNDRAINED TRIAXIAL SHEAR.
SPECIMEN PI 5-8#80 40-50 cm

Figure 4.30 BACK PRESSURE SATURATED CONSOLIDATED
DYNAMIC UNDRAINED TRIAXIAL SHEAR.
SPECIMEN PI 5-8#76 40-50 cm

Figure 4.31 BACK PRESSURE SATURATED CONSOLIDATED
DYNAMIC UNDRAINED TRIAXIAL SHEAR.
SPECIMEN PI 5-8#86 40-50 cm

Figure 4.32 BACK PRESSURE SATURATED CONSOLIDATED
DYNAMIC UNDRAINED TRIAXIAL SHEAR.
SPECIMEN PI 5-8#70 40-50 cm

Figure 4.33 BACK PRESSURE SATURATED CONSOLIDATED DYNAMIC UNDRAINED TRIAXIAL SHEAR, SPECIMEN PI 5-8#77 40-50 cm

Figure 4.34 BACK PRESSURE SATURATED CONSOLIDATED STATIC UNDRAINED TRIAXIAL SHEAR

Figure 4.35 BACK PRESSURE SATURATED CONSOLIDATED
UNDRAINED TRIAXIAL SHEAR
PI 5-8 SPECIMENS

Figure 4.36 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED TRIAXIAL SHEAR

VOLUMETRIC STRAIN, percent
Figure 4.39 DRAINED HYDROSTAT
SPECIMEN PI 4.5-1A 43-53 cm

VOLUMETRIC STRAIN, percent
Figure 4.40 BACK PRESSURE SATURATED
DRAINED HYDROSTAT
SPECIMEN PI 5-8#88 40-50 cm

Figure 4.41 BACK PRESSURE SATURATED
DRAINED HYDROSTAT

Figure 4.42 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED HYDROSTAT
SPECIMEN PI 5-8#99 40-50 cm

Figure 4.43 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED HYDROSTAT
SPECIMEN PI 5-8#93 40-50 cm

Figure 4.44 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED HYDROSTAT
SPECIMEN PI 5-8#89 40-50 cm

PRINCIPAL STRAIN DIFFERENCE, percent
Figure 4.45 BACK PRESSURE SATURATED CONSOLIDATED
UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 5-8#89 40-50 cm

PRINCIPAL STRAIN DIFFERENCE, percent
Figure 4.46 BACK PRESSURE SATURATED CONSOLIDATED
UNDRAINED TRIAXIAL SHEAR
SPECIMEN PI 5-8#93 40-50 cm

Figure 4.47 BACK PRESSURE SATURATED CONSOLIDATED UNDRAINED STATIC TRIAXIAL SHEAR

Figure 4.48 BACK PRESSURE SATURATED CONSOLIDATED STATIC UNDRAINED UNIAXIAL STRAIN.

SPECIMEN MA-12 GC-19 S#2

Figure 4.49 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED UNIAXIAL STRAIN.
SPECIMEN MA-12 GC-19 S#2

Figure 4.50 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED UNIAXIAL STRAIN.
SPECIMEN MA-12 GC-19 S#3

Figure 4.51 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED UNIAXIAL STRAIN.
SPECIMEN MA-12 GC-19 S#3

Figure 4.52 DYNAMIC UNDRAINED UNIAXIAL
STRAIN
SPECIMEN MA-12 GC-19 S#4

Figure 4.53 DYNAMIC UNDRAINED UNIAXIAL STRAIN
SPECIMEN MA-12 GC-19 S#4

Figure 4.54 DYNAMIC UNDRAINED UNIAXIAL STRAIN
SPECIMEN MA-12 GC-19 S#5

Figure 4.55 DYNAMIC UNDRAINED UNIAXIAL
STRAIN
SPECIMEN MA-12 GC-19 S#5

Figure 4.56 DYNAMIC UNDRAINED UNIAXIAL
STRAIN
SPECIMEN MA-12 GC-19 S#6

Figure 4.57 DYNAMIC UNDRAINED UNIAXIAL STRAIN
SPECIMEN MA-12 GC-19 S#6

Figure 4.58 BACK PRESSURE SATURATED DRAINED UNIAXIAL STRAIN
SPECIMEN MA-12 GC-19 S#7

Figure 4.59 BACK PRESSURE SATURATED
DRAINED UNIAXIAL STRAIN
SPECIMEN MA-12 GC-19 S#7

Figure 4.60 BACK PRESSURE SATURATED
DRAINED UNIAXIAL STRAIN
SPECIMEN MA-12 GC-19 S#8

Figure 4.61 BACK PRESSURE SATURATED
DRAINED UNIAXIAL STRAIN
SPECIMEN MA-12 GC-19 S#8

Figure 4.62 BACK PRESSURE SATURATED
DRAINED UNIAXIAL STRAIN
SPECIMEN MA-12 GC-19 S#9

CHAPTER 5

RECOMMENDED MATERIAL PROPERTIES

One objective of the theoretical portion of SDP was to fit the effective-stress constitutive model (Part I, Chapter 3) to the available experimental data. The purpose of this fit was to demonstrate the general ability of the model to simulate the mechanical behavior of seabed sediments. The information required for such a fit includes (a) the hydrostatic response of the material under both fully drained and fully undrained conditions, (b) the shearing stress-strain-pore pressure behavior of the material under undrained conditions, and (c) a failure envelope in terms of effective stresses. It was originally assumed that these properties would be developed from a consistent set of data from one material at a given set of composition properties. However, three different materials were tested (tank No. 1 and No. 8 remolded specimens and undisturbed MA-12 GC-19 specimens). Each group had an insufficient number of specimens to perform the full suite of tests required. Thus one consistent set of property data did not exist. However, because the purpose of this exercise was to demonstrate the general capabilities of the model, all of the available data were considered to be descriptive of one unique material. Thus, composite properties were selected for this representative material as follows:

Wet density: 1.500 g/cc
Water content: 100%
Dry density: 0.750 g/cc
Specific gravity of solids: 2.70
Volume of air: 0%
Volume of water: 72.2%
Volume of solids: 27.8%

Figures 5.1 through 5.5 show the recommended mechanical properties for this material, which were selected primarily from static test data obtained from those specimens with densities and water contents close to the selected composition values. Figures 5.1 and 5.2 show the recommended low-pressure and high-pressure drained hydrostatic relations (loading and unloading), respectively, plotted as effective mean normal stress versus volumetric strain. The recommended undrained hydrostatic relation is shown in Figure 5.3. Three recommended undrained triaxial shear relations are shown in Figure 5.4 in terms of principal stress difference versus axial strain and pore pressure versus axial strain for three levels of initial effective mean normal stress. The effective-stress paths associated with these loadings, along with the recommended effective-stress failure envelope, are shown in Figure 5.5. The envelope was extrapolated back to intercept the principal stress difference axis at an assumed value of 0.007 MPa (there was no strength data below an effective mean normal stress of 0.01 MPa).

Figure 5.1 Recommended Low-Pressure Hydrostatic Relation for Drained Conditions.

Figure 5.2 Recommended High-Pressure Hydrostatic Relation for Drained Conditions.

Figure 5.3 Recommended Hydrostatic Relation for Undrained Conditions.

Figure 5.4 Recommended (Static) Undrained Shear Relations.

Figure 5.5 Recommended (Static) Effective Failure Relation

REFERENCES

1. Akers, S. A. and Silva, A. J.; "Stress-Strain and Strength Properties of Marine Sediments from the North Pacific"; Technical Report, 1980; University of Rhode Island.
2. Silva, A. J. and Calnan, D. I.; "Geotechnical Aspects of Subseabed Disposal of High Level Radioactive Wastes"; Annual Progress Report No. 6, January-December 1979, to DOE; 1980; University of Rhode Island.
3. Silva, A. J. and Calnan, D. I.; "Geotechnical Aspects of Subseabed Disposal of High Level Radioactive Wastes"; Annual Progress Report No. 5, January-December 1978, to DOE; 1979; University of Rhode Island.
4. Personal communications with Stephen Akers, 1980, University of Rhode Island.
5. Bishop, A. W. and Henkel, D. J.; The Measurement of Soil Properties in the Triaxial Test; 2nd Edition, 1962; London: Edward Arnold.
6. Ehrgott, J. Q. and Sloan, R. C.; "Development of a Dynamic High-Pressure Triaxial Test Device"; WES Technical Report S-71-15, 1971; U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS.
7. Ehrgott, J. Q.; "Calculation of Stress and Strain from Triaxial Test Data on Undrained Soil Specimens"; Miscellaneous Paper S-71-9, 1971; U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS.
8. Taylor, D. W.; Fundamentals of Soil Mechanics; 1948; John Wiley & Sons, Inc.; pp 238-241.
9. Noorany, I.; "Measurement of Engineering Properties of Submarine Soils"; ONR Symposium on the Physical and Engineering Properties of Deep-Sea Sediments, 24-27 April; Airlie, VA.

PART III: COMPARISONS OF LABORATORY TEST DATA WITH MODEL BEHAVIOR

BACKGROUND

A set of representative properties for Pacific illite was presented in Chapter 5 of Part II and consisted of pressure-volumetric strain relations for both drained and undrained hydrostatic test conditions and principal stress difference-axial strain relations, pore pressure-axial strain relations and effective-stress paths from undrained triaxial shear tests. These data are used in this part of the report (a) to obtain the numerical values of the material constants of the effective stress model presented in Chapter 3 of Part I and (b) to compare the test data with the corresponding behavior predicted by the resulting model.

The representative data are in terms of engineering strains as discussed in Chapter 3 of Part II. The data had to be converted to natural strains before attempting to fit the model. This conversion was necessary since the model is to be used in two-dimensional wave codes which are based on the natural rather than engineering definition of strain. In order to complete this conversion, a tensorial relationship was established between natural strain and engineering strain. This relationship is developed in the following section and was used to convert the representative properties to natural strain for model fitting and comparison of the data with model predictions.

RELATIONSHIP BETWEEN ENGINEERING STRAIN AND NATURAL STRAIN

The relationship between the strain rate tensor corresponding to natural strains and the particle velocity gradients at a point is

$$\frac{d\epsilon_{ij}^n}{dt} = \frac{1}{2} \left(\frac{\partial v_i}{\partial \bar{x}_j} + \frac{\partial v_j}{\partial \bar{x}_i} \right) \quad (1)$$

where $\frac{d\epsilon_{ij}^n}{dt}$ = strain rate tensor

ϵ_{ij}^n = natural strain tensor

v_i = particle velocity in the i th direction

$\bar{x}_i$ = local coordinate system

Applying the chain rule of differentiation to the right-hand side of Equation 1, we obtain

$$\frac{d\epsilon_{ij}^n}{dt} = \frac{1}{2} \left(\frac{\partial v_i}{\partial x_m} \frac{\partial x_m}{\partial \bar{x}_j} + \frac{\partial v_j}{\partial x_m} \frac{\partial x_m}{\partial \bar{x}_i} \right) \quad (2)$$

where x_m = reference coordinate system; but

$$\frac{\partial \bar{x}_j}{\partial x_m} = \text{coordinate gradient matrix} = \delta_{jm} - \frac{\partial u_j}{\partial x_m} \quad (3)$$

where $\frac{\partial u_j}{\partial x_m}$ = displacement gradient matrix = $\epsilon_{jm}^e + R_{jm}$

ϵ_{jm}^e = Cauchy (engineering) strain tensor

R_{jm} = rotation tensor

Substitution of Equation 3 into Equation 2 yields

$$\frac{d\epsilon_{ij}^n}{dt} = \frac{1}{2} \left(\frac{\frac{\partial v_i}{\partial x_m}}{\delta_{mj} - \frac{\partial u_j}{\partial x_m}} + \frac{\frac{\partial v_j}{\partial x_m}}{\delta_{mi} - \frac{\partial u_i}{\partial x_m}} \right) \quad (4)$$

For the special situation in which one only deals with principal axes as in the case for this entire report, Equation 4 can be written as

$$\frac{d\epsilon_{ij}^n}{dt} = \frac{1}{2} \left(\frac{\frac{\partial v_i}{\partial x_m}}{\delta_{mj} - \epsilon_{jm}^e} + \frac{\frac{\partial v_j}{\partial x_m}}{\delta_{mi} - \epsilon_{im}^e} \right) \quad (5)$$

We now proceed to use Equation 5 to relate the components of the natural strain tensor with the corresponding components of engineering strain.

For the hydrostatic state of strain Equation 5 results in

$$d\epsilon_{kk}^n = \frac{3 d\epsilon_{kk}^e}{3 - \epsilon_{kk}^e} \quad (6)$$

For the uniaxial state of strain, Equation 5 reduces to

$$d\epsilon_{11}^n = \frac{d\epsilon_{11}^e}{1 - \epsilon_{11}^e} \quad (7)$$

For the triaxial shear test, Equation 5 results in the following expression for the axial strain ϵ_{11} and lateral strain ϵ_{33} (with $\epsilon_{22} = \epsilon_{33}$)

$$d\epsilon_{11}^n = \frac{d\epsilon_{11}^e}{1 - \epsilon_{11}^e} \quad (8)$$

$$d\epsilon_{33}^n = d\epsilon_{22}^n = \frac{d\epsilon_{33}^e}{1 - \epsilon_{33}^e} \quad (9)$$

Equations 6 through 9 were used to convert the engineering strains associated with the representative sediment properties from Part II to natural strains.

MATERIAL CONSTANTS

The effective-stress model described in Chapter 3 of Part I contains 14 material constants. The numerical values of these constants must be determined experimentally by fitting the model to laboratory test results. Eleven of the material constants are associated with drained behavior and three are associated with the undrained (hydrostatic only) behavior of the material. Using the computer program SANDR (Addendum A), the numerical values of the material constants were determined by fitting the model to the representative properties (in terms of natural strains). The numerical values of these constants are summarized in Table 1. The subscript *s* in Table 1 is assigned to material constants associated with the drained behavior of the model and the subscript *m* is assigned to those constants associated with the undrained behavior.

COMPARISON OF TEST RESULTS WITH MODEL BEHAVIOR

Figures 1 through 5 compare the representative properties with the corresponding model fits. Figures 1 and 2 compare the fits to the isotropic consolidation test data up to stress levels of 1.0 and 60 MPa, respectively. These figures indicate that the proposed model cannot quantitatively fit both the low- and high-pressure responses of the material under drained hydrostatic states of stress. In order to have a better quality fit, the bulk modulus (Equation 3.3, Part I) would have to be expressed in terms of the plastic volumetric strain which would increase the number of constants in the hardening function (Equation 3.9, Part I).

Effective stress path fits for consolidated-undrained triaxial shear tests at various confining pressure levels are compared with the data in Figure 3. It should be noted that the representative failure envelope is a curve while the model failure envelope is a straight line. This is due to the fact that Equation 3.7 of Part I is a linear equation in terms of J_1' . In order to obtain a nonlinear failure envelope, Equation 3.7 has to be made nonlinear in terms of J_1' .

Principal stress difference versus axial strain fits and pore pressure versus axial strain fits associated with the effective-stress paths of Figure 3 are compared with the data in Figure 4. Figure 4 clearly shows that the initial stiffness of the principal stress difference-axial strain curves is independent of confining pressure. In order to make this stiffness a function of confining pressure, the shear modulus (Equation 3.5, Part I) can be

made a function of plastic volumetric strain. Figure 4 also shows that pore pressures at the lower stress levels are lower for the higher confining pressure tests which is in contrast to the representative data. In order to change this behavior in the model, the parameter R (Part I) can be made a function of L .

Figure 5 compares the undrained hydrostat with the model behavior.

Figures 1 through 4 clearly show that the present version of the effective-stress constitutive model qualitatively simulates the various observed stress-strain and pore pressure response features of the seabed sediment, but there is also much room for improvement.

Table 1. Numerical values of material constants for drained and undrained behavior of Pacific illite

Material Constants			
Name	Notation , Units		Numerical Values
Density	ρ	, g/cc	1.5
Effective Failure Envelope Parameters	C_s	, MPa	0.00866
	α_s	, ---	0.133336
Hardening Surface Parameters	R_s	, ---	4.00
	W_s	, ---	0.42
	D_s	, (MPa) ⁻¹	1.20
Effective Bulk Modulus Parameters	K_{is}	, MPa	20.00
	K_{1s}	, ---	0.999
	K_{2s}	, (MPa) ⁻¹	0.0002
Total Bulk Modulus Parameters	K_{im}	, MPa	1875.00
	K_{1m}	, ---	0.35
	K_{2m}	, (MPa) ⁻¹	0.05
Shear Modulus Parameters	G_{is}	, MPa	0.60
	G_{1s}	, ---	-1.00
	G_{2s}	, (MPa) ⁻¹	200.00

Figure 1. Isotropic consolidation response; representative properties versus model fit.

Figure 2. Isotropic consolidation response; representative properties versus model fit.

Figure 3. Effective stress paths for consolidated-undrained triaxial test; representative properties versus model fit.

Figure 4. Principal stress difference and pore pressure versus axial strain for consolidated-undrained triaxial test; representative properties versus model fit.

Figure 5. Isotropic compression response; representative properties versus model fit.

PART IV: SUMMARY AND RECOMMENDATIONS

THEORETICAL PROGRAM

The FY 80 accomplishments of the theoretical program are summarized below:

- a. An elastic-plastic effective-stress constitutive model was developed for saturated marine sediments. The constitutive model includes 14 material constants which must be determined experimentally.
- b. The model was implemented into a numerical algorithm.
- c. A computer driver was developed and was coupled with the numerical algorithm of the model for simulating the behavior of the constitutive model under a variety of laboratory test boundary conditions.
- d. Using this computer program and the available experimental data, numerical values of the material constants in the constitutive model were determined for Pacific illite. Comparisons of model behavior with the corresponding experimental data indicate that the model (in its present form) is capable of reasonable (qualitative and quantitative) replication of the various observed stress-strain-pore pressure responses of the material.
- e. With assistance from SNL personnel, the model was successfully incorporated into SNL two-dimensional wave codes for dynamic penetration calculations of waste canister and hole closure simulations.

Comparisons of representative laboratory material property test data with corresponding model predictions (Figures 1 through 5, Part III) indicate that the present model cannot quantitatively fit all salient features of the mechanical response of the material. There are several features of the model that can be improved in order to more accurately simulate the overall behavior of the material. However, before major modifications of the model are undertaken, it is important to know which aspects of the mechanical behavior of seabed sediments significantly affect the mechanisms of dynamic penetration and hole closure. This can be ascertained through parametric calculations of penetration and hole closure phenomena using the present model with an appropriate wave code. Several first-order modifications of the model, however, are recommended purely for the purpose of obtaining a better fit to the available test data:

- a. The bulk modulus (Equation 3.3, Part I) should be expressed in terms of the plastic volumetric strain ϵ_{kk}^p as well as J_1 .
- b. A different hardening function (Equation 3.9, Part I) with a larger number of material constants should be chosen.
- c. The failure envelope (Equation 3.7, Part I) should be expressed as a nonlinear function of J_1 (as opposed to the present linear form).
- d. The shear modulus (Equation 3.5, Part I) should be expressed in terms of the plastic volumetric strain as well as $\sqrt{J_2}$.

- e. The parameter R should be a function of stress level through the parameter κ (Equation 3.11, Part I) rather than as a constant.

EXPERIMENTAL PROGRAM

The three major tasks outlined for the FY 80 experimental program in Section 1.1, Part II, were accomplished. The conclusions presented below address each of these tasks in sequence.

The static and dynamic low-pressure (LPTX) shear tests showed that an increase in strain rate from 10^{-6} /second to 1/second produced an increase in strength between 67 and 145 percent. More confidence, however, is given to the value of 67 percent due to the better quality specimens tested. For specimens consolidated to the same initial effective-stress state, the strength at failure was found to be independent of total confining pressure for the range of pressures investigated. This observation was true for both the static and dynamic LPTX shear tests. Finally, in comparing the WES LPTX data to URI's static triaxial test data on Pacific illite, the WES Mohr-Coulomb friction angle was found to be 4.1 degrees lower (i.e., 20.5 versus 24.6 degrees). The lower friction angle was attributable to the poor quality of the tank No. 1 test specimens furnished to WES, which contained numerous cavities. Qualitatively, the normalized URI stress-strain curves exhibited, a somewhat stiffer response than the WES specimens (15 percent) during initial loading, which is consistent with the higher friction angle of the URI data. In all, the WES/URI comparisons are considered reasonable.

High-pressure uniaxial strain data were obtained for both drained and undrained static loadings and undrained dynamic loadings. Two static undrained tests to 60 MPa produced saturated constrained modulus values of 2425 and 2554 MPa. Due to equipment limitations the three dynamic tests conducted could not be consolidated prior to live loading. This may have been a factor in the unexpected finding that dynamic constrained moduli decreased with decreasing rise time. Equipment modifications have since been made to the test device and additional dynamic tests will be conducted in the FY 81 experimental program. Drained static uniaxial strain data were obtained for three specimens; volumetric strains as great as 70 percent were measured at 67 MPa. Significant differences were noted in these tests between volumetric strains inferred from burette measurements and volumetric strains determined from axial deformation measurements. Further improvements to both measurement systems appear warranted and will be pursued in FY 81.

Serious problems were encountered in attempting to conduct static high-pressure triaxial shear tests. Eight of the ten tests attempted had to be terminated prior to the completion of the shear portion of the test. Long test durations and the extreme volumetric strains that occurred were contributing factors to the major problem of membrane leakage. Test procedures will be thoroughly reviewed before FY 81 experimental work is commenced in an attempt to improve this success-to-failure ratio. Only two shear tests were successfully completed; however, five good hydrostats were obtained from this test series. Pore pressure measurements in the HPTX tests were not of sufficient resolution to accurately define the effective-stress response of the material undergoing shear at high pressures, i.e., pore pressure changes during shear were within the noise level of the pore pressure transducer

(e.g., it is difficult to detect a change in pore pressure of 0.005 MPa when the ambient pore pressure is 50 MPa).

No drained shear tests were conducted in the FY 80 program.

ADDENDUM A

The following is a complete list of a computer program called "SANDR" which can be used for simulating the behavior of the effective-stress constitutive model under triaxial compression test boundary conditions. Both the hydrostatic and shear portions of the triaxial test can be exercised. Throughout this program compression is considered negative, which is contrary to the sign convention used in the main text. The reason for switching the sign convention in SANDR was the desire to make it compatible with the Sandia wave codes.

The program SANDR consists of a driver and a model algorithm.

```

C      COMPUTER PROGRAM SANDR, SUBSEAED DISPOSAL PROGRAM
C      -----
C
C      SANDR IS A PROGRAM FOR SIMULATING THE BEHAVIOR OF MATERIALS
C      UNDER GENERAL TEST BOUNDARY CONDITIONS
C
C      DIMENSION SDIFF(500),EDIFF(500),EZZ(500),EKK(500),PRESS(500),
C      &      TPRESS(500),UPRESS(500),VSTRES(500),RATIO(500),
C      &      TITLE(12),TVSTR(500)
C      INTEGER STATE
C      CHARACTER XINPUT*8,OUTPUT*8,SYMBOL*1/1HY/,ANSER*1/1HY/
C      COMMON/STRESS/ SIGR,SIGT,SIGZ,SIGRZ,P,S(3),EF
C      COMMON/STRAIN/ EPSR,EPST,EPSTZ,EPSTRZ,EPSTRZ,E(3)
C      COMMON/STRINC/ DEPSR,DEPST,DEPSZ,DEPSRZ
C      COMMON/DUMMY/  MTYPE,LTYPE,TCUT,FCUT,JT,NDCON,STATE,ISTOR(10)
C      COMMON/PROPER/ AKI,AKI,AK2,AKIM,AKIM,AK2M,AGI,AG1,AG2,AG3,AG4,
C      &      AC,AM,ARI,ARI,AR2,AM,AD,AKH,AKHM
C      COMMON/PREPRO/ XL,EL,CAP,GR,GRP,IUSE,IUNHY
C      COMMON/NUMBER/ QGAMMA,QDELTA,CONS,VV,VH,KOUNT,IDUX,IUUX
C      CALL FXOPT(89,1,1,0)
C
C      OPEN FILES
C
C      PRINT,"WHAT IS THE INPUT DATA FILE"
C      READ,XINPUT
C      ENCODE(XINPUT,305)
C      PRINT,"IF YOU WANT TABLES IBOB SHOULD BE ZERO"
C      READ,IBOB
C      CALL ATTACH(1,XINPUT,3,0,ISTAT,0)
C
C      INPUT PARAMETERS
C
C      READ(1,900) TITLE
C      READ(1,813) LIN,AKI,AKI,AK2,AKIM,AKIM,AK2M,AGI,AG1,AG2,AG3,AG4
C      READ(1,813) LIN,AC,AM,ARI,ARI,AR2
C      READ(1,813) LIN,AM,AD,SA,VST,GP,GRP
C      READ(1,813) LIN,VV,VH,NSTEPS,QALPHA,ISKIP,CONS,STATE
C      813 FORMAT(V)
C
C      COMPUTE CONSTANTS FROM QALPHA (PATH SLOPE)
C
C      IF(QALPHA.LT.3.0) GO TO 60
C      IF(QALPHA.GT.100.0) GO TO 61
C      QGAMMA = 1./3. - 1./QALPHA
C      QDELTA = 2./3. + 1./QALPHA
C      GO TO 62
C 60 QGAMMA = 1.
C      QDELTA = 0.

```

```

GO TO 62
61 QGAMMA = 1./3.
QDELTA = 2./3.
62 CONTINUE

```

```

C      INITIAL POSITION OF CAP
C
C      X = (AC*ARI-3.0*GRP)/(1.0+AM*ARI)
C 53 ASTART = X
C      PRINT,"DO YOU WANT THE CAP-YES OR NO?"
C      READ,ANSER
C      IF(ANSER.NE.SYMBOL) READ,ASTART
C 55 PRINT,"ASTART = ",ASTART
C      CAP = ASTART
C
C      HYDRO PORTION
C
C      P = GR
C      AKH = EXP(-3.*AK2*GRP)
C      AKHM = EXP(-3.*AK2M*GRP)
C      EP = GRP
C      NDCOUNT = 1
C      IDUX = 0
C      IUUX = 0
C      E(1) = CAP
C      EKK(1) = 0.0
C      PRESS(1) = EP
C      TPRESS(1) = P
C      UPRESS(1) = P - EP
C      VSTRES(1) = GRP
C      TVSTR(1) = GR
C      SIGR = GRP
C      SIGT = GRP
C      SIGZ = GRP
C      SIGRZ = 0.0
C      EPSR = 0.0
C      EPST = 0.0
C      EPSZ = 0.0
C      EPSTRZ = 0.0
C      DX = VV
C      E(2) = 0.0
C      E(3) = 0.0
C      S(1) = 0.0
C      S(2) = 0.0
C      S(3) = 0.0
C      ESAVE = E(1)
C      PSAVE = GR
C      EPSAVE = GRP
C      DEPSR = VV
C      DEPSZ = VV
C      DEPST = VV
C      DEPSRZ = 0.0
C      X = DX
C      XSAVE = 0.0

```

```

IUNHY = 0
PRINT, "DO YOU WANT UNDRAINED HYDRO TEST, YES OR NO?"
READ, ANSWER
IF (ANSWER.EQ.SYMBOL) IUNHY = 1
24 CONTINUE
NCOUNT = 1
DO 2 M = 1, 499
CALL MODEL
IF (IUNHY.EQ.1) CALL TMODEL
IF (IUNHY.EQ.0) P = EP
IF (VV.LT.0.0) GO TO 58
IF (CONS-P) 3,5,7
58 CONTINUE
IF (P-CONS) 3,5,7
7 IF (ABS(P-CONS)-2.E-04) 4,4,6
6 DX = DX/2.0
X = XSAVE
DEPSR = DX
DEPSZ = DX
DEPST = DX
E(1) = ESAVE
P = PSAVE
EP = EPSAVE
GO TO 2
3 ESAVE = E(1)
NCOUNT = NCOUNT + 1
PRESS(NCOUNT) = EP
TPRESS(NCOUNT) = P
UPRESS(NCOUNT) = P - EP
VSTRES(NCOUNT) = -SIGZ
TVSTR(NCOUNT) = -SIGZ + P - EP
EKK(NCOUNT) = -3.0*X*100.
PSAVE = P
EPSAVE = EP
XSAVE = X
2 X = X + DX
4 E(1) = ESAVE
5 CONTINUE
X = XSAVE
EPSKKH = 3.0*X
EKK(NCOUNT) = -3.0*X*100.
PRESS(NCOUNT) = EP
TPRESS(NCOUNT) = P
UPRESS(NCOUNT) = P - EP
VSTRES(NCOUNT) = -SIGZ
TVSTR(NCOUNT) = -SIGZ + P - EP
PRINT,
PRINT, "CAP AT THE END OF HYDRO PHASE = ", E(1)
EZ0 = X
EPSZ = X
EPSR = X
EPST = X
PRINT 700, PSAVE, EPSAVE, CONS, 100.*X
12 CONTINUE

```

```

PRINT, "P VS EKK"
READ, ANSWER
IF (ANSWER.EQ.SYMBOL) CALL PLOT2(EKK,TPRESS,NCOUNT)
PRINT, "EP VS EKK"
READ, ANSWER
IF (ANSWER.EQ.SYMBOL) CALL PLOT2(EKK,PRESS,NCOUNT)
PRINT, "DO YOU WANT A REPLOT ? (YES OR NO)"
READ, ANSWER
IF (ANSWER.EQ.SYMBOL) GO TO 12
PRINT, "DO YOU WANT UNLOADING/RELOADING HYDRO TEST-YES OR NO?"
READ, ANSWER
IF (ANSWER.NE.SYMBOL) GO TO 23
PRINT, "READ CONS, VV, VH"
READ, CONS, VV, VH
DX = VV
X = X+DX
TPRESS(1) = P
EKK(1) = -3.*X*100.
PRESS(1) = EP
UPRESS(1) = P-EP
VSTRES(1) = -SIGZ
TVSTR(1) = -SIGZ + P - EP
DO 54 JK=2, NCOUNT
EKK(JK) = 0.0
TPRESS(JK) = 0.0
UPRESS(JK) = 0.0
VSTRES(JK) = 0.0
TVSTR(JK) = 0.0
54 PRESS(JK) = 0.0
NCOUNT = 1
DEPSR = VV
DEPSZ = VV
DEPST = VV
DEPSRZ = 0.0
ESAVE = E(1)
PSAVE = P
EPSAVE = EP
XSAVE = X
GO TO 24
23 CONTINUE
PRINT, "DO YOU WANT TRIAXIAL TEST-YES OR NO?"
READ, ANSWER
IF (ANSWER.NE.SYMBOL) GO TO 22
C INITIALIZE VALUES FOR TRIAX
PRINT, "READ VV, VH"
READ, VV, VH
IUSE = 0
PRINT, "DO YOU WANT UNDRAINED SHEAR PHASE - YES OR NO?"
READ, ANSWER
IF (ANSWER.NE.SYMBOL) GO TO 21
IUSE = 1
21 CONTINUE

```

```

IF(IUNHY.EQ.0 .AND. IUSE.EQ.1) P = EP+GR-GRP
IF(IUNHY.EQ.0 .AND. IUSE.EQ.1) CONS = CONS+GR-GRP
EDIFF(1) = 0.0
SDIFF(1) = 0.0
EZZ(1) = 0.0
EKK(1) = 0.0
TPRESS(1) = P
PRESS(1) = EP
UPRESS(1) = P-EP
VSTRESS(1) = -SIGZ
TVSTR(1) = -SIGZ + P - EP
DO 57 KI=2,NCOUNT
EKK(KI) = 0.0
PRESS(KI) = 0.0
TPRESS(KI) = 0.0
UPRESS(KI) = 0.0
VSTRESS(KI) = 0.0
TVSTR(KI) = 0.0
57 CONTINUE
IPLOT = 1
KOUNT = 0
IKOUNT = KOUNT
VH1 = VH
NUNLD = 0
PRINT,"DO YOU WANT DRAINED UNIAXIAL STRAIN TEST, YES OR NO?"
READ,ANSER
IF(ANSER.EQ.SYMBOL) IDUX = 1
PRINT,"DO YOU WANT UNDRAINED UNIAXIAL STRAIN TEST, YES OR NO?"
READ,ANSER
IF(ANSER.EQ.SYMBOL) IUUX = 1
IF(IDUX.NE.1.AND.IUUX.NE.1) GO TO 26
PRINT,"READ VH"
READ,VH
26 CONTINUE
IDUPUU = IDUX+IUUX
PRINT,"VH(INITIAL) = ",VH
PRINT,"VV(INITIAL) = ",VV
IF(IBOB.NE.0) GO TO 420
PRINT 301
PRINT 300,SDIFF(1),EDIFF(1),PRESS(1),TPRESS(1),EKK(1)

```

C TRIAX PHASE

```

420 CALL VELHOR(NUNLD)
430 IF(KOUNT.GE.NSTEPS) GO TO 431
KOUNT = KOUNT + 1
IKOUNT = IKOUNT + 1
DIFF = -(SIGZ - SIGR)
VESTR = -SIGZ + P - EP
EPSZ = EPSZ + DEPSZ
EPSR = EPSR + DEPSR
EPST = EPST + DEPST
EPSDIF = -(EPSZ-EZ0)*100.
IF(IKOUNT/ISKIP.NE.IPLOT) GO TO 400

```

```

IPLOT = IPLOT + 1
SDIFF(IPLOT) = DIFF
EDIFF(IPLOT) = -(EPSZ - EPSR)*100.
EZZ(IPLOT) = -(EPSZ - EZ0)*100.
EKK(IPLOT) = -(EPSZ+EPST+EPSR-3.0*EZ0)*100.
TPRESS(IPLOT) = P
PRESS(IPLOT) = EP
UPRESS(IPLOT) = P-EP
VSTRESS(IPLOT) = -SIGZ
TVSTR(IPLOT) = -SIGZ + P - EP
RATIO(IPLOT) = 0.0
IF(ABS(SIGR).GT.0.0) RATIO(IPLOT) = SIGZ/SIGR
IF(IBOB.EQ.0)
&PRINT 300,SDIFF(IPLOT),EDIFF(IPLOT),PRESS(IPLOT),
&TPRESS(IPLOT),EKK(IPLOT)
400 CONTINUE
IF(NUNLD.EQ.1) GO TO 550
IF(IDUPUU.GE.1.AND.VESTR.LT.VST) GO TO 420
IF(IDUPUU.EQ.0.AND.EPSDIF.LT.SA) GO TO 420
GO TO 500
550 CONTINUE
IF(IDUPUU.EQ.0.AND.DIFF.GT.SA) GO TO 420
IF(IDUPUU.GE.1.AND.VESTR.GT.VST) GO TO 420
500 PRINT,SDIFF(IPLOT),EDIFF(IPLOT),PRESS(IPLOT),TPRESS(IPLOT),
&EKK(IPLOT)
PRINT,"KOUNT = ",KOUNT
PRINT,"NUNLD,SA,VST,ISKIP,VV,VH"
PRINT,"NUNLD = 1 FOR UNLOADING"
PRINT,"NUNLD = 0 FOR LOADING"
PRINT,"NUNLD = 9999 TO TERMINATE"
READ,NUNLD,SA,VST,ISKIP,VV,VH
IF(NUNLD.EQ.9999) GO TO 431
IF(NUNLD.EQ.0) VH = VH1
IKOUNT = (IPLOT-1)*ISKIP
GO TO 420
431 CONTINUE
22 CONTINUE
PRINT 301
PRINT 300,SDIFF(IPLOT),EDIFF(IPLOT),PRESS(IPLOT),TPRESS(IPLOT),
&EKK(IPLOT)
4001 CONTINUE
PRINT,"TOTAL STRESS PATH"
READ,ANSER
IF(ANSER.EQ.SYMBOL) CALL PLOT2(TPRESS,SDIFF,IPLOT)
PRINT,"EFFECTIVE STRESS PATH"
READ,ANSER
IF(ANSER.EQ.SYMBOL) CALL PLOT2(PRESS,SDIFF,IPLOT)
PRINT,"STRESS DIFF VS AXIAL STRAIN"
READ,ANSER
IF(ANSER.EQ.SYMBOL) CALL PLOT2(EZZ,SDIFF,IPLOT)
PRINT,"STRESS DIFF VS STRAIN DIFF"
READ,ANSER
IF(ANSER.EQ.SYMBOL) CALL PLOT2(EDIFF,SDIFF,IPLOT)
IF(IDUX.EQ.1.OR.IUUX.EQ.1) GO TO 15

```

```

PRINT,"P VS. EKK"
READ,ANSER
IF (ANSER.EQ.SYMBOL) CALL PLOT2(PRESS,EKK,IPLOT)
PRINT,"EKK VS. STRAIN DIFF"
READ,ANSER
IF (ANSER.EQ.SYMBOL) CALL PLOT2(EDIFF,EKK,IPLOT)
PRINT,"AXIAL STRAIN VS. EKK"
READ,ANSER
IF (ANSER.EQ.SYMBOL) CALL PLOT2(EZZ,EKK,IPLOT)
PRINT,"PORE PRESSURE VS AXIAL STRAIN"
READ,ANSER
IF (ANSER.EQ.SYMBOL) CALL PLOT2(EZZ,UPRESS,IPLOT)
PRINT,"STRESS RATIO VS AXIAL STRAIN"
READ,ANSER
IF (ANSER.EQ.SYMBOL) CALL PLOT2(EZZ,RATIO,IPLOT)
GO TO 17
15 CONTINUE
PRINT,"EFFECTIVE AXIAL STRESS VS AXIAL STRAIN"
READ,ANSER
IF (ANSER.EQ.SYMBOL) CALL PLOT2(EZZ,VSTRES,IPLOT)
PRINT,"TOTAL AXIAL STRESS VS AXIAL STRAIN"
READ,ANSER
IF (ANSER.EQ.SYMBOL) CALL PLOT2(EZZ,TVSTR,IPLOT)
PRINT,"PORE PRESSURE VS AXIAL STRAIN"
READ,ANSER
IF (ANSER.EQ.SYMBOL) CALL PLOT2(EZZ,UPRESS,IPLOT)
17 CONTINUE
PRINT,"DO YOU WANT REPLOTS-IF YES,TYPE YES"
READ,ANSER
IF (ANSER.EQ.SYMBOL) GO TO 4001
CALL DETACH(1,,)
STOP

```

C FORMATS

```

301 FORMAT(///5X,11HSIGZ - SIGR,5X,11HEPSZ - EPSR,
      &5X,4HPRES,5X,5HTPRES,11X,3HEKK, /8X,5H(MPA),9X,10H(PERCENT ),
      &5X,5H(MPA),6X,5H(MPA),8X,10H(PERCENT ),/)
300 FORMAT(F13.6,F17.6,F14.6,2F13.6,F12.6)
305 FORMAT(T8,";")
100 FORMAT(3F10.1)
700 FORMAT(// "PSAVE = ",E12.5," MPA",/"EPSAVE = ",E12.5," MPA",/
      &"CONS = ",E12.5," MPA"/"EKK/3(HYDRD) = ",E14.7," PERCENT"//)
900 FORMAT(3X,12A4)
END

```

C VELHOR

```

SUBROUTINE VELHOR(NUNLD)
COMMON/STRESS/ SIGR,SIGT,SIGZ,SIGRZ,P,S(3),EP
COMMON/STRAIN/ EPSR,EPST,EPSZ,EPSRZ,EPSKK,E(3)
COMMON/STRINC/ DEPSR,DEPST,DEPSZ,DEPSRZ
COMMON/DUMMY/ MTYPE,LTYPE,TCUT,FCUT,JT,NDCON,STATE,ISTOR(10)
COMMON/PROPER/ AK1,AK1,AK2,AKIM,AK1M,AK2M,AG1,AG1,AG2,AG3,AG4,

```

```

& AC,AM,ARI,AR1,AR2,AM,AD,AKH,AKHM
COMMON/PREPRO/ XL,EL,CAP,GP,GRP,IUSE,IUNHY
COMMON/NUMB/ QGAMMA,QDELTA,CONS,VV,VH,KOUNT,IDUX,IUUX
DATA ERROR/0.0002/
ICOUNT = 0
PA = P
EPA = EP
SA = S(1)
SB = S(2)
SC = S(3)
ESAVE = E(1)
BTrial = VH
CALL STR(NUNLD)
CALL MODEL
IF (IUSE.EQ.1) CALL TMODEL
IF (IUSE.EQ.0) P = EP
IF (IDUX.EQ.1.OF.IUUX.EQ.1) GO TO 20
SIGRR = P - S(1)
SIGZZ = P + S(1) + S(2)
TEST = SIGZZ*QGAMMA + SIGRR*QDELTA - CONS
IF (ABS(TEST).LT.ERROR) GO TO 20
TSAVE = TEST
IF (TEST) 10,20,30
10 IF (BTrial) 50,40,40
30 IF (BTrial) 40,50,50
40 DB = -BTrial/2.0
GO TO 60
50 DB = BTrial
60 BT = BTrial + DB
65 VH = BT
P = PA
EP = EPA
S(1) = SA
S(2) = SB
S(3) = SC
E(1) = ESAVE
CALL STR(NUNLD)
CALL MODEL
IF (IUSE.EQ.1) CALL TMODEL
IF (IUSE.EQ.0) P = EP
ICOUNT = ICOUNT + 1
SIGRR = P - S(1)
SIGZZ = P + S(1) + S(2)
TEST = SIGZZ*QGAMMA + SIGRR*QDELTA - CONS
IF (ICOUNT.GT.500) GO TO 21
IF (ABS(TEST).LT.ERROR) GO TO 20
BTrial = BT
BT = BT - TEST*DB/(TEST-TSAVE)
DB = BT - BTrial
TSAVE = TEST
GO TO 65
20 CONTINUE
RETURN
21 PRINT,"DID NOT CONVERGE"

```

```

PRINT, "KOUNT = ", KOUNT
25 CONTINUE
RETURN
END

```

STRAIN

```

SUBROUTINE STR(NUNLD)
COMMON/STRESS/ SIGR, SIGT, SIGZ, SIGRZ, P, S(3), EP
COMMON/STRAIN/ EPSR, EPST, EPSZ, EPSRZ, EPSKK, E(3)
COMMON/STRINC/ DEPSR, DEPST, DEPSZ, DEPSRZ
COMMON/DUMMY/ MTYPE, LTYPE, TCUT, FCUT, JT, NOCON, STATE, ISTD(10)
COMMON/PROPER/ AK1, AK1, AK2, AK1M, AK1M, AK2M, AG1, AG1, AG2, AG3, AG4,
& AC, AM, ARI, AR1, AR2, AW, AD, AKH, AKHM
COMMON/PREPRO/ XL, EL, CAP, GR, GRP, IUSE, IUNHY
COMMON/NUMBR/ QGAMMA, QDELTA, CONS, VV, VH, KOUNT, IDUX, IUUX
DEPSR = VH
DEPST = DEPSR
DEPSZ = VV
DEPSRZ = 0.0
IF (NUNLD.EQ.0) RETURN
DEPSR = -DEPSR
DEPSZ = -DEPSZ
DEPST = -DEPST
RETURN
END

```

MODEL

```

SUBROUTINE MODEL
INTEGER STATE
COMMON/STRESS/ SIGR, SIGT, SIGZ, SIGRZ, P, S(3), EP
COMMON/STRAIN/ EPSR, EPST, EPSZ, EPSRZ, EPSKK, E(3)
COMMON/STRINC/ DEPSR, DEPST, DEPSZ, DEPSRZ
COMMON/DUMMY/ MTYPE, LTYPE, TCUT, FCUT, JT, NOCON, STATE, ISTD(10)
COMMON/PROPER/ AK1, AK1, AK2, AK1M, AK1M, AK2M, AG1, AG1, AG2, AG3, AG4,
& AC, AM, ARI, AR1, AR2, AW, AD, AKH, AKHM
COMMON/PREPRO/ XL, EL, CAP, GR, GRP, IUSE, IUNHY
COMMON/NUMBR/ QGAMMA, QDELTA, CONS, VV, VH, KOUNT, IDUX, IUUX

LTYPE = 1
LAYER = 1
IF (LAYER.GE.STATE) LTYPE = 2
TCUT = 0.0
SIGR = S(1) - EP
SIGT = S(2) - EP
SIGZ = -(SIGR + SIGT) - 3.*EP
SIGRZ = S(3)
EL = E(1)
CALL MATLAW
EP = -(SIGR+SIGT+SIGZ)/3.0
S(1) = SIGR + EP
S(2) = SIGT + EP
S(3) = SIGRZ

```

```

E(1) = E L
RETURN
END

```

MATLAW

```

SUBROUTINE MATLAW
INTEGER STATE
COMMON/STRESS/ SIGR, SIGT, SIGZ, SIGRZ, P, S(3), EP
COMMON/STRAIN/ EPSR, EPST, EPSZ, EPSRZ, EPSKK, E(3)
COMMON/STRINC/ DEPSR, DEPST, DEPSZ, DEPSRZ
COMMON/DUMMY/ MTYPE, LTYPE, TCUT, FCUT, JT, NOCON, STATE, ISTD(10)
COMMON/PROPER/ AK1, AK1, AK2, AK1M, AK1M, AK2M, AG1, AG1, AG2, AG3, AG4,
& AC, AM, ARI, AR1, AR2, AW, AD, AKH, AKHM
COMMON/PREPRO/ XL, EL, CAP, GR, GRP, IUSE, IUNHY
COMMON/NUMBR/ QGAMMA, QDELTA, CONS, VV, VH, KOUNT, IDUX, IUUX

```

```
DATA CONVNIT/0.00001,60/
```

C FAILURE ENVELOPE FUNCTION FOR SJ2

```
F(SJ1) = -AM*SJ1 + AC
```

C HARDENING STATEMENT FUNCTIONS

```

BIGL(EL) = AMIN1(0.,EL)
R(CAPL) = ARI
X(EL) = EL - R(BIGL(EL))*F(EL)
EVP(XL) = AM*(EXP(AD*XL+3.*AD*GRP)-1.0)
SJ2C(SJ1,XL,CAPL)=SQRT(ABS((XL-CAPL)**2-(SJ1-CAPL)**2))
& /R(CAPL)

```

C ELASTIC MODULI FUNCTIONS

```

BMOD(SJ1,EVPL) = AK1*(1.-AK1*AKH*EXP(AK2*(SJ1+3.*GRP)))/
& (1.-AK1*AKH)
SMOD(SJ2,EVPL) = AG1*(1.-AG1*EXP(-AG2*SJ2))/(1.-AG1)

IT = 0
NOCON = 0
DEV = DEPSR + DEPST + DEPSZ
DEVB3 = DEV/3.0
DERR = DEPSR - DEVB3
DETT = DEPST - DEVB3
PRESS = -(SIGR + SIGT + SIGZ)/3.0
SRR = SIGR + PRESS
STT = SIGT + PRESS
SJ1I = -3.*PRESS
SJ2I = SQRT(SRR*SRR+STT*STT+SRR*STT+SRZ*SRZ)
CAPL = BIGL(EL)
XL = X(EL)
EVPI = EVP(XL)

```

C ELASTIC MATERIAL PROPERTIES

THREEK = 3.0*BMOD(SJ11,EVPI)
 TWOG = 2.0*SNOD(SJ21,EVPI)

C ELASTIC TRIAL

SJ1 = THREEK*DEV+SJ11
 SRR = SRR + TWOG*DERR
 STT = STT + TWOG*DETT
 SRZ = SRZ + TWOG*DEPSRZ
 RATIO = 1.0
 MTYPE = 1

C TENSILE CODING

IF(SJ1,LT.0.0) GO TO 10
 SJ1 = 0.
 RATIO = 0.
 MTYPE = 0
 IF(LTYPE,EQ.2 .OR. EL,GE.0.0) GO TO 200

C TENSION DILATENCY CODING

ELL = AMAX1(0.0,EL*CONV+F(EL))
 XLL = X(ELL)
 DENOM = EVP(XLL)-EVPI
 IF(DENOM,GT.0.0) GO TO 5
 EL = 0.0
 GO TO 200
 5 DEVP = DEV-(SJ1-SJ11)/AMAX1(0.0001,THREEK)
 EL = EL+DEVP*(ELL-EL)/DENOM
 EL = AMIN1(0.0,EL)
 GO TO 200

C CHECK FAILURE ENVELOPE

10 CONTINUE
 SJ2 = SQRT(SRR*SRP+STT*STT+SRR*STT+SRZ*SRZ)
 IF(SJ1,LT,CAPL) GO TO 30
 TMISES = SJ2C(CAPL,XL,CAPL)
 FJ1 = F(SJ1)
 FF = SJ2 - AMIN1(FJ1,TMISES)
 IF(FF,LE.0.0) GO TO 200

C FAILURE SURFACE CALCULATION

MTYPE = 2
 DFDJ1 = 0.0
 IF(FJ1,LT,TMISES)
 & DFDJ1 = (FJ1-F(SJ1+CONV*SJ2))/(CONV*SJ2)
 DEVP = 3.0*DFDJ1*FF/(3.0*THREEK*DFDJ1+DFDJ1+0.5*TWOG)
 SJ1E = SJ1
 SJ1 = SJ1 - THREEK*DEVP

C DILATANCY AND CORNER CODING

IF(LTYPE,EQ.1.AND.EL,LT.0.0) GO TO 60
 SJ1 = AMAX1(SJ1,CAPL)
 GO TO 70
 60 CONTINUE
 ELL = AMAX1(SJ1E,EL+CONV*SJ2)
 XLL = X(ELL)
 DENOM = EVP(XLL)-EVPI
 IF(DENOM,GT.0.0) GO TO 65
 SJ1 = SJ1E
 EL = AMIN1(0.0,SJ1)
 GO TO 70
 65 DILAT = (ELL-EL)/DENOM
 ELINT = EL
 EL = AMIN1(0.0,(ELINT+DEVP*DILAT))
 IF(SJ1,GE,BIGL(EL)) GO TO 70
 SJ1 = (DILAT*SJ1E+THREEK*ELINT)/(DILAT+THREEK)
 EL = AMIN1(0.,SJ1)
 70 CONTINUE
 FJ1 = F(SJ1)
 RATIO = AMIN1(FJ1,TMISES)/SJ2
 GO TO 200

C HARDENING CALCULATION

30 CONTINUE
 IF(SJ1,LT,XL) GO TO 40
 IF(SJ2,LE,SJ2C(SJ1,XL,CAPL)) GO TO 200
 40 CONTINUE
 SJ1E = SJ1
 SJ2E = SJ2
 ELL = EL
 ELR = SJ1E
 IF(SJ1E,LE,XL) FL=(EL-SJ1E)/(EL-XL)
 IF(SJ1E,GT,XL) FL=2.0*SJ2E/(SJ2E+SJ2C(SJ1E,XL,CAPL))-1.0
 XR = X(ELR)
 SJ1R = SJ1E-THREEK*(EVP(XR)-EVPI)
 FR = (XR-SJ1R)/(ELR-XR)
 COMP = CONV*(FL*XR-FR*XL)/(FL-FR)
 IF(ABS(SJ1)+SJ2,LT,COMP) GO TO 200
 MTYPE = 3
 FOLD = 0.0
 DO 190 IT = 1,NIT
 EL = (FL*ELR-FR*ELL)/(FL-FR)
 XL = X(EL)
 DEVP = EVP(XL) - EVPI
 SJ1 = SJ1E - THREEK*DEVP
 CAPL = BIGL(EL)
 IF(SJ1,LE,XL) FC=(EL-SJ1)/(EL-XL)
 IF(SJ1,GE,CAPL) FC=(XL-SJ1)/(CAPL-XL)
 IF(SJ1,LE,XL.OR,SJ1,GE,CAPL) GO TO 300
 SJ2 = SJ2C(SJ1,XL,CAPL)


```

      DELJ1 = CONV*(XL-SL1)
      DESP = 0.0
      IF (DELJ1) 205,206,205
205  DESP=(DEVP/6.)* (DELJ1/(SJ2-SJ2C(SJ1+DELJ1,XL,CAPL)))
206  CONTINUE
      SJ2TRY = SJ2 + TWDE*DESP
      FC = (SJ2E-SJ2TRY)/(SJ2E + SJ2TRY)
      IF (ABS(SJ2E-SJ2TRY).LE.COMP) GO TO 195
      IF (FC.GT.0.0.AND.(SJ1-CAPL).GE.DELJ1) GO TO 195
300  IF (FC.GT.0.0) GO TO 320
      ELR = EL
      FR = FC
      IF (FOLD.LT.0.) FL = 0.5*FL
      GO TO 190
320  CONTINUE
      ELL = EL
      FL = FC
      IF (FOLD.GT.0.) FR = 0.5*FR
190  FOLD = FC
      NOCON = 1
      SJ1 = AMAX1(SJ1,XL)
      IF (SJ1.GT.BIG*(ELR)) SJ1 = CAPL
      SJ2 = AMIN1(SJ2E,SJ2C(SJ1,XL,CAPL))
195  RATIO = 0.0
      IF (SJ2E) 201,200,201
201  RATIO=SJ2/SJ2E
200  CONTINUE
      SRR = SRR+RATIO
      STT = STT+RATIO
      SRZ = SRZ+RATIO
      PRESS = -SJ1/3.
      SIGR = SRR - PRESS
      SIGT = STT - PRESS
      SIGZ = -3.0*PRESS - SIGR - SIGT
      RETURN
      END

```

C TMODEL

```

SUBROUTINE TMODEL
COMMON/STRESS/ SIGR,SIGT,SIGZ,SIGRZ,P,S(3),EP
COMMON/STRAIN/ EPSR,EPST,EPSZ,EPSRZ,EPKK,E(3)
COMMON/STRINC/ DEPSR,DEPST,DEPSZ,DEPSRZ
COMMON/DUMMY/ MTYPE,LTYPE,TCUT,FCUT,JT,NOCON,STATE,ISTOR(10)
COMMON/PROPER/ AK1,AK1,AK2,AKIM,AKIM,AK2M,AG1,AG1,AG2,AG3,AG4,
& AC,AM,ARI,AR1,AR2,AW,AD,AKH,AKHM
COMMON/PREPRO/ XL,EL,CAP,GR,GRP,IUSE,IUNHY
COMMON/NUMBER/ QGAMMA,QDELTA,CONS,VV,VH,KOUNT,IDUX,IUUX

```

C UNDRAINED BULK MODULUS

```

      UK(SJ1) = AKIM*(1.-AKIM*AKHM*EXP(AK2M*(SJ1+3.*GR)))/
& (1.-AKIM*AKHM)

```

```

      DEVP = DEPSR+DEPST+DEPSZ
      SJ11 = -3.*P
      THREEK = 3.*UK(SJ11)
      SJ1 = THREEK*DEVP+SJ11
      P = -SJ1/3.
      RETURN
      END

```

ADDENDUM B

DATA REDUCTION PROGRAMS

The primary data reduction programs used to process the raw test data generated for the SDP experimental program are documented in this addendum. These programs were written for a Hewlett-Packard 9835 calculator which uses enhanced basic as its programming language. Three programs are included: LPTX-A (for the LPTX tests), SHYDRO (for the HPTX tests), and PPUX-C (for the PPUX tests).

All three programs read from digital tape the unprocessed data obtained during a given test, including all transducer calibration constants which are recorded along with the unprocessed test data. Each program calculates the desired stresses and strains and either plots the calculated results in a standard format or stores the data on digital tape to be plotted at a future date. These programs were developed in-house as part of the FY 80 experimental SDP work.

```

10  ! ----->>>  Program Title:  LPTX_A
20  PRINTER IS 7,6
30  DIM Test$(8)(25),Const(12),Data(100,5)
40  SHORT Plot(100,5)
50  INPUT "Load Data File ?",File$
60  ASSIGN #1 TO File$
70  READ #1,Test$(*),Const(*),Data(*)
80  INPUT "Do you want printout?",Print$
90  INPUT "Enter plot file title",Plot$
100 IF Print$="NO" THEN GOTO 270
110 PRINT USING 120                                     !--->>  Title Block
120 IMAGE 5/,20X,40(" "),/,20X,"",38X,""
130 PRINT USING 140
140 IMAGE 20X,"",9X,"WATERWAYS EXPERIMENT",9X,"",/,20X,"",15X,"STATION",16X,
    "",/,20X,"",38X,""
150 PRINT USING 160
160 IMAGE 20X,"",10X,"GEOMECHANICS DIV.",11X,"",/,20X,"",38X,"",/,20X,40(" ")
170 PRINT USING "/,10X,K,K","Project: ",Test$(1)
180 PRINT USING "/,10X,K,K","WES Job No.: ",Test$(2)
190 PRINT USING "/,10X,K,K","Test No.: ",Test$(3)
200 PRINT USING "/,10X,K,K","Test Device: ",Test$(4)
210 PRINT USING "/,10X,K,K","Project Eng.: ",Test$(5)
220 PRINT USING "/,10X,K,K","Date: ",Test$(6)
230 PRINT USING "/,10X,K,K","Remarks: ",Test$(7)
240 PRINT USING "/,10X,K,K","File No.: ",Test$(8)
250 PRINT USING 260
260 IMAGE /,2X,77(" ")
270 Conver=6.894757
280 X1=Const(1)*Conver
290 X2=Const(2)*Conver
300 X3=Const(12)*Conver
310 X4=Const(1)-Const(2)
320 Y1=X4*Conver
330 X5=Const(6)*2*PI/4*Const(7)
340 IF Print$="NO" THEN GOTO 490
350 PRINT USING 360,X1,Const(1)
360 IMAGE /,10X,"Confining Pr.: ",DDDD.DDD," kPa",5X,"(",K," psi)"
370 PRINT USING 380,X2,Const(2)
380 IMAGE /,10X,"Back Pr.: ",DDDD.DDD," kPa",5X,"(",K," psi)"
390 PRINT USING 400,X3,Const(12)
400 IMAGE /,10X,"Live Confining Pr.: ",DDDD.DDD," kPa",5X,"(",K," psi)"
410 PRINT USING 420,Y1,X4
420 IMAGE /,10X,"Consolidation Pr.: ",DDDD.DDD," kPa",5X,"(",K," psi)"
430 PRINT USING "/,10X,K,K,K","Initial Sample Length: ",Const(7)," cm."
440 PRINT USING "/,10X,K,K,K","Initial Sample Diameter: ",Const(6)," cm."
450 PRINT USING "/,10X,K,DDD.DDD,K","Initial Sample Volume: ",X5," cc."
460 PRINT USING "/,10X,K,DDD.DDD,K","Change in Volume: ",Const(8)," cc."
470 PRINT USING "/,10X,K,DDD.DDD,K","Change in Length: ",Const(9)," cm."
480 ! --->>>  Determine units to be used!  <<<
490 Kgc=0.070307
500 Kpascal=6.894757
510 INPUT "Enter units (SI or CGS)",Units$
520 Conver=Kgc                                          !--->> Conversion Constant

```

```

530 IF Units$="SI" THEN Conver=Kpascal
540 !
550 ! --->>> Calculate initial sample constants. <<<---
560 !
570 Const(1)=Const(1)*Conver !--- Confining Pressure
580 Const(2)=Const(2)*Conver !--->> Back Pressure
590 Sigma_3=Const(1)-Const(2) !--- Consolidation Pr.
600 !
610 Length=Const(7)-Const(9)
620 Area=(PI*Const(6)^2/4*Const(7)-Const(8))/Length !--->> sq cm
630 !
640 ! ---> Calculations <---
650 Numpts=Const(11)
660 IF Print$="NO" THEN GOTO 680
670 PRINT USING 680
680 IMAGE 2/,3X,"Strain",5X,"Time",5X,"Area",7X,"Load",4X,"Dev Stress",5X,"q",8
X,"p",9X,"J",/,22X,"Pore 1",5X,"Pore 2",5X,"Af",2/
690 FOR I=1 TO Numpts
700 Time=Data(I,5)
710 Strain=(Data(I,1)-Data(1,1))*Const(3)*2.54/Length*100
720 Area_corr=Area/(1-Strain/100) !--- Corrected Area
730 Conver2=.4535924
740 IF Units$="SI" THEN Conver2=.004448222 !--->> kN
750 Load=(Data(I,2)-Data(1,2))*Conver2*Const(4)
760 Dev_stress=Load/Area_corr !--->> kg/sqcm_
770 IF Units$="SI" THEN Dev_stress=Load/Area_corr*1000 !--->> kPa
780 Sigma_1=Dev_stress+Sigma_3 !--- Total stress
790 Pore_1=(Data(I,3)-Data(1,3))*Conver*Const(5) !--- Abs. XDCR
800 Pore_2=(Data(I,4)-Data(1,4))*Conver*Const(10) !--- Diff. XDCR
810 Sigma1_1=Sigma_1-Pore_2
820 Sigma3_3=Sigma_3-Pore_2
830 Q=Dev_stress/2
840 Pbar=(Sigma1_1+Sigma3_3)/2
850 J=(Sigma1_1+2*Sigma3_3)/3
860 IF Dev_stress=0 THEN GOTO 890
870 A_factor=Pore_1/Dev_stress
880 GOTO 900
890 A_factor=0
900 IF Print$="NO" THEN GOTO 930
910 PRINT USING 920;Strain,Time,Area_corr,Load,Dev_stress,Q,Pbar,J,Pore_1,Pore_
2,A_factor
920 IMAGE 4X,DD.D,5X,DDD.D,6(4X,DDD.DDD),/,18X,3(4X,DDD.DDD)
930 Plot(I,1)=Strain
940 Plot(I,2)=Dev_stress
950 Plot(I,3)=Pore_2
960 Plot(I,4)=A_factor
970 Plot(I,5)=Pbar
980 ! Plot(I,2)=J
990 NEXT I
1000 Print$="NO"
1010 Plottape$=Plot$
1020 ASSIGN #1 TO Plottape$
1030 PRINT #1;Plot(*),Numpts,END
1040 DISP ">>>> End of Calculations <<<<"
1050 END

```

```

10  ! >>>>  Program Title: SHYDRO  <<<<
20  ! --->  This program calculates volumetric strains.
30  OPTION BASE 1
40  DIM Plot$(18)
50  COM Chan(7),Calv(7,7),Cal(7,7),Slope(7),Volt(7),Value(8),Ref(8)
60  INPUT "Insert TAPE...Enter Data File Name",File$
70  INPUT "Do you want voltages printed out?",Print$
80  PRINTER IS 0
90  PRINT "",""," PLOT TYPE","_____",""
100 PRINT "YES-1....VD1"
110 PRINT "YES-2....VD2"
120 PRINT "YES-3....Ave"
130 PRINT "YES-4....LD1"
140 PRINT "YES-5....VOL STR","          CONE"
150 PRINT "YES.....VOL STR"
160 INPUT "Do you want to plot data?",Plot$
170 IF Again$="YES" THEN GOTO 200
180 IF Plot$(1,3)="YES" THEN CALL Plot_setup(Xmax,Ymax,Xmin,Ymin)
190 PRINTER IS 7,6.
200 ASSIGN #1 TO File$
210 ON END #1 GOTO 670
220 READ #1;Time$
230 READ #1;Test$,Ht,Dia,Numchan
240 IF Plot$(1,3)="YES" THEN GOTO 310
250 PRINT USING 260;Test$,File$
260 IMAGE 10X,"Test No. : ",K,10X,"File Name : ",K,2/
270 PRINT USING 280;Ht,Dia
280 IMAGE 10X,"Sample Height : ",3D.3D," (inches)",/,10X,"Sample Diameter : ",3
D.3D," (inches)",/
290 PRINT USING 300;Numchan
300 IMAGE 10X;"Number of Channels Monitored : ",DD,2/
310 IF Print$="NO" THEN GOTO 330
320 PRINT "Channel      0          A          B          C          D
E"
330 FOR I=1 TO Numchan
340 READ #1;Chan(I),Calv(I,1),Calv(I,2),Calv(I,3),Calv(I,4),Calv(I,5),Calv(I,6)
350 IF Print$="NO" THEN GOTO 380
360 PRINT USING 370;Chan(I),Calv(I,1),Calv(I,2),Calv(I,3),Calv(I,4),Calv(I,5),C
alv(I,6)
370 IMAGE /,2X,DD,5X,6(3D.6D,2X)
380 READ #1;Chan(I),Cal(I,1),Cal(I,2),Cal(I,3),Cal(I,4),Cal(I,5),Cal(I,6)
390 IF Print$="NO" THEN GOTO 420
400 PRINT USING 410;Cal(I,1),Cal(I,2),Cal(I,3),Cal(I,4),Cal(I,5),Cal(I,6)
410 IMAGE 7X,6(7D.2D,2X)
420 NEXT I
430 INPUT "Enter Time for Start of Hydro",Ref_time$
440 INPUT "Enter time for start of SHEAR",Ref_time_shear$
450 Shear_ref=0
460 Skip$="NO"
470 Data: READ #1;T$,Volt(1),Volt(2),Volt(3),Volt(4),Volt(5),Volt(6),Volt(7)
480 Count1=Count1+1
490 IF Ref_time$=T$ THEN Skip$="YES"
500 FOR I=1 TO Numchan
510 CALL Value(I)

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520     NEXT I
530     IF Print$="NO" THEN GOTO 580
540 PRINT USING 550;T$,Count1,Volt(1),Volt(2),Volt(3),Volt(4),Volt(5),Volt(6),V
olt(7)
550 IMAGE 14A,2X,DDD,2X,7(2D.6D)
560 PRINT USING 570;Value(1),Value(2),Value(3),Value(4),Value(5),Value(6),Value
(7)
570 IMAGE 5X,7(7D.2D,2X)
580 IF Skip$<>"YES" THEN GOTO 620
590 Count=Count+1
600 IF Ref_time_shear$=T$ THEN Shear_ref=Count
610 CALL Volume(Dia,Ht,Count,Shear_ref,Plot$)
620 GOTO Data
630 IF Plot$(1,3)="YES" THEN GOTO 660
640 IMAGE 2/,5X," * Assumes uniform deformation.",/,5X,"** Assumes truncated co
ne deformation."
650 PRINT USING 640
660 REWIND
670 IF Again$="YES" THEN GOTO 690
680 IF Plot$(1,3)="YES" THEN CALL Plot_end(Xmax,Ymax,Xmin,Ymin)
690 INPUT "Plot again on same graph??",Again$
700 IF Again$="YES" THEN GOTO 80
710 END
720 !
730 !
740 SUB Value(I)
750 !
760 !
770 COM Chan(*),Calv(*),Cal(*),Slope(*),Volt(*),Value(*),Ref(*)
780 FOR J=2 TO 6
790     IF Volt(I)<Calv(I,J) THEN GOTO 860
800     IF J<6 THEN GOTO 850
810     Calv(I,7)=2*Calv(I,6)
820     Cal(I,7)=2*Cal(I,6)
830     J=7
840     GOTO 860
850 NEXT J
860 Slope(I)=(Cal(I,J)-Cal(I,J-1))/(Calv(I,J)-Calv(I,J-1))
870 Value(I)=Slope(I)*(Volt(I)-Calv(I,J-1))+Cal(I,J-1)
880 SUBEND
890 !
900 !
910 SUB Volume(Dia,Ht,Count,Shear_ref,Plot$)
920 !
930 !
940 OPTION BASE 1
950 COM Chan(*),Calv(*),Cal(*),Slope(*),Volt(*),Value(*),Ref(*)
960 IF Count<>1 THEN GOTO 1080
970 IF Plot$(1,3)="YES" THEN GOTO 1060
980 PRINT USING 990
990 IMAGE 2/,3X,"VERTICAL",15X,"LATERAL",6X,"VOLUMETRIC",5X,"FILM"
1000 PRINT USING 1010

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1010 IMAGE 2X,"DEFORMATION",11X,"DEFORMATION",6X,"STRAIN",7X,"POT",7X,"STRESS",
7X,"LOAD"
1020 PRINT USING 1030
1030 IMAGE 5X,"MILS",19X,"MILS",12X,"Z",9X,"MILS",5X,"PSI",5X,"MPa",6X,"LBS"
1040 PRINT USING 1050
1050 IMAGE 2X,"#1",6X,"#2",6X,"Avg",7X,"****",8X,"*",6X,"**",5X,"****",9X,"***",
5X,"**",/
1060 Dia=Dia*1000
1070 Ht=Ht*1000
1080 IF Count=1 THEN MAT Ref=Value
1090 Vd1=Value(1)-Ref(1)
1100 Vd2=Value(2)-Ref(2)
1110 Ave=(Vd1+Vd2)/2
1120 Ld1=Value(3)-Ref(3)
1130 Ea1=Vd1/Ht*100
1140 Ea2=Vd2/Ht*100
1150 Fp=Value(4)-Ref(4)
1160 Ea_ave=(Ea1+Ea2)/2
1170 Er=Ld1/Dia*100
1180 Evol_uniform=Ea_ave+2*Er
1190 Evol_cone=Ea_ave+Er
1200 IF Shear_ref(>)Count THEN GOTO 1240
1210 Ref(4)=Value(4)
1220 Ref(5)=Value(5)
1230 Ref(8)=Ave
1240 Axial_strain=(Ref(8)+Value(4)-Ref(4))/Ht*100
1250 IF Shear_ref=0 THEN Axial_strain=Ea_ave
1260 Mpascal=Value(7)/145
1270 Pore_pr=Value(6)/145
1280 Load=Value(5)-Ref(5)
1290 IF Shear_ref=0 THEN Load=0
1300 Area=((Dia-Ld1)/1000)*2*PI/4
1310 Stress_diff=Load/Area/.145
1320 Strain_diff=Axial_strain-Er
1330 IF Plot$="YES-1" THEN CALL Plot_pts(Mpascal,Vd1)
1340 IF Plot$="YES-2" THEN CALL Plot_pts(Mpascal,Vd2)
1350 IF Plot$="YES-4" THEN CALL Plot_pts(Mpascal,Ld1)
1360 IF Plot$="YES-3" THEN CALL Plot_pts(Mpascal,Ave)
1370 IF Plot$="YES" THEN CALL Plot_pts(Mpascal,Evol_uniform)
1380 IF Plot$="YES-5" THEN CALL Plot_pts(Mpascal,Evol_cone)
1390 IF Plot$="YES-6" THEN CALL Plot_pts(Stress_diff,Strain_diff)
1400 IF Plot$(1,3)="YES" THEN GOTO 1450
1410 PRINT USING 1420,Vd1,Vd2,Ave,Ld1,Evol_uniform,Evol_cone,Fp,Value(7),Mpascal
,Load
1420 IMAGE 3(3D.2D,2X),4X,4(3D.2D,2X),5D.D,2X,2D.D,2X,5D.2D
1430 PRINT USING 1440,Ea_ave,Er,Axial_strain,Pore_pr,Strain_diff,Stress_diff
1440 IMAGE 5X,(2D.2D,3X),4D.2D,5X,2(4D.2D,4X)
1450 SUBEND
1460 !
1470 !
1480 SUB Plot_setup(Xmax,Ymax,Xmin,Ymin)
1490 !
1500 !

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```

1510 INPUT "Plot on Plotter-Printer??",A$
1520 PLOTTER IS 7,5,"9872A"
1530 IF A$="YES" THEN GOTO 1550
1540 PLOTTER IS 7,1,"9872A"
1550 DEG
1560 LIMIT 0,400,0,260
1570 INPUT "Do you want large plot",Plotsizes$
1580 LOCATE 15,65,25,95
1590 IF A$="YES" THEN GOTO 1610
1600 IF Plotsizes$="YES" THEN LOCATE 10,130,15,95
1610 FRAME
1620 CSIZE 2.2,9/15
1630 INPUT "ENTER MAXIMUM X VALUE",Xmax
1640 INPUT "ENTER MAXIMUM Y VALUE",Ymax
1650 INPUT "ENTER MINIMUM X VALUE",Xmin
1660 INPUT "ENTER MINIMUM Y VALUE",Ymin
1670 INPUT "PLACE Y-TIC EVERY ? UNITS",Ytic
1680 INPUT "PLACE X-TIC EVERY ? UNITS",Xtic
1690 SCALE Xmin,Xmax,Ymin,Ymax
1700 AXES Xtic,Ytic,Xmax,Ymax,2,2
1710 AXES Xtic,Ytic,Xmin,Ymin,2,2
1720 PLOT Xmin,Ymin,1
1730 FOR I=1 TO (Xmax-Xmin)/(2*Xtic)+1          !PRINT VALUES ON X AXIS
1740 IF I<>1 THEN GOTO 1770
1750 Xlab=Xmin
1760 GOTO 1780
1770 Xlab=Xlab+2*Xtic
1780 Ypos=Ymin-.030*(Ymax-Ymin)
1790 PLOT Xlab,Ypos,1
1800 LDIR 0
1810 LORG 6
1820 LABEL USING "K",Xlab
1830 NEXT I
1840 FOR I=1 TO (Ymax-Ymin)/(2*Ytic)+1          !PRINT VALUES ON Y AXIS
1850 IF I<>1 THEN GOTO 1880
1860 Ylab=Ymin
1870 GOTO 1890
1880 Ylab=Ylab+2*Ytic
1890 Xpos=Xmin-.020*(Xmax-Xmin)
1900 PLOT Xpos,Ylab,1
1910 LDIR 0
1920 LORG 8
1930 LABEL USING "K",Ylab
1940 NEXT I
1950 SUBEND
1960 !
1970 !
1980 SUB Plot_pts(Y,X)
1990 !
2000 !
2010 PLOT X,Y,1
2020 LORG 5
2030 IF Symbol$="" THEN GOTO 2050

```



```

2040 LABEL USING "K",Symbol$
2050 PLOT X,Y,-1
2060 SUBEND
2070 !
2080 !
2090 SUB Plot_end(Xmax,Ymax,Xmin,Ymin)
2100 !
2110 !
2120 DIM Label$(2)[40]
2130 PENUP
2140 IF Plot$="YES" THEN GOTO 2170
2150 CSIZE 2.2,9/15
2160 Ypos=(Ymax+Ymin)/2
2170 Xpos=Xmin-.115*(Xmax-Xmin)
2180 INPUT "Enter Y-axis label, units!",Label$(1),Label$(2)
2190 CALL Center(90,Label$(#),4,Xpos,Ypos,Comma)      !PRINT Y AXIS LABE
L
2200 Xpos=(Xmax+Xmin)/2
2210 Ypos=Ymin-.08*(Ymax-Ymin)
2220 INPUT "Enter X-axis label, units!",Label$(1),Label$(2)
2230 CALL Center(0,Label$(#),6,Xpos,Ypos,Comma)      !PRINT X AXIS LABE
L
2240 Ypos=1.5*Ypos
2250 Comma=1      ! FOR REMARKS
2260 INPUT "Enter Test Remarks!",Label$(1),Label$(2)
2270 CSIZE 2.2,9/15
2280 CALL Center(0,Label$(#),6,Xpos,Ypos,Comma)      !PRINT TEST REMARK
S
2290 Ypos=1.3*Ypos
2300 INPUT "Enter Test Remarks!",Label$(1),Label$(2)
2310 CSIZE 2.2,9/15
2320 CALL Center(0,Label$(#),6,Xpos,Ypos,Comma)      !PRINT TEST REMARK
S
2330 SUBEND
2340 !
2350 !
2360 SUB Center(Ldir,Label$(#),Lorg,Xpos,Ypos,Comma)
2370 !
2380 !
2390 DEG
2400 PLOT Xpos,Ypos,1
2410 LDIR Ldir
2420 LORG Lorg
2430 IF Comma<>0 THEN GOTO 2460
2440 LABEL USING "K",Label$(1)," ",Label$(2)
2450 GOTO 2470
2460 LABEL USING "K",Label$(1)," ",Label$(2)
2470 SUBEND
2480 END

```

```

10  ! >>>>  Program Title: PPUX_C  <<<<
20  ! --->  This program calculates verticle strains.
30  OPTION BASE 1
40  DIM Plot$(8)
50  COM Chan(3),Calv(3,8),Cal(3,8),Slope(3),Volt(3),Value(3),Ref(3)
60  INPUT "Insert TAPE...Enter Data File Name",File$
70  INPUT "Do you want voltages printed out?",Print$
80  PRINTER IS 0
90  PRINT "","", "  PLOT TYPE","-----",""
100 PRINT "YES-1....VD"
110 PRINT "YES-2....PP"
120 PRINT "YES.....VER STR"
130 INPUT "Do you want to plot data?",Plot$
140 IF Again$="YES" THEN GOTO 170
150 IF Plot$(1,3)="YES" THEN CALL Plot_setup(Xmax,Ymax,Xmin,Ymin)
160 PRINTER IS 7,5
170 ASSIGN #1 TO File$
180 ON END #1 GOTO 600
190 READ #1;Time$
200 READ #1;Test$.Ht,Dia,Numchan
210 IF Plot$(1,3)="YES" THEN GOTO 280
220 PRINT USING 230;Test$,File$
230 IMAGE 10X,"Test No. : ",K,10X,"File Name : ",K,2/
240 PRINT USING 250;Ht,Dia
250 IMAGE 10X,"Sample Height : ",3D.3D," (inches)",/,10X,"Sample Diameter : ",3
D.3D," (inches)",/
260 PRINT USING 270;Numchan
270 IMAGE 10X,"Number of Channels Monitored : ",3D,2/
280 IF Print$="NO" THEN GOTO 300
290 PRINT "Channel      0          A          B          C          D          E
F"
300 FOR I=1 TO Numchan
310 READ #1;Chan(I),Calv(I,1),Calv(I,2),Calv(I,3),Calv(I,4),Calv(I,5),Calv(I,6)
,Calv(I,7)
320 IF Print$="NO" THEN GOTO 350
330 PRINT USING 340;Chan(I),Calv(I,1),Calv(I,2),Calv(I,3),Calv(I,4),Calv(I,5),C
alv(I,6),Calv(I,7)
340 IMAGE /,2X,DD,5X,7(2D.6D,1X)
350 READ #1;Chan(I),Cal(I,1),Cal(I,2),Cal(I,3),Cal(I,4),Cal(I,5),Cal(I,6),Cal(I
,7)
360 IF Print$="NO" THEN GOTO 390
370 PRINT USING 380;Cal(I,1),Cal(I,2),Cal(I,3),Cal(I,4),Cal(I,5),Cal(I,6),Cal(I
,7)
380 IMAGE 7X,7(6D.1D,2X)
390 NEXT I
400 INPUT "Enter Time for Start of Hydro",Ref_time$
410 Skip$="NO"
420 Data: READ #1;T$,Volt(1),Volt(2),Volt(3)
430 Count1=Count1+1
440 IF Ref_time$=T$ THEN Skip$="YES"
450 FOR I=1 TO Numchan

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460 CALL Value(I)
470 NEXT I
480 IF Print$="NO" THEN GOTO 530
490 PRINT USING 500,T$,Count1,Volt(1),Volt(2),Volt(3)
500 IMAGE 14A,2X,DDD,2X,3(2D.6D,4X)
510 PRINT USING 520,Value(1),Value(2),Value(3)
520 IMAGE 5X,3(7D.2D,4X)
530 IF Skip$(">YES") THEN GOTO 560
540 Count=Count+1
550 CALL Volume(Dia,Ht,Count,Vol_ref,Plot$)
560 GOTO Data
570 IF Plot$(1,3)="YES" THEN GOTO 580
580 REWIND
590 IF Again$="YES" THEN GOTO 610
600 IF Plot$(1,3)="YES" THEN CALL Plot_end(Xmax,Ymax,Xmin,Ymin)
610 INPUT "Plot again on same graph??",Again$
620 IF Again$="YES" THEN GOTO 80
630 END
640 !
650 !
660 SUB Value(I)
670 !
680 !
690 COM Chan(*),Calv(*),Cal(*),Slope(*),Volt(*),Value(*),Ref(*)
700 FOR J=2 TO 7
710 IF Volt(I)<Calv(I,J) THEN GOTO 790
720 IF J<7 THEN GOTO 770
730 Calv(I,8)=2*Calv(I,7)
740 Cal(I,8)=2*Cal(I,7)
750 J=8
760 GOTO 780
770 NEXT J
780 Slope(I)=(Cal(I,J)-Cal(I,J-1))/(Calv(I,J)-Calv(I,J-1))
790 Value(I)=Slope(I)*(Volt(I)-Calv(I,J-1))+Cal(I,J-1)
800 SUBEND
810 !
820 !
830 SUB Volume(Dia,Ht,Count,Vol_ref,Plot$)
840 !
850 !
860 OPTION BASE 1
870 COM Chan(*),Calv(*),Cal(*),Slope(*),Volt(*),Value(*),Ref(*)
880 IF Count<>1 THEN GOTO 960
890 IF Plot$(1,3)="YES" THEN GOTO 940
900 PRINT USING 910
910 IMAGE 2/,3X,"VERTICAL DEFORMATION",5X,"PORE PRESSURE",5X,"CONFINING PRESSU
RE"
920 PRINT USING 930
930 IMAGE 5X,"Mils",8X,"X",11X,"PSI kPa",10X,"PSI MPa",/
940 Dia=Dia*1000
950 Ht=Ht*1000
960 IF Count=1 THEN MAT Ref=Value
970 Vd1=Value(3)-Ref(3)

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```

980 Ea1=Vd1/(Ht-Ref(3))*100
990 E_vol=Ea_ave+2*Ea_r
1000 Vol=Dia^2*PI/4*(Ht-Value(1))
1010 Vol=Vol/10^9
1020 IF Count=1 THEN Vol_ref=Vol
1030 Vol_strain=(Vol-Vol_ref)/Vol_ref*100
1040 Mpascal=Value(2)/145
1050 Pore_pr=Value(1)/145
1060 IF Plot$="YES-1" THEN CALL Plot_pts(Mpascal,Vd1)
1070 IF Plot$="YES-2" THEN CALL Plot_pts(Mpascal,Pore_pr)
1080 IF Plot$="YES" THEN CALL Plot_pts(Mpascal,Ea1)
1090 IF Plot$(1,3)="YES" THEN GOTO 1120
1100 PRINT USING 1110,Vd1,Ea1,Value(1),Pore_pr,Value(2),Mpascal
1110 IMAGE 3X,3D.D,7X,2D.2D,6X,2(5D.D,1X),3X,2(6D.D,2X)
1120 SUBEND
1130 !
1140 !
1150 SUB Plot_setup(Xmax,Ymax,Xmin,Ymin)
1160 !
1170 !
1180 INPUT "Plot on Plotter-Printer?",A$
1190 PLOTTER IS 7,5,"9872A"
1200 IF A$="YES" THEN GOTO 1220
1210 PLOTTER IS 7,1,"9872A"
1220 DEG
1230 LIMIT 0,400,0,260
1240 INPUT "Do you want large plot",Plotsize$
1250 LOCATE 15,65,25,95
1260 IF A$="YES" THEN GOTO 1280
1270 IF Plotsize$="YES" THEN LOCATE 10,130,15,95
1280 FRAME
1290 CSIZE 2.2,9/15
1300 INPUT "ENTER MAXIMUM X VALUE",Xmax
1310 INPUT "ENTER MAXIMUM Y VALUE",Ymax
1320 INPUT "ENTER MINIMUM X VALUE",Xmin
1330 INPUT "ENTER MINIMUM Y VALUE",Ymin
1340 INPUT "PLACE Y-TIC EVERY ? UNITS",Ytic
1350 INPUT "PLACE X-TIC EVERY ? UNITS",Xtic
1360 SCALE Xmin,Xmax,Ymin,Ymax
1370 AXES Xtic,Ytic,Xmax,Ymax,2,2
1380 AXES Xtic,Ytic,Xmin,Ymin,2,2
1390 PLOT Xmin,Ymin,1
1400 FOR I=1 TO (Xmax-Xmin)/(2*Xtic)+1      !PRINT VALUES ON X AXIS
1410 IF I<>1 THEN GOTO 1440
1420 Xlab=Xmin
1430 GOTO 1450
1440 Xlab=Xlab+2*Xtic
1450 Ypos=Ymin-.030*(Ymax-Ymin)
1460 PLOT Xlab,Ypos,1
1470 LDIR 0
1480 LORG 6
1490 LABEL USING "K",Xlab

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```

1500 NEXT I
1510 FOR I=1 TO (Ymax-Ymin)/(2*Ytic)+1
1520 IF I<>1 THEN GOTO 1550
1530 Ylab=Ymin
1540 GOTO 1560
1550 Ylab=Ylab+2*Ytic
1560 Xpos=Xmin-.020*(Xmax-Xmin)
1570 PLOT Xpos,Ylab,1
1580 LDIR 0
1590 LORG 8
1600 LABEL USING "K",Ylab
1610 NEXT I
1620 SUBEND
1630 !
1640 !
1650 SUB Plot_pts(Y,X)
1660 !
1670 !
1680 PLOT X,Y,1
1690 LORG 5
1700 IF Symbol$="" THEN GOTO 1720
1710 LABEL USING "K",Symbol$
1720 PLOT X,Y,-1
1730 SUBEND
1740 !
1750 !
1760 SUB Plot_end(Xmax,Ymax,Xmin,Ymin)
1770 !
1780 !
1790 DIM Label$(2)[40]
1800 PENUP
1810 IF Plot$="YES" THEN GOTO 1840
1820 CSIZE 2.2,9/15
1830 Ypos=(Ymax-Ymin)/2
1840 Xpos=Xmin-.115*(Xmax-Xmin)
1850 INPUT "Enter Y-axis label, units!",Label$(1),Label$(2)
1860 CALL Center(90,Label$(*),4,Xpos,Ypos,Comma)
1870 Xpos=(Xmax-Xmin)/2
1880 Ypos=Ymin-.09*(Ymax-Ymin)
1890 INPUT "Enter X-axis label, units!",Label$(1),Label$(2)
1900 CALL Center(0,Label$(*),6,Xpos,Ypos,Comma)
1910 Ypos=1.5*Ypos
1920 Comma=1 ! FOR REMARKS
1930 INPUT "Enter Test Remarks!",Label$(1),Label$(2)
1940 CSIZE 2.2,9/15
1950 CALL Center(0,Label$(*),6,Xpos,Ypos,Comma)
1960 Ypos=1.3*Ypos
1970 INPUT "Enter Test Remarks!",Label$(1),Label$(2)
1980 CSIZE 2.2,9/15

```

!PRINT VALUES ON Y AXIS

!PRINT Y AXIS LABEL

!PRINT X AXIS LABEL

!PRINT TEST REMARK

```

1390 CALL Center(0,Label$(#),6,Xpos,Ypos,Comma)
S
2000 SUBEND
2010 !
2020 !
2030 SUB Center(Ldir,Label$(#),Long,Xpos,Ypos,Comma)
2040 !
2050 !
2060 DEG
2070 PLOT Xpos,Ypos,1
2080 LDIR Ldir
2090 LONG Long
2100 IF Comma<>0 THEN GOTO 2130
2110 LABEL USING "K";Label$(1)," ",Label$(2)
2120 GOTO 2140
2130 LABEL USING "K";Label$(1)," ",Label$(2)
2140 SUBEND
2150 END

```

'PRINT TEST REMARK

ADDENDUM C

DETERMINATIONS OF VOLUMETRIC STRAIN

As discussed in the main text, volume changes occurring during drained HPTX tests were calculated using three methods. Using the vertical and lateral deformer measurements, two deformed specimen shapes were assumed from which two values of volumetric strain could be computed (Reference 7, Part II). Assuming that the specimen deforms as a right-circular cylinder over its entire length, the volumetric strain can be calculated as $\epsilon_a + 2\epsilon_r$, where ϵ_a is the axial strain ($\Delta H/H_0$) and ϵ_r is the radial strain ($\Delta D/D_0$). Assuming that the sample deforms in the shape of two truncated cones, volumetric strain can be calculated as $\epsilon_a + \epsilon_r$. In addition, during drained hydrostatic loading, the volumetric strain can be calculated from burette measurements as $\Delta V/V_0$, where ΔV is the change in volume and V_0 is the original specimen volume.

Figures C.1a and C.1b are taken from Reference 7, Part II, and illustrate the two assumed deformed shapes and the corresponding equations for calculating volumetric strain. These analyses assume that the overall specimen axial deformation is measured and that radial deformation is measured at the midheight of the specimen. The uniform and truncated cone methods of strain calculation used in the present test program ignored the second order terms which are only significant for large strains, i.e., greater than 20 percent. Calculated volumetric strains from deformer measurements were limited to approximately 15 percent by the range of the deformers.

The volumetric strains calculated by the three methods for four HPTX tests are compared in Figures C.2 through C.5 in terms of volumetric strain versus the square root of time. These figures show that the volumetric strains calculated by the burette measurements are bounded by those computed from the deformer measurements. As observed, the uniform cylinder assumption consistently resulted in larger volumetric strains and the truncated cone assumption consistently resulted in smaller volumetric strains. Moreover, where posttest water content data were available, there was good agreement between the final burette-based volumetric strain and that calculated from the final water content.

Posttest observations of specimen deformed shapes could only be made on specimens that underwent extreme volumetric strains (greater than 30 percent). The deformed shapes of these specimens approximated the cylindrical "spool" shape of Figure C.1c.

In two drained uniaxial strain tests both burette volume change measurements and axial deformation measurements were made. In both cases, the burette measurements of volumetric strain did not agree with the axial strains. Posttest water contents in one case gave a final volume which agreed well with the axial deformation measurement but not with the burette measurement.

In conclusion, the measurement of volumetric strain is a difficult undertaking, subject to significant experimental problems as well as

uncertain analytical interpretations. In no case was any one of the methods tried for measuring/computing volumetric strain consistently better than the others. However, in those tests where measurements of two different types are available (burette and deformers) and when accurate posttest specimen dimension and water content measurements are made, a reasonable and confident inference of the volumetric strain can be made.

$$\Delta V/V_0 = \epsilon_a + 2\epsilon_r - 2\epsilon_r\epsilon_a + \epsilon_r^2 (\epsilon_a - 1)$$

Figure C.1a Uniform Deformed Shape Assumption.

$$\Delta V/V_0 = \epsilon_a + \epsilon_r - \epsilon_r\epsilon_a + \frac{2}{3}\epsilon_r^2 (\epsilon_a - 1)$$

Figure C.1b Truncated Cone Deformed Shape Assumption.

Figure C.1c Typical Observed Posttest Specimen Shape.

Figure c.4 BACK PRESSURE SATURATED
DRAINED HYDROSTAT

Figure c.5 BACK PRESSURE SATURATED
DRAINED HYDROSTAT

ADDENDUM D

SALT CORRECTED INDEX PROPERTY FORMULAS

All index property calculations for marine sediment samples must be corrected for the presence of salt in the oven-dried water content specimens. The most widely used salt corrected formulas were developed by Noorany (Reference 9, Part II). After a careful study of Noorany's index property formulas a small discrepancy was found. The analysis to follow identifies this discrepancy and presents revised index property formulas.

The problem source in Noorany's formulation is the calculated weight of salt water in the sediment sample. He assumes a salt content of 35 parts per thousand by weight for seawater, which is a generally accepted value. Therefore, the weight of salt in the oven-dried sample is

$$\begin{aligned} W_{\text{salt}} &= 0.035 (W_{\text{water}}) \\ &= 0.035 (W_{\text{wet}} - W_{\text{dry}}) \end{aligned} \quad (\text{D.1})$$

However, when calculating the weight of salt water in the water content sample, instead of adding the weight of salt to the weight of water

$$\begin{aligned} W_{\text{sw}} &= W_{\text{water}} + W_{\text{salt}} \\ &= (W_{\text{wet}} - W_{\text{dry}}) + 0.035 (W_{\text{wet}} - W_{\text{dry}}) \\ &= 1.035 (W_{\text{wet}} - W_{\text{dry}}) \end{aligned} \quad (\text{D.2})$$

Noorany used the unit weight of salt water to calculate the weight of salt water in the sample:

$$\begin{aligned} W_{\text{sw}} &= \gamma_{\text{sw}} (W_{\text{water}}) \\ &= 1.03 (W_{\text{wet}} - W_{\text{dry}}) \end{aligned} \quad (\text{D.3})$$

The two formulations D.2 and D.3 result in different values of corrected water content, dry density, void ratio, and degree of saturation.

As the unit weight of seawater is both temperature- and salt content-dependent, Equation D.2 is preferred over Equation D.3. Equation D.2 is consistent with Noorany's initial assumption of Equation D.1. The unit weight of salt water can be factored out of Noorany's index property equations and Equation D.2 used in the formulations. This exercise has been performed and the revised index property formulas are presented below.

One must always be cautious of the standard relationships between soil composition properties when working with marine samples. For example, $Se = wG_s$ is a commonly used formula to calculate void ratio. However, when using marine samples the equation must be changed to $1.035 Se = wG_s$ to account for the salt water.

Marine Soil Composition Property Equations

Definitions:

- W_{wet} = wet weight of sediment sample
 W_{dry} = oven-dried weight
 W_{salt} = weight of dissolved salt, assuming 35 parts salt content by weight = $0.035 (W_{wet} - W_{dry})$
 W_s = $W_{solids} = W_{dry} - W_{salt} = W_{dry} - 0.035 (W_{wet} - W_{dry})$
 $\quad = 1.035 W_{dry} - 0.035 W_{wet}$
 γ_w = unit weight of distilled water = 1.0 g/cc at 4°C
 γ_{sw} = unit weight of salt water = 1.02766 g/cc at 4°C = 1.03
 W_{sw} = weight of salt water
 V_{sw} = volume of salt water
 G_s = specific gravity of solids (desalinized soil)
 V = volume of sediment
 V_s = volume of solids
 V_a = volume of air
 V_v = volume of voids

Unit weight: $\gamma = \frac{W_{wet}}{V}$

Dry density: $\gamma_d = \frac{W_s}{V} = \frac{\gamma}{1+w}$

Degree of saturation: $S = \frac{V_{sw}}{V_v} = \frac{\gamma_d G_s w}{(\gamma_w G_s - \gamma_d) 1.035}$

Percent volume of air: $\%V_a = (V - V_s - V_{sw})/V = (1 - S) \left(1 - \frac{\gamma_d}{\gamma_w G_s}\right)$

Percent volume of solids: $\%V_s = V_s/V = \frac{\gamma_d}{\gamma_w G_s}$

Percent volume of water: $\%V_w = 100 - \%V_s - \%V_a$

Water content: $w = \frac{W_{sw}}{W_s} = \frac{1.035(W_{wet} - W_{dry})}{1.035 W_{dry} - 0.035 W_{wet}}$

Void ratio: $e = \frac{V_v}{V_s} = \frac{\gamma_w G_s}{\gamma_d} - 1$

ADDENDUM E

BAD DATA

In most experimental programs there are usually tests which are considered unacceptable or questionable for one reason or another. This program is no exception. Table E.1 lists the tests which were not reported in the main text due to equipment malfunction and/or failure. Therefore, no data other than composition property data could be reported.

The first year of the SDP experimental program at WES was identified as a period in which to gain experience in working with seabed materials; therefore, some problems were expected. This first year, however, was very beneficial in that procedures and techniques necessary to conduct a successful high-pressure static or dynamic testing program were indeed developed. Some of the unsuccessful tests reported herein contributed to these developments.

Two triaxial shear tests, PI 4.5-1E 75-85 cm, and PI 4.5-1D 28-38 cm, developed membrane leaks or drainage valve leaks during their undrained hydrostatic phases; hence, no shear data were obtained. The available data (Figures E.1 and E.2) are considered valid up to the point where the leaks occurred but not beyond. These undrained hydrostatic tests were loaded incrementally in the same manner (24 hours per increment) and with the same stress increments (3.4 and 6.8 MPa) as previous drained hydrostatic tests. However, this loading procedure (used early on in the test program) prolonged the duration of the undrained tests, which greatly increased the chances of a membrane or valve leak. The experience gained from these two tests led to the adoption of a much more successful procedure for conducting undrained hydrostatic loadings; namely the entire load was manually applied in 5 minutes.

Partial drainage occurred during two static uniaxial strain tests, MA-12 GC-19 S#1 and S#9, that were intended to be undrained tests. The data from these tests are of questionable utility; i.e., they are neither fully drained nor fully undrained test results. Plots of vertical stress versus vertical strain and vertical stress versus pore pressure for both specimens are presented in Figures E.3 through E.6.

Table E.1 Bad Test Specimens.

Test No.	Type of Test	Remarks
PI 4.5-1C 75-85 cm	Dynamic Shear/LPTX	Oscillograph paper broke during test.
PI 4.5-1G 43-53 cm	Static Shear/LPTX	Load cell bad.
PI 5-8#81 40-50 cm	Static Shear/LPTX	Load cell bad.
PI 5-8#69 40-50 cm	Dynamic Shear/LPTX	Oscillograph malfunctioned.
PI 5-8#74 40-50 cm	Dynamic Shear/LPTX	Load cell bad.
PI 4.5-1A 75-85 cm	Drained Hydrostat/HPTX	Membrane leaked after one load increment.
PI 5-8#97 40-50 cm	Static Shear/HPTX	Data acquisition system failed, test terminated.

Figure E.1 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED HYDROSTAT
SPECIMEN PI 4.5-1E 75-85 cm

Figure E.2 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED HYDROSTAT
SPECIMEN PI 4.5-1D 28-38 cm

Figure E.3 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED UNIAXIAL STRAIN.
SPECIMEN MA-12 GC-19 S#1

Figure E.4 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED UNIAXIAL STRAIN.
SPECIMEN MA-12 GC-19 S#1

Figure E.5 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED UNIAXIAL STRAIN.
SPECIMEN MA-12 GC-19 S#9

Figure E.6 BACK PRESSURE SATURATED CONSOLIDATED
STATIC UNDRAINED UNIAXIAL STRAIN.
SPECIMEN MA-12 GC-19 S#9

ADDENDUM F

WES/URI SHEAR DATA COMPARISON

STRENGTH

URI has reported the effective Mohr-Coulomb parameters $\bar{c}$ and $\bar{\phi}$ for four series of LPTX tests on illite material from MPG-1 (Reference 1 of Part II). The parameters shown in the following tabulation are reported for three series of tests on reconsolidated-reconstituted (remolded) specimens:

URI			WES		
Test Specimen Designation/ Orientation	$\bar{c}$, MPa	$\bar{\phi}$, deg	Test Specimen Designation/ Orientation	$\bar{c}$, MPa	$\bar{\phi}$, deg
PI-18 Vertical	0.0099	30.4	PI 4.5-1 Vertical	0.0065	20.5
PI-2 Vertical	0.0013	24.6	PI 5.8 Vertical	NA	NA
PI-2 Horizontal	0.0025	22.8	---	---	---

Fitting the failure data from the WES series PI 4.5-1 with a linear Mohr-Coulomb envelope resulted in an effective cohesion intercept of 0.0065 MPa and an effective friction angle of 20.5 degrees. Another WES series, PI 5-8, did not have sufficient failure data to determine a failure envelope.

Cavities were observed in the two series of remolded specimens PI-2 Vertical and PI-2 Horizontal. PI-18 series specimens were of good quality and contained no visible cavities. The lower friction angles exhibited by the PI-2 Vertical and PI-2 Horizontal series in comparison to the PI-18 series were attributed to the observed cavities. It is probable that the significantly large number of cavities in the PI 4.5-1 specimens likewise resulted in the low friction angle of 20.5 degrees. Therefore a comparison of the WES/URI Mohr-Coulomb parameters is considered reasonable between the WES PI 4.5 and the URI PI-2 series.

STRESS-STRAIN

To make a quantitative comparison of the URI and WES shear stress-strain curves for reconstituted specimens, the secant modulus at one percent axial strain was determined for all of the above tests and then normalized with respect to effective confining pressure. The average normalized secant modulus for each specimen group was calculated, resulting in the following values:

PI-18 Vertical	75 (URI)
PI-2 Vertical	65 (URI)
PI-2 Horizontal	51 (URI)
PI 4.5-1	57 (WES)
PI 5-8	79 (WES)

The three specimen groups which exhibited cavities (PI-2 Vertical, PI-2 Horizontal, and PI 4.5-1) have the lower normalized moduli. The PI 4.5-1 specimens, however, have lower normalized moduli in comparison to the PI-2 Vertical specimens. This is consistent with the previous comparison of the friction angles for these two groups of data. The two groups of specimens which were of high quality and had no cavities (PI-18 and PI 5-8) have the highest normalized moduli for the entire group of data. Again, the comparison of the WES/URI data (normalized moduli) is considered reasonable.

STRESS PATHS

Finally, comparisons of the WES/URI effective-stress paths (Reference 1 of Part II and data presented in Part II, Chapter 4) indicate that the overall character of the curves is very similar, that is the WES and URI specimens all behaved as normally consolidated clays.

ADDENDUM G

CONSOLIDATION-TIME HISTORIES

All drained consolidation tests were conducted in incremental fashion. For each load increment the specimen was allowed to reach "equilibrium" before the next increment of load was applied. The criterion for equilibrium was chosen as the time at 90 percent consolidation (i.e., t_{90}) as determined from a plot of observed volume change versus the square root of time (Reference 8, Part II). It should be emphasized that in reality this was a minimum criterion and that most tests were allowed to consolidate under each load increment for a 24-hour period even though t_{90} was often less than 24 hours. For some specimens, however, t_{90} greatly exceeded 24 hours.

Typical plots of volume change versus time for two specimens are presented in Figures G.1 through G.9. Each figure presents consolidation-time histories for one to four increments of loading as identified in the legend. The volume change data points were read from a burette system. The value of the back-pressure saturation stress is indicated on each plot.

Figures G.1 through G.5 are for sample PI 4.5-1A 43-53 cm, which was hydrostatically loaded in the HPTX test device. As observed in Figures G.4 and G.5, at higher ambient stress levels, increased periods (up to several days) were required before the next increment of loading could be added. Figures G.6 through G.9 are for specimen MA-12 GC-19 S#8 which was tested in the PPUX device. The shorter consolidation times required for this uniaxial strain specimen in comparison to the triaxial shear specimen were due to (a) the shorter drainage path of the PPUX specimen and (b) the larger stress increments used during the PPUX test.

Figure 6.9 BACK PRESSURE SATURATED
DRAINED UNIAXIAL STRAIN

Appendix M

Annual Report on Three Dimensional Stress
Relaxation in Clay

E. E. Drumright and J. D. Nelson

Annual Report on Three Dimensional
Stress Relaxation in Clay

Subseabed Disposal Program

Submitted by
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THREE DIMENSIONAL STRESS RELAXATION IN CLAY

I. INTRODUCTION

In order to model with some degree of confidence, hole closure after penetrometer implantation, constitutive relationships are needed for the soil with respect to plastic deformation of the ocean sediments. Several investigators have studied stress relaxation in clays (Lacerda and Houston, 1973; Murayama and Shibata, 1974; and Peng, 1972). This research was conducted using a standard triaxial test, with some modifications in test procedures and equipment. The standard triaxial test is convenient to use because of the radial symmetry, but the intermediate and minor principal stresses must be equal. The purpose of this research is to investigate the effect of the intermediate principal stress on stress relaxation, and to develop a model that will accurately represent the experimental results.

Two different soils have been tested during this investigation. These include marine sediment and a low plasticity clay. Both undisturbed and remolded samples of the marine sediment have been used, whereas only remolded samples of the low plasticity clay were investigated. Experiments were conducted for isotropic ($\sigma_1 = \sigma_2 = \sigma_3$), axisymmetric ($\sigma_1 > \sigma_2 = \sigma_3$) and anisotropic ($\sigma_1 > \sigma_2 > \sigma_3$) states of stress. Experiments were performed for several different values of octahedral shear stress. The effect of the intermediate principal stress on the relaxation parameters for particular levels of octahedral shear stress can then be investigated.

This report discusses the experimental procedures used, and the results obtained from relaxation tests. The results are currently being analyzed as part of an M.S. thesis. The analyses will be presented in the near future.

II. LITERATURE REVIEW

A. Load-Deformation-Time Behavior of Soils

On a microscopic scale, stress relaxation occurs due to the viscoelastic nature of soil. Elastic and inelastic deformations of soil particles, combined with viscous interaction between the soil's liquid and solid phase, have formed the basis for a number of theories related to both creep and stress relaxation. Several thoroughly tested hypotheses are based upon the rate process theory.

1. Rate Process Theory

Rate process theory, GLASSTONE, et al., (1941) considers that the movement of particles from one equilibrium position to another requires the accumulation of the activation energy, the sources of which are external forces and thermal energy of the medium. The rate of deformation is dictated by the frequency with which the particles can overcome the activation energy required to achieve movement. Rate process theory has been used in the study of metals, ceramics, plastics, and concrete; and has contributed to the understanding of viscosity, elasticity, friction, lubrication, and diffusion (EYRING, et al., 1936).

MURAYAMA and SHIBATA (1964) based a rheological theory of flow and stress relaxation in non-fissured clays on assumptions regarding the viscoelastic

nature and behavior of the clay skeleton. The mineral segments were assumed to exist in a face to edge structure, where deformations occurred as a result of fluid and particle interaction at the bonds. They introduced the concept of the "upper yield value" for clay soils, and defined it as the critical maximum shearing stress below which no fracture of the soil skeleton occurs. Their study was limited to stresses less than or equal to the upper yield value. A mechanical model composed of a series of springs and dashpots was developed, and its parameters were chosen to reflect data trends exhibited by laboratory tests.

FUJIMOTO (1964) developed a rheologic model for clay behavior, based on thermodynamic and statistical concepts. Those laws were applied to an isotropic, homogeneous cardhouse clay structure. The result was a rheologic equation similar to that developed for high-polymer materials. The equation was solved for the boundary conditions associated with stress relaxation, using the spring and dashpot model proposed by Murayama and Shibata.

MITCHELL (1964) extended the theory of rate processes to soil behavior. He assumed that resistance to relative movement between particles was accomplished by frictional resistance across the bonds due to normal stress, stress independent cohesion based on physio-chemical aspects, and work required to permit dilation and particle movement. He proposed that the shearing resistance of a given soil is dependent on frictional characteristics, effective stress, void ratio, temperature, strain rate, and soil structure. The resulting equation of behavior was shown to reduce to the Coulomb equation under conditions of constant temperature, structure, and strain rate.

CHRISTENSEN and WU (1964) also utilized rate process theory to develop a spring and dashpot model of clay behavior. For the case of a clay undergoing shear, strain was considered to result from relative movement at particle contacts. This "slip" was assumed to be governed by rate process theory, and the model's performance was correlated with results from constant stress creep tests of clay specimens.

2. Creep

Considerable attention has been devoted to investigations of creep in soils. Perhaps the reason for the extensive research in this area is that prediction and design for tolerable deformations in foundations forms the basis for the "ultimate stress" method of geotechnical engineering design.

SINGH and MITCHELL (1968) developed a three parameter creep equation of the following form:

$$\dot{\epsilon} = A \exp(\alpha D) \cdot (t_1/t)^m \quad (1)$$

where $\dot{\epsilon}$ = creep strain rate,
 A = a parameter which reflects the composition, structure, and stress history of soil,
 α = the value of the slope of the linear portion of the logarithm of strain rate vs. deviator stress plot, and indicates the effect of stress intensity on creep rate,

D = stress intensity, or the ratio of applied stress to the strength of the soil before creep,

t_1 = unit time, after which creep begins,

t = any time greater than t_1 ,

m = absolute value of the slope of the straight line on the log-strain rate vs. log time plot, found to lie between 0.75 and 1.0.

In developing Equation 2, it was intended to derive a creep relationship that would exhibit a linear relationship between the logarithm of strain rate and the logarithm of time, regardless of stress intensity. Such a relationship had been suggested by previous research. In addition, the equation had to account for linear and non-linear relationships between strain and the logarithm of time. Finally, it was required that the equation account for an observed linear relationship between log-strain rate and deviator stress, which appears to exist for many soils over a significant range of creep stresses. The theory was applied to constant stress creep tests on an illitic clay and a coastal marine clay.

In order to determine the effect of method of consolidation on soil creep, CAMPANELLA and VAID (1974) conducted undrained creep rupture (failure) tests using conventional triaxial testing procedures. Undisturbed, saturated, normally consolidated marine clay samples were consolidated under isotropic and plane strain conditions prior to loading. By restricting drainage and corresponding strength gain with time, and by "instantaneously" applying the desired creep stress after the consolidation phase, the authors observed the following results: 1) for a given test type, a linear relationship exists between the log of minimum creep rate and the log of rupture life, 2) for a given creep rate, conventional triaxial tests overestimate rupture life by a factor of four over K_0 or plane strain conditions, 3) creep rupture and failure in standard strain-controlled triaxial tests are both governed by a linear failure envelope, because the shear resistance of a normally consolidated clay depends only on effective stresses, and 4) the undrained porewater pressure development is dependent on axial strain only, and is independent of strain rate history. The last conclusion had also been proposed by LO (1969).

Creep failure theories have also been developed for over-consolidated clays. NELSON and SIU (1971) proposed that bonds formed during the over-consolidation process were capable of storing strain energy, the release of which contributes to dilatation of over-consolidated clays during shear. NELSON and THOMPSON (1977) hypothesized that the accumulation of plastic creep strains resulted in a breakdown of a clay's bonded structure, leading to a reduction in shear strength.

3. Stress Relaxation

A second load-deformation-time behavior exhibited by soils is stress relaxation, the focal point of this paper. Stress relaxation has been previously defined as a decrease in load under conditions of negligible strain, and is closely related to soil creep.

MURAYAMA and SHIBATA (1964) developed a stress relaxation relationship from a spring and dashpot model of soil flow. The equation expresses a

linear relationship between axial stress and logarithm of time for a range of initial strain rates. Eventually, the stress reaches a limiting value established by the model. The slope of the linear portion of the stress vs. log time curve is computed by differentiating the flow equation. The result takes the following form:

$$\frac{-d\sigma}{d(\log t)} = \frac{E_1^2}{B_2(E_1 + E_2)} \epsilon_0 \quad (2)$$

where σ = axial stress in uniaxial test,
 t = time,
 ϵ_0 = strain at time $t=0$
 B_2 = a coefficient dependent on soil structure and temperature,
 E_1 = value of Young's modulus at a condition of zero strain,
 E_2 = value of Young's modulus for a second spring in the model.

E_2 is found by inserting the measured values of limiting stress, initial strain, and E_1 into the following equation:

$$\sigma_{t \rightarrow \infty} = \frac{E_1 E_2}{E_1 + E_2} \epsilon_0 \quad (3)$$

LACERDA and HOUSTON (1973) solved the creep equation developed by SINGH and MITCHELL (1968) for the case of stress relaxation. Their result is of the following form:

$$\frac{\bar{D}}{\bar{D}_0} = 1 - s \log (t/t_0), \text{ for } t > t_0 \quad (4)$$

where $\bar{D}$ = deviator stress level = $D/D_{\max}$,
 D = deviator stress
 $\bar{D}_0$ = deviator stress level at time t_0 ,
 t_0 = time at beginning of stress relaxation,
 s = the slope for the stress level vs. log time curve = $\phi/\bar{D}_0$,
 ϕ = a creep parameter dependent on soil type.

Experiments were performed on clay samples for undrained conditions, in a standard triaxial apparatus. A typical plot of stress level vs. log time is shown in Figure 1. By projecting the linear portion of the curve onto the time axis, the time at the start of relaxation (t_0) was found.

FIGURE 1. TYPICAL PLOT OF STRESS LEVEL VS. LOG TIME FROM AN UNDRAINED STRESS RELAXATION TEST. (AFTER LACERDA AND HOUSTON, 1973).

The value of t_0 was found to be dependent on soil type and the strain rate prior to the relaxation portion of the test. The higher the strain rate, the smaller the value of t_0 . Values of t_0 between 0.001 and 4 minutes were observed for an undisturbed marine clay, and a range between 0.01 and 1.9 minutes was reported for a low plasticity clay.

On the basis of multiple state tests on each sample, the investigators concluded that stress relaxation appeared to be dependent solely on the strain rate and initial stress level prior to relaxation. The results of the stress relaxation experiments were correlated with results from constant stress creep tests, performed according to procedures outlined by SINGH and MITCHELL (1968). It was also concluded that in undrained stress relaxation, the variation of porewater pressure during the relaxation period was small.

4. Three Dimensional Aspects of Stress Relaxation

Little or no previous research on three dimensional stress relaxation has been reported. It was the purpose of this investigation to investigate the effect of variations in the intermediate principal stress on stress relaxation. The results were compared primarily with the results presented previously by LACERDA and HOUSTON (1973).

In contrast to the axisymmetric tests performed by other researchers ($\sigma_1 > \sigma_2 = \sigma_3$), a multiaxial load testing system, capable of applying a different stress to each of three faces of a cubical specimen, has been developed at Colorado State University. Results from these tests were interpreted in light of changes in the octahedral shear stress that occurs during relaxation.

B. Characteristics of Marine Sediments

One of the soils used in this investigation was an illitic marine clay, obtained from the ocean floor of the North Pacific. The samples were taken during the MARA expedition of August 1978. Detailed geotechnical engineering studies on this soil have been performed at the University of Rhode Island (Silva, 1979).

The structural characteristics of ocean sediments will significantly influence their behavior. Due to the slow average deposition rates (one centimeter per 1000 years), and the presence of carbonates, silicas, and oxides, a well-cemented, flocculated clay structure results (Nacci and Huston, 1969).

The sediments that were tested were taken from cores taken from the upper two meters, where the dominant mineral is illite. The clay content of the sediment is approximately 70%. The liquid and plastic limits of the soil are 90% and 50% respectively, and the specific gravity of the material ranges from 2.65 to over 3.00 (Silva, 1979).

PETERSON (1980) conducted consolidated, undrained triaxial tests on undisturbed and remolded samples similar to those used in this study. Values of the angle of internal friction were reported to be between 30 and 32 degrees, and cohesion values were cited in the range of 50 to 100 pounds per square foot.

C. Hyperbolic Fit of Data from Stress Relaxation Tests

The stress-strain behavior of soils was modeled by KONDNER (1963) using a hyperbolic equation containing two constants. The relationship has the following form:

$$\sigma = \frac{\epsilon}{a+b\epsilon} \quad (5)$$

where σ = major deviator stress ($\sigma_1 - \sigma_3$),

ϵ = strain,

a, b = constants to be determined for the particular soil.

The hyperbolic relationship can be used to evaluate the ultimate value of the deviator stress. Thus,

$$\sigma_{ult} = \lim_{\epsilon \rightarrow \infty} \frac{\epsilon}{a+b\epsilon} = \frac{1}{b} \quad (6)$$

Also, the value of the initial tangent modulus of the soil is given by:

$$E_t = \left. \frac{d\sigma}{d\epsilon} \right|_{\epsilon=0} = \frac{1}{a} \quad (7)$$

where E_t is the initial tangent modulus.

This general concept of fitting data to a hyperbolic relationship will be used in this investigation to evaluate the limiting values of stress at $t = \infty$.

III. EXPERIMENTAL INVESTIGATION

A. Description of Soils

Two clay soils were investigated in this study. These included the Pacific marine sediments previously mentioned, and a local silty clay from Fort Collins, Colorado.

The marine sediment corings were gathered in the Pacific Ocean, approximately 3,000 miles north of Hawaii, as part of the Subseabed Project at Sandia Laboratories, Albuquerque, New Mexico. University of Rhode Island researchers have classified the upper five metres as highly plastic, illitic clays, with permeabilities on the order of 1×10^{-7} centimetres per second. The time for 100% primary consolidation to occur was shown to be approximately 250 days (Silva, 1979).

The local silty clay was taken from the Nelson Farm Subdivision in Fort Collins, Colorado and is referred to as Nelson Farm Clay. It is an

aeolian deposit from the front range of the Rocky Mountains. The soil is a tan, silty clay of low plasticity and is classified as CL according to the Unified Soil Classification System. The samples were prepared by sedimentation and pressure saturation of material passing the number twenty mesh sieve.

B. Testing Procedure

1. Apparatus and equipment. The three dimensional triaxial apparatus used for the testing program consisted of an electronically controlled hydraulic system, capable of applying loads in three mutually perpendicular directions to a cubical specimen. The equipment was originally assembled to perform tests on four inch cubical samples of Ottawa sand (Hurley, 1972). The testing chamber was made of case-hardened steel, approximately three inches thick. Five sides of the chamber were permanently fastened together. The sixth, or top, section was removed using an overhead gantry, to allow access to the chamber during sample placement and instrumentation. A cross-section of the chamber is shown in Figure 2.

A hydraulic cylinder, or actuator, was attached to each of three adjacent exterior faces of the chamber. Each actuator was capable of delivering a maximum of 19,000 pounds of force when the hydraulic supply pump was set at its threshold of 3,000 pounds per square inch of pressure. In order to attain the desired resolution during the testing of the clay soils, the hydraulic supply pressure was reduced to approximately 775 pounds per square inch, so that the maximum force applied by an actuator was limited to the rated capacity of the loads cells in use (5000 lb.).

Force transducers of 5,000 pound capacity were mounted on the three exterior faces of the test chamber opposite to the actuators. The force transducers were connected to the chamber by high strength steel bolts tapped directly into the walls of the chamber. Force from the sample inside the chamber was transmitted to the load cell through the use of a spindle and bearing plate mechanism as shown in Figure 3.

The deformation of the sample along each axis was monitored through the use of linear variable differential transformers (LVDT's). Each LVDT was mounted on the actuator and was connected to the hydraulic cylinder by means of a brass rod, as shown in Figure 4. Control of the hydraulic system was accomplished by the use of a Materials Testing System (MTS) console. A diagram of the "closed loop" hydraulic system is shown in Figure 5.

Each loading axis could be operated under either load or deformation control. Communication between the hydraulic ram and the electronic console was accomplished through the use of servovalves mounted on each actuator. The servovalves allowed hydraulic fluid to flow into either side of the hydraulic ram, causing motion in a compressive or tensile direction.

The MTS console housed three sets of electronic components, one set for each channel. One servocontroller, feedback selector, alternating current conditioner, and direct current conditioner were required to control each axis of the testing system. The feedback selector switch could be set to define whether load or stroke signals were allowed to control the movement of a particular actuator.

1. MTS load actuator (Major principal stress)
2. MTS load actuator (Intermediate principal stress)
3. Hold down bolts for top
4. Loading plates
5. Teflon spacer plates
6. Load bearing plates
7. Strainert load cells
8. LVDT rods

Figure 2. Cross Section of Three Dimensional Compression Test Chamber

FIGURE 3. TRANSMISSION OF LOAD FROM AN ACTUATOR TO A LOAD CELL.

FIGURE 4. SCHEMATIC OF DEFORMATION MEASURING SYSTEM.

FIGURE 5. DIAGRAM OF THE CLOSED-LOOP HYDRAULIC SYSTEM.

While under stroke control, the LVDT associated with a particular channel sensed the position of the ram with respect to the location of the core inside the coil housing. A continuous signal corresponding to that position was fed back to the console. The signal was sent to the servocontroller, where a comparison between the feedback signal and an externally applied command signal was made. The difference between command and feedback signals, known as the "error signal", initiated a command signal to the actuator's servovalve, causing a directionally correct movement in the ram until the magnitude of the error signal reached zero. The command signal was applied manually through a "set point" control, located on the front of each channel in the console.

Any of the three channels could also be operated under load control by having the load cell associated with that actuator supply the feedback portion of the error signal. However, only stroke control was used in this investigation. Both load and deformation were monitored at all times during the tests.

2. Specimen preparation. The undisturbed marine sediment samples were prepared from the cores by trimming and shaping with a wire saw and spatula. The remolded specimens were hand-packed in a plastic-lined wooden mold. Samples were cubical and were 2.6 inches on each side. The water contents and densities of the samples are presented in Table 1.

The specimens were hand painted with several coats of a liquid latex material, which was air dried between placement of each layer. The final thickness of the membranes was approximately 0.04 inches. After weighing, the samples were shielded with 0.005 inch thick aluminum strips along the three edges interior to the chamber. The aluminum strips served to transfer stresses around the edges of the sample that were not in direct contact with the loading heads. They also helped to maintain the overall cubical shape of the specimens during the loading phase of the tests.

3. Test set-up and stress application. Before placement in the test chamber, the sample faces and the chamber's teflon bearing plates were sprayed with a silicon spray lubricant, in order to reduce membrane friction. The sample was positioned and the two lateral loading heads were adjusted. The top of the chamber was then bolted to the chamber body. The loading heads were brought up to the point where they just contacted the sample and the load cell bridges were balanced.

The ram heads were then moved inward until the desired initial stress level had been applied. At that point the stop watch was started, and the loading heads were maintained at a constant position during the remainder of the experiment.

4. Monitoring of stress relaxation with time. Three digital voltmeters, each capable of three digit accuracy, were used to monitor loads during the relaxation phase of the tests. In addition, the output voltages from the LVDT's were periodically checked, to insure that the loading heads were stationary during the relaxation phase of each test.

5. Porewater pressure measurement. All samples were tested under unconsolidated, undrained conditions. Additional development of the porewater pressure instrumentation would be necessary to allow porewater pressure to be monitored.

IV. RESULTS

A considerable amount of data has been collected to date. The data is currently in the process of being interpreted in accordance with a functional relationship similar to that presented by HOUSTON and LACERDA (1973). Therefore, only the data is presented herein. Discussion and interpretation of the data will be presented shortly.

Table 2 presents a summary of the initial and final conditions for each experiment that was performed. Figure 6 through 17 present the normalized octahedral shear stress as a function of time on a logarithmic scale. This data will be used to evaluate the relaxation parameters. Figure 18 through 29 show the data plotted in a form to allow determination of the parameters for expression of the data in a hyperbolic form as discussed previously. Use of these hyperbolic parameters can be used to extrapolate to the minimum stress levels to which relaxation will extend.

Table 1 presents the water content, density and saturation data for each experimental specimen.

V. DISCUSSION

This data represents the first that has been collected after development of the equipment. Particular problems had been encountered in developing procedures to provide for encapsulation of the sample in a rubber membrane. These methods have now been worked out. It is recommended that further effort be devoted to development of a porewater pressure instrumentation system and that experiments be conducted in which porewater pressures are monitored. The experiments presented herein were performed on undrained samples. Although the octahedral shear stress is not a function of the porewater pressure, it is highly recommended that redistribution of porewater pressures during relaxation be incorporated into the analysis. Further recommendations will be presented at the time that the analysis and data are completed.

TABLE 1. Water Content, Density and Saturation Data for Stress Relaxation Test Specimens.

Sample	Water Content (%)	Wet Density (pcf)	Degree of Saturation (%)
MSU01	91.8	85.7	90.0
MSU02	91.8	85.7	90.0
MSU03	106.8	87.6	97.0
MSU04	104.4	87.1	94.8
MSU05	94.9	83.1	86.1
MSU06	92.1	87.3	92.0
MSR01	90.7	85.7	88.9
MSR02	90.7	85.7	88.9
MSR03	91.8	90.9	97.0
MSR04	91.8	95.7	100.0
MSR05	88.8	94.8	100.0
MSR06	88.8	94.8	100.0
MSR07	106.8	94.8	100.0
MSR08	90.9	95.1	100.0
NFC01	31.3	117.9	100.0
NFC02	29.4	116.8	92.1
NFC03	29.7	109.8	81.4
NFC04	27.2	117.9	90.4
NFC05	28.3	118.3	92.7
NFC06	29.4	117.4	92.1
NFC07	27.2	115.0	85.2

TABLE 2. Summary of Test Data from Stress Relaxation Tests

Sample	Stress Mode	Octahedral Shear Stress (psi)		Total Stresses (psi)					
		τ_{oct_0}	τ_{oct_f}	σ_{x_0}	σ_{x_f}	σ_{y_0}	σ_{y_f}	σ_{z_0}	σ_{z_f}
MSU01	Isotropic	0.37	0.38	14.93	2.90	15.68	2.24	14.88	2.00
MSU02	Isotropic	0.24	0.05	5.12	2.18	5.68	2.14	5.28	2.06
MSU03	Axisymmetric	1.68	0.77	10.00	2.34	6.40	0.74	6.45	0.66
MSU04	Axisymmetric	1.46	0.85	10.00	2.72	6.81	1.02	6.99	0.83
MSU05	Anisotropic	2.04	1.09	13.02	4.00	10.40	2.40	8.03	1.36
MSU06	Anisotropic	1.93	0.91	13.10	3.14	10.14	1.62	8.40	0.96
MSR01	Isotropic	0.18	0.17	15.01	6.00	14.80	5.60	15.23	5.92
MSR02	Isotropic	0.07	0.10	5.15	2.64	5.33	2.80	5.26	2.56
MSR04	Isotropic	0.35	0.19	15.39	1.42	14.59	1.26	14.75	0.98
MSR06	Isotropic	0.14	0.11	5.24	1.02	5.39	0.86	5.04	0.75
MSR03	Axisymmetric	1.04	0.54	14.96	2.56	12.58	1.45	12.96	1.36
MSR05	Axisymmetric	1.75	0.50	10.00	1.87	5.98	0.83	6.67	0.78
MSR07	Anisotropic	0.66	0.30	10.00	1.36	8.40	0.91	9.07	0.64
MSR08	Anisotropic	1.54	0.76	12.96	3.14	10.40	1.87	9.28	1.33
NFC01	Isotropic	0.46	0.12	5.01	2.35	4.83	2.06	5.89	2.16
NFC02	Isotropic	0.52	0.27	14.80	5.04	15.98	4.93	14.99	4.42
NFC03	Isotropic	0.78	0.21	28.18	9.92	29.58	10.19	30.00	9.68
NFC04	Axisymmetric	3.40	1.66	14.82	5.31	7.68	1.90	7.54	1.70
NFC05	Axisymmetric	2.89	2.15	15.04	9.44	8.80	5.07	9.07	4.70
NFC06	Anisotropic	2.67	1.40	15.26	5.79	10.59	3.63	8.94	2.40
NFC07	Anisotropic	3.79	2.91	14.88	9.55	9.70	5.44	5.60	2.45

FIGURE 6. NORMALIZED OCTAHEDRAL SHEAR STRESS VS. LOG TIME FOR MARINE SEDIMENT SAMPLE MSU03

FIGURE 7. NORMALIZED OCTAHEDRAL SHEAR STRESS VS. LOG TIME FOR MARINE SEDIMENT SAMPLE MSU04

FIGURE 8. NORMALIZED OCTAHEDRAL SHEAR STRESS VS. LOG TIME FOR MARINE SEDIMENT SAMPLE MSU05

FIGURE 9. NORMALIZED OCTAHEDRAL SHEAR STRESS VS. LOG TIME FOR MARINE SEDIMENT SAMPLE MSU06

FIGURE 10. NORMALIZED OCTAHEDRAL SHEAR STRESS VS. LOG TIME FOR MARINE SEDIMENT SAMPLE MSR03

FIGURE 11. NORMALIZED OCTAHEDRAL SHEAR STRESS VS. LOG TIME FOR MARINE SEDIMENT SAMPLE MSR05

FIGURE 12. NORMALIZED OCTAHEDRAL SHEAR STRESS VS. LOG TIME FOR MARINE SEDIMENT SAMPLE MSR07

FIGURE 13. NORMALIZED OCTAHEDRAL SHEAR STRESS VS. LOG TIME FOR MARINE SEDIMENT SAMPLE MSR08

FIGURE 14. NORMALIZED OCTAHEDRAL SHEAR STRESS VS. LOG TIME FOR NELSON FARM CLAY SAMPLE NFC04

FIGURE 15. NORMALIZED OCTAHEDRAL SHEAR STRESS VS. LOG TIME FOR NELSON FARM CLAY SAMPLE NFC05

FIGURE 16. NORMALIZED OCTAHEDRAL SHEAR STRESS VS. LOG TIME FOR NELSON FARM CLAY SAMPLE NFC06

FIGURE 17. NORMALIZED OCTAHEDRAL SHEAR STRESS VS. LOG TIME FOR NELSON FARM CLAY SAMPLE NFC07

FIGURE 18. TIME/NORMALIZED OCTAHEDRAL SHEAR STRESS VS. TIME FOR MARINE SEDIMENT SAMPLE MSUB3

FIGURE 19. TIME/NORMALIZED OCTAHEDRAL SHEAR STRESS VS. TIME FOR MARINE SEDIMENT SAMPLE MSUB4

FIGURE 20. TIME/NORMALIZED OCTAHEDRAL SHEAR STRESS VS. TIME FOR MARINE SEDIMENT SAMPLE MSU05

FIGURE 21. TIME/NORMALIZED OCTAHEDRAL SHEAR STRESS VS. TIME FOR MARINE SEDIMENT SAMPLE MSU06

FIGURE 22. TIME/NORMALIZED OCTAHEDRAL SHEAR STRESS VS. TIME FOR MARINE SEDIMENT SAMPLE MSR03

FIGURE 23. TIME/NORMALIZED OCTAHEDRAL SHEAR STRESS VS. TIME FOR MARINE SEDIMENT SAMPLE MSR05

FIGURE 24. TIME/NORMALIZED OCTAHEDRAL SHEAR STRESS VS. TIME FOR MARINE SEDIMENT SAMPLE MSR07

FIGURE 25. TIME/NORMALIZED OCTAHEDRAL SHEAR STRESS VS. TIME FOR MARINE SEDIMENT SAMPLE MSR08

FIGURE 26. TIME/NORMALIZED OCTAHEDRAL SHEAR STRESS VS. TIME FOR NELSON FARM CLAY SAMPLE NFC04

FIGURE 27. TIME/NORMALIZED OCTAHEDRAL SHEAR STRESS VS. TIME FOR NELSON FARM CLAY SAMPLE NFC05

FIGURE 28. TIME/NORMALIZED OCTAHEDRAL SHEAR STRESS VS. TIME FOR NELSON FARM CLAY SAMPLE NFC86

FIGURE 29. TIME/NORMALIZED OCTAHEDRAL SHEAR STRESS VS. TIME FOR NELSON FARM CLAY SAMPLE NFC87

REFERENCES

- Campanella, R. G., and Vaid, Y. P., 1974. "Triaxial and Plane Strain Creep Rupture of an Undisturbed Clay." Canadian Geotechnical Journal, 11(1): 1-10.
- Christensen, R. W., and Wu, T. H., 1964. "Analysis of Clay Deformation as a Rate Process." Journal of the Soil Mechanics and Foundations Division, ASCE, 90:125-157.
- Eyring, H., 1936. "Viscosity, Plasticity and Diffusion as Examples of Absolute Reaction Rates." Journal of Chemical Physics, 4: 283-291.
- Fujimoto, H., 1964. "The Theoretical Research on the Stress Relaxation of Clay by Thermo-Dynamics and Statistical Mechanics." Proceedings, Rheology and Soil Mechanics Symposium of the International Union of Applied Mechanics, Grenoble, France, 130-141.
- Glasstone, S., Laidler, K., and Eyring, H., 1941. The Theory of Rate Process. New York: McGraw Hill Book Co., Inc.
- Hurley, R. D., 1972. "Three Dimensional Stress Strain Soil Apparatus." Master's Thesis, Colorado State University, Fort Collins, Colorado, U.S.A.
- Kondner, R. L., 1963. "Hyperbolic Stress-Strain Response: Cohesive Soils." Journal of the Soil Mechanics and Foundation Division, ASCE, 89: 115-143.
- Lacerda, W. A., and Houston, W. N., 1973. "Stress Relaxation in Soils." Proceedings, Eighth International Conference on Soil Mechanics and Foundation Engineering, Moscow, U.S.S.R., 1:221-227.
- Lo, K. Y., 1969. "The Pore Pressure-Strain Relationships of Normally Consolidated Undisturbed Clays." Canadian Geotechnical Journal, 6(4): 395-412.
- Mitchell, J. K., 1964. "Shearing Resistance of Soils as a Rate Process." Journal of the Soil Mechanics and Foundations Division, ASCE, 90: 29-61.
- Murayama, S., and Shibata, T., 1964. "Flow and Stress Relaxation of Clays." Proceedings, Rheology and Soil Mechanics Symposium of the International Union of Applied Mechanics, Grenoble, France, 99-129.
- Nacci, V. A., and Huston, M. T., 1969. "Structure of Deep Sea Clays." Proceedings, Civil Engineering in the Oceans, 2: 599-619.
- Nelson, J. D., and Siu, K. L., 1971. "The Influence of Structure on the Dilation of Clay." Proceedings, First Australian-New Zealand Conference on Geomechanics, Melbourne, Australia, 1: 197-203.
- Nelson, J. D., and Thompson, E. G., 1977. "A Theory of Creep Failure in Overconsolidated Clay." Journal of the Geotechnical Engineering Division, ASCE, 103: 1281-1294.

Peng, S. S., 1972. "Time Dependent Aspects of Rock Behavior as Measured by a Servocontrolled Hydraulic Testing Machine." International Journal of Rock Mechanics, Mineral Sciences, and Geomechanics Abstracts, 10: 235-246.

Peterson, D. J., 1980. "Multiple Stage Triaxial Testing of Clays." Master's Thesis, Colorado State University, Fort Collins, Colorado, U.S.A.

Silva, A. J., 1979. Research Progress Report for the Annual Workshop of the Seabed Disposal Program, Department of Ocean Engineering, University of Rhode Island.

Silva, A. J., and Calnan, D. I., 1979. Geotechnical Aspects of Subsurface Seabed Disposal of High Level Radioactive Wastes, Annual Progress Report No. 5, Department of Ocean Engineering, University of Rhode Island.

Singh, A. and Mitchell, J. K., 1968. "General Stress-Strain-Time Function for Soils." Journal of the Soil Mechanics and Foundations Division, ASCE, 94: 21-46.

Appendix N

Annual Report on the High Temperature
Triaxial Compression Device

N. D. Williams, P. Menk, R. Tully and W. N. Houston

ANNUAL REPORT ON THE HIGH TEMPERATURE TRIAXIAL COMPRESSION DEVICE

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INTRODUCTION

The investigation of the environmental effects on the mechanical and engineering properties of deep-sea sediments was initiated on June 15, 1980. The task is divided into three categories. First, the design and fabrication of a High Temperature Triaxial Compression Device (HITT). Second, an investigation of the mechanical and engineering properties of the deep-sea sediments at temperatures ranging from 277 to 473 degrees kelvin. Third, assist in the development of constitutive relationships and an analytical model which describe the temperature dependent creep deformations of the deep-sea sediments.

The environmental conditions under which the soil specimens are to be tested are variations in temperature from 277 to 473 degrees kelvin. The corresponding water pressure will vary up to about 2.75 MPa as required to prevent boiling of the water and assure saturation of the test specimens. Two groups of tests are to be performed. First, triaxial compression tests during which strength measurements and constant head permeability determinations shall be made. Second, constant stress creep tests, during which axial and lateral strains shall be measured. In addition to the aforementioned variables, data shall also be acquired to incorporate the effects of consolidation history, strain rate, and heating rate. The bulk of the triaxial tests are to be performed undrained. The strength measurement tests are at constant-rate-of-strain and the creep tests are to be constant-stress tests.

The study of the mechanical properties of the deep-sea sediments as a function of temperature is an integrated program. However, the low temperature tests (277 and 313 degrees kelvin) are being performed in a different laboratory and by different personnel. Therefore, for convenience in reporting, the annual report will be subdivided into two sections: 1) High Temperature Triaxial Compression Device and 2) Low Temperature Test Program. The third section is devoted to a discussion of the data acquired to date.

HITT EQUIPMENT DESIGN

The High Temperature Triaxial Compression Device (HITT) is shown in Figure 1. Soil samples which are 3.56 cm in diameter can be tested at temperatures ranging from 293 to 473 degrees kelvin at pressures ranging from 0.1 to 14.0 MPa. The major components of the system are fabricated from bar stock type 321 stainless steel. Type 321 stainless steel was selected because of its thermal properties and its resistance to corrosion. All system components were annealed to relieve stresses induced by machining.

The Main Chamber Reservoir is sealed vertically into the Top Plate and Bottom Guide using viton o-rings and tie-down rods. Viton o-rings were used because they remain elastic at all temperatures used in the investigation and because the maximum temperature used in the HITT is lower than the heat distortion temperature of the viton. The seals at the top and bottom of the Main Chamber Reservoir are designed to be semi-permanent to minimize the risk of leakage and to prevent damage to the heating system. The top plate is gently sloped from the edge of the cylinder to the load rod to facilitate air removal and to inhibit air bubble

Figure 1. High Temperature Triaxial Cell Assembly

entrapment.

The load rod enters the Main Chamber Reservoir through the Rod Guide. The Load Rod is made of type 440C stainless steel which has been case hardened to 60C and has been stabilized by freezing. The case hardening is necessary to prevent biting by the balls in the ball bushings. The Load Rod is then ground to the desired diameter and annealed to relieve stresses induced by the machining and case hardening processes. Type 316 stainless steel ball bushings are used to guide the rod into a vertical position. The Rod Guide is sealed to the top plate through a semi-permanent o-ring seal. The load rod is sealed using two reciprocating, inside-seal o-rings. The space between the o-rings is tapped and a purge valve has been placed on the tap to prevent pressure build-up between the two o-rings. The second o-ring is used to prevent leak development of the high temperature and pressure chamber fluid.

The soil sample is mounted between the Bottom Sample Holder and the Top Cap. The Bottom Sample Holder is grooved to facilitate even distribution of backpressure. The top cap has a recessed connection to the Load Rod. This recessed connection allows free rotation of the Top Cap through 2 degrees from the vertical, but prevents further rotation. This prevents premature failure of anisotropic samples or samples which have not been trimmed perfectly horizontal at the top and bottom. In addition the recessed connection prevents transmission of a moment to the top of the sample until the 2 degree rotation has been reached. The influent salt water line is connected to the Bottom Sample Holder by a coiled copper tube. The effluent salt water line is connected to the Top Cap by a coiled copper tube which spirals vertically around the soil sample.

The Sample Membranes seal to the Top Cap and Bottom Sample Holder with viton o-rings. The Sample Membranes are made of viton and are cast and ground to a wall thickness of 0.0635 cm with an allowable tolerance of plus or minus 0.0025 cm. Grinding is required of the viton Sample Membranes in order to construct a membrane for which compliance can be quantified. The membranes are flexible at room temperature and remain intact and impermeable at elevated temperatures. Problems encountered in membrane compliance tests and recommendations are discussed in a later section of the report.

There are two heaters in the system. The Zone 1 Heater is a flexible 1500 watt silicone rubber heater backed by 0.64 cm of silicone rubber insulation. The Zone 1 Heater is 26.67 by 45.95 cm and is affixed to the exterior surface of the Main Chamber Reservoir by 5 hose clamps. The Zone 2 Heater is a 12.70 cm diameter 500 watt silicone rubber heater without insulation which is mounted to the base Plate. The Zone 2 Heater is provided to add heat to the system which is lost due to conduction through the base plate. The temperature of the system is controlled by thermocouples located in the Main Chamber Reservoir. Each zone has a Proportional Controller capable of maintaining the cell temperature at elevated temperature (to 533 degrees kelvin) for an extended period of time with an accuracy of 1 degree kelvin. In addition to the Zone 1 and Zone 2 Controllers there is an alarm system which is designed to shut the system down should thermal runaway occur. The controllers are programmable so that variable heating rate and transient problems can be investigated using the system.

The Load Cell is fabricated from type 321 stainless steel. The Load Cell is a diaphragm type as shown in Figure 2. The full wheatstone bridge is located on the bottom side of the diaphragm. The Load Cell is mounted inside the Main Chamber Reservoir and is bolted to the Bottom Plate. A viton o-ring seal is provided between the Load Cell and the Bottom Plate. The Bottom Sample Holder screws into the center of the Load Cell. The use of an internal load cell eliminates the need for a frictionless connection at the top of the Triaxial Cell. The loads which are measured by the Load Cell are the actual loads on the sample. No further calibration is required for load rod friction or for spring resistance in the effluent saltwater line.

The Load Cell is designed for a maximum axial load of 85 N. This is well above the anticipated failure load of the soil sample. The Load Cell has a minimum resolution of approximately 0.09 N. The cell is designed to bottom out before the elastic limit of the diaphragm is reached. The top side of the diaphragm is immersed in the glycerine chamber fluid, while the bottom side of the diaphragm is backpressured to the same pressure with nitrogen gas. This

TOP VIEW

SECTION A - A

NOTE: MAXIMUM AXIAL LOAD = 19.45 LB.

Figure 2. Load Cell

prevents contamination and fouling of the strain gages, but introduces an extra degree of complexity into the design of the constant effective stress apparatus. The electrical leads to the strain gages are taken out of the system through a multi-lead feed through. The feed through has a maximum pressure rating of 3.44 MPa at a temperature of 294 degrees kelvin, which necessitates isolation of the feed through from the elevated temperatures of the system. Temperature compensation of the wheatstone bridge is taken care of by locating the entire bridge within the temperature regime. The strain gages used in the system are temperature compensating and are recommended for use in the elevated temperature range in which they are placed.

The Constant Effective Stress Apparatus is shown in Figure 3. There are four main components in the Constant Effective Stress Apparatus; the nitrogen gas driving pressure system, the mercury manometer, the salt water influent, and the glycerine cell fluid.

The nitrogen gas driving pressure is provided by bottled nitrogen gas. The system pressure is controlled by a flow regulator and fed to the mercury manometer, the load cell, and the volume change device. The reason that a conventional constant effective stress apparatus can not be used is because the cell pressure must be equal to the nitrogen driving pressure in order to prevent pressure loading of the Load Cell.

The Mercury Monometer consists of two small acrylic reservoirs connected by 0.318 cm (0.125 inch) O.D. flexible tubing. The manometer is enclosed in a closet to prevent lab contamination in case of leakage in the manometer lines. One of the reservoirs is suspended by a spring. The spring is designed to compensate for changes in the mercury level, thus providing a constant effective stress. The manometer is designed to provide effective stresses from 0.00 to 0.362 MPa. Higher effective stress can be achieved by providing another reservoir and operating it in series with the existing system. The minimum resolution of the system is about 0.10 kPa.

The glycerine used in the HITT is contained in the accumulator. The accumulator has a rubber diaphragm which eliminates a gas fluid interface. The Main Chamber Reservoir of the HITT can be charged by pressurizing the accumulator. After the tests have been completed, the glycerine is returned to the accumulator by backpressuring the Main Chamber Reservoir.

The Volume Change Device shown in Figure 4 is designed to provide automatic volume change measurement capability. The device has a resolution of 0.1 cc change in volume, a total capacity of 60 cc, and operates at backpressures up to 6.9 MPa. The change in volume of the specimen is measured by weighing the expelled pore water fluid. This is accomplished by suspending the fluid reservoir from the ends of cantilever beams and instrumenting the cantilever beams with strain gages. The cantilever beams consist of the sample effluent and back-pressure tubes. The tubes used for the cantilever beams are designed to withstand the back-pressure, to be short enough to be practical, to have measurable strain, to have adequate resolution, to be stable under locally induced variations in temperatures (under strain gages), to be stable under the total load, to be resistant to corrosion by the saltwater, to have low water adsorption properties, and be capable of being machined to the required dimensions. Several materials were investigated including stainless steel, aluminum, beryllium copper, lexan, acrylic, rigid PVC, and type 6 cast nylon. The only material which was found suitable for all of the above conditions and could be machined using existing equipment was type 6 cast nylon. The cantilever beams deflect approximately 0.635 cm (0.250 inch) under maximum load and have a strain of about 2.5 micrometers/meter for a change in load of 0.0004448 N. The beams are pressure fit into a clear plexiglass protection cubical and connected to the clear acrylic main reservoir. The pore water effluent enters the main reservoir at the bottom center and the back-pressure at the top of the side wall. Oil is placed at the interface between the fluid and the gas to prevent evaporation of the fluid.

Figure 3. Constant Effective Stress Apparatus Assembly Diagram

Figure 4. Volume Change Device

HITT FABRICATION AND ASSEMBLY

The HITT assembly diagram is shown in Figure 5. The valves are mounted in a tinted plexiglass panel as shown in Figures 6 and 7. After a sample has been mounted between the Bottom Sample Holder and the Top Cap, a viton sample membrane is placed over the specimen and sealed to the Bottom Sample Holder and Top Cap with viton o-rings. The Main Chamber reservoir is then sealed and the glycerine is introduced into the system by pressurizing the accumulator and opening the Glycerine Influent Valve. The system is filled when the pressure transducer, used to monitor cell pressure, and the nitrogen driving pressure are equal. Care must be taken to pressurize the system slowly so that the cell pressure and the load cell back-pressure don't differ by an amount large enough to damage the Load Cell or the Volume Change Device. Purge valves are located on the glycerine influent and effluent lines. These valves can be used to bleed off any gas which may be trapped in the system. A bleed screw is provided on the pressure transducer to vent any air trapped in the transducer.

The salt water influent and effluent lines have been deaired by first pulling a vacuum on the system, introducing carbon dioxide gas, and pushing deaired salt water through the system. Further deairing can be accomplished if necessary by flooding the required portions of the system with carbon dioxide gas and introducing deaired salt water. It will always be necessary to deair and fill the effluent salt water line which coils around the sample inside the Main Chamber Reservoir and to check for entrapped air in the salt water lines.

After the glycerine and salt water lines have been deaired the soil sample can be saturated. This can be accomplished by pressuring the influent salt water line and pushing deaired salt water through the soil sample. The pressure is monitored using the salt water pressure transducer. The "B" value, which is the change in pore pressure divided by the corresponding change in chamber pressure under undrained conditions, increases with increasing degree of saturation. Saturation is achieved as the "B" value approaches 1.0.

The soil sample can be consolidated either isotropically or anisotropically. The effective stress used for consolidation is achieved by adjusting the mercury manometer reservoirs to a given difference in height which can be simply determined (See Figure 8). If anisotropic consolidation is required, the desired axial stress can be achieved by loading the sample axially. Axial loads on the sample are provided by a Bellofram Loader which is extended into the low load range using a pressure pot. Using this system, any desirable stress path can be followed during consolidation.

After consolidation of the sample is complete, the drained, strain controlled triaxial compression test can progress. Volume change in the soil sample is measured in two ways. First, the axial deformation is measured using a DCDT. Second, the average volumetric strain is measured by measuring the volume (weight) of the expelled pore water. If for any reason this system is found to be inadequate, a 12 point fin type radial strain device has been designed which can be located inside the cell. This, however, would require extensive design remodification of the Main Chamber Reservoir so that the lead wires could be taken out of the cell. It is not anticipated that such a problem will occur.

In addition to the strain-controlled consolidated drained triaxial compression test, stress controlled CD tests, stress and strain controlled CU or UU tests, and constant stress or constant load creep tests can be run on the system. A simple design modification would also allow one-dimensional consolidation tests to be run on the system. These tests can be run at any temperature from 294 to 473 degrees kelvin and at any pressure from 0.0 to 3.44 MPa. In addition, transient problems such as variable heating rate can be run by programming the temperature controllers. Constant head permeability tests can be run at any temperature, in the range previously mentioned, at any chosen point during the triaxial compression test.

When the test has been completed, the glycerine is removed from the Main Chamber Reservoir by backpressuring the system with nitrogen gas at the On Line Pressure Transducer Calibration Port located on the glycerine effluent line. It is necessary to pressurize the bottom side of the load cell during removal of the glycerine. When the glycerine is removed, the

Figure 5. Hitt Assemble

Figure 6. The High Temperature Triaxial Compression Device

Figure 7. The Triaxial Cell with the Zone 1 Heater

p_N = nitrogen gas pressure

$p_A = p_N$

$p_B = p_A - h_1 p_{Hg}$

$p_C = p_E - h_2 p_{Hg} = p_A - (h_1 + h_2) p_{Hg} = p_N - (h_1 + h_2) p_{Hg}$

$p_C = p_D$

$p_E = p_D + h_2 p_{H_2O} = p_N - (h_1 + h_2) p_{Hg} + h_2 p_{H_2O}$

$p_F = p_E = u_{\text{specimen}} = \text{back pressure} = \text{b.p.} = u_{bp} = p_{bp}$

$p_G = p_N$

$p_H = p_G - h_3 p_{Gly} = p_N - h_3 p_{Gly}$

$T'_{3c} = \text{effective stress} = p_H - p_F = \text{chamber press} - u_{\text{spec}}$

$$T'_{3c} = \begin{cases} (p_N - h_3 p_{Gly}) - \\ (p_N - (h_1 + h_2) p_{Hg} + h_2 p_{H_2O}) \end{cases}$$

$$= p_N - h_3 p_{Gly} - p_N + (h_1 + h_2) p_{Hg} - h_2 p_{H_2O}$$

$$= -h_3 p_{Gly} + h_1 p_{Hg} + h_2 p_{Hg} - h_2 p_{H_2O}$$

$$= h_1 p_{Hg} + (h_2) (p_{Hg} - p_{H_2O}) - h_3 p_{Gly}$$

$$T'_{3c} = h_1 p_{Hg} + h_2 (p_{Hg} - p_{H_2O}) - h_3 p_{Gly}$$

Figure 8. Effective Stress Calculations

bottom seal is broken by removing 4 bolts, and the upper portion of the Triaxial Cell is hoisted up using a block and tackle assembly. The connection of the effluent salt water line to the base plate is broken and the sample, sample membrane, top cap, salt water effluent coil and o-rings are removed as a single unit. The soil sample can then be removed and used for further tests or examined for changes in physical appearance.

CALIBRATION OF HITT EQUIPMENT

The internal Load Cell used in the system was calibrated inside the Main Chamber Reservoir. The Load Cell was initially calibrated at 294 degrees kelvin. This was accomplished by successively loading and unloading the Load Cell in 9.79 N increments from 0.0 to 127.22 N a total of 6 times. The calibration curve for the 294 degree tests is shown in Figure 9. The heating system was then engaged and the system was brought to a temperature of 380 degrees kelvin and allowed to stabilize. When the system was stable the same loading procedure was used as previously explained. The final series of tests were run at a temperature of 474 degrees kelvin.

The calibration curves at all temperatures are linear and the slope of the line is not greatly affected by temperature. However, the zero shift of the Load Cell Bridge is nonlinear and difficult to quantify. During the transient stage of heating up there is a large zero shift due to temperature induced strains in the Load Cell. As equilibrium is approached the zero shift reverses direction. At equilibrium, the zero position of the bridge output varies through plus or minus 0.0015 points on the voltmeter. This would correspond to a change in load of 0.127 N. This shift is proportional to the change in temperature about the set point; therefore, it may be possible to fine tune the zero shift so that a resolution of 0.02 to 0.03 N is achievable.

There are two differential pressure transducers in the system, one for measuring the head difference in the permeability test, and one for measuring the difference in cell pressure and backpressure or the effective stress. These transducers are isolated from temperature and are calibrated at a temperature of 294 degrees kelvin. The cell pressure and backpressure transducer has a diaphragm which allows a 3.44 MPa pressure differential between the two sides. Each side is calibrated at 0.173 MPa intervals to 3.41 MPa. The calibration is repeated 8 times and is linear and reproducible. The loading is accomplished using a piston type dead weight pressure gage calibrator with weights which are traceable to the National Bureau of Standards. The permeability pressure transducer has a maximum allowable pressure differential of 0.653 MPa. The transducer was calibrated in 0.098 MPa intervals to 0.587 MPa. The transducer was calibrated by applying house air pressure through a pressure regulator and an accurate pressure gage which is traceable to the National Bureau of Standards. Both transducers have linear calibration curves and are reproducible. The minimum resolution of the first transducer is approximately 0.0004 MPa and the second is approximately 0.00007 MPa.

The Volume Change Device is isolated from temperature and will be calibrated at 294 degrees kelvin. Calibration will be accomplished by successively loading the reservoir with known and traceable weights from 0.0 to 0.391 N in 0.049 N intervals. The Volume Change Device has not yet been calibrated, but calibration will proceed as outlined when the containment cubical has been completed.

MEMBRANE COMPLIANCE TESTS FOR THE HITT

Henkel and Gilbert (1952) have concluded that the correction for the contribution to the measured strength by the sample membrane can be estimated from the membrane extension modulus. The extension modulus can be determined at all temperatures at which triaxial compression tests are to be run.

The extension modulus is measured by applying a load to a section of sample membrane and measuring the resulting deformation. The apparatus used to measure the extension modulus is mounted inside the HITT as shown in Figure 10. Two sections of viton sample membrane 3.56 cm in diameter by 2.54 cm long by 0.064 cm (0.025 inch) thick are cut and mounted on the top and bottom sample holders. Weights are then placed on the loading yoke

Figure 9. Load Cell Calibration Curves

Figure 10. Membrane Extension Modulus Measurement Apparatus

and the resulting deformation is measured using a dial gage. The tests are conducted at 3 temperatures, 294, 382, and 472 degrees kelvin. The results of the tests are shown in Figures 11 and 12. There is a slight curvature to the data of Figure 11, but the data can be represented by a straight line with satisfactory accuracy. The inverse of the slope of the best fit straight line is the extension modulus, which is equal to the load per unit length divided by the axial deformation. The effect of temperature on the extension modulus is shown in Figure 12.

The extension modulus for the viton membrane is approximately 1 order of magnitude higher than the extension modulus of a thick rubber sample membrane. Therefore, the previous empirical work by Henkel and Gilbert cannot be extended to predict an accurate correction factor for the viton sample membrane, unless it is simply assumed that the membrane correction is directly proportional to the modulus.

There are several methods which can be used to determine a satisfactory correction factor for membrane compliance. One method is to determine the Young's Modulus for the membrane (can be determined from the extension modulus) and perform an elastic analysis. This approach gives only a gross approximation because the deformation of the membrane is not elastic. During the consolidation process the viton membrane may fold or crease, and as the sample is deformed axially the response of the membrane would be something less than that predicted by an elastic analysis.

A second method to estimate the correction factor would be to run a Finite Element Analysis of the sample and sample membrane during consolidation and loading. Single or multiple folds could be modeled and an approximate correction factor could be found.

A third method would be to extend the work done by Henkel and Gilbert. This would involve running a series of unconfined compression tests and triaxial compression tests at room temperature and plotting the data in a manner similar to that used by Henkel and Gilbert. This would place an upper bound on the correction factor and the correction factors at elevated temperatures could be estimated using the extension modulus variation shown in Figure 12.

As of the writing of this report it is planned that two or more of these methods will be used to determine a suitable correction factor. Because it may yet be found that the relatively thick, stiff viton membranes are unsuitable in this application, other types of membranes are being investigated to determine their potential value to the project. Based on very recent tests it has been tentatively concluded that ordinary latex membranes can be used at temperatures up to at least 373 degrees kelvin.

LOW TEMPERATURE TRIAXIAL TESTING PROGRAM

Work performed in 1980 consisted of efforts in three areas; overhaul and refurbishing of existing testing facilities, modification of existing testing facilities, equipment calibration, and the development and implementation of a Quality Assurance Program.

The complete overhaul of the testing facilities included replacement of virtually all tubing and fittings. Air pressure regulators and pore pressure transducers were tested, and those found sub-standard were replaced. The electrical system was renovated. Wiring was replaced as needed, and was bundled, labeled, and more efficiently routed. All unshielded portions of wire were minimized, and detachment plugs were installed on LVDT connections for easier maintenance and calibration. Components in the automatic data acquisition system were removed for cleaning, checking, and maintenance.

Modifications of the existing testing system were necessary to accommodate the SDP. The cyclic loading system was removed to allow performance of static tests. Existing air bellofram loaders were found to be inadequate for long term stress control, requiring design and installation of a dead weight loading system to be used for creep and permeability tests. Stress may be held constant during the course of the creep tests with incremental adjustments to the weight made by adding weighted lead shot. Permeability measurements may be made by inducing a small head differential across the sample, and recording the flow in and out per unit of time. Further modifications of the testing cells were needed to incorporate this capability. New

Figure 11. Viton Membrane Compliance Experiment
Extension Test

Figure 12. Viton Membrane Compliance Test
Extension Modulus vs. Temperature

volume change devices were constructed and installed to measure water flowing into the sample during a permeability test. This provides a check on those volume change devices measuring the outgoing water, and insures that any extra water flowing out due to sample consolidation will be noted and not included in the permeability calculations. Installation of extra sensitive pressure transducers were required to accurately control and measure the small head differential.

An oil bellofram loading system shown in Figure 13, was constructed to perform strain controlled strength tests. New pressure regulators were added to deliver driving pressure to the oil reservoirs feeding the belloframs. Selection of a bellofram model with a large piston area allows accurate strain control at low, steady rates. External load cells attached to the bellofram piston measure the load applied to the sample. Figures 14 and 15 show completed modifications to the pressure system and electrical system, respectively. In addition, the general scheme of the new testing system may be seen.

A Quality Assurance Program was developed so that National Bureau of Standards (NBS) traceability was obtainable for all measurements to be taken during tests. Companies certified for NBS calibration provided official traceability to:

- 1) A Fluke Voltage Calibrator for calibration of all voltmeters used,
- 2) Micrometer actuated LVDT calibrators,
- 3) Wall-mounted HEIZE pressure gauges for transducer calibration,
- 4) Mettler balances, and
- 5) A series of thermometers.

Pore pressure transducers, LVDT's, load cells, voltmeters, weights, and volume change devices are all calibrated to NBS traceability, and will be checked at 6 month intervals.

A Quality Assurance Officer has been appointed to maintain all documents and records concerning NBS certification, and insure continued equipment calibration checks.

CONSOLIDATION TESTS

One dimensional consolidation tests were run on remolded and undisturbed samples of seafloor sediment at temperatures of 277 and 294 degrees kelvin. The 277 degree tests were run in a constant temperature compartment while the 294 degree tests were run in the constant temperature soil mechanics laboratory. The shear strengths of the respective soils were obtained at the completion of the consolidation test. Care was taken to remove and test the samples at identical strain rates. The shear strengths were measured using a 1 inch diameter vane shear device. Two tests were performed with the vane shear device for each desired measurement and the results were then averaged. The parameters which were identified to be of special interest in the investigation were the Coefficient of Secondary Compression, the Shear Strength, the Coefficient of Consolidation, the Strain Consolidation Index, the change in Void Ratio with Effective Stress, the change in Axial Strain with log Time, and the Permeability. The Permeability of the soil samples was back calculated from the coefficient of consolidation for each effective stress increment.

The change in axial strain with log time for an undisturbed soil with an effective stress of 52 kPa is shown in Figure 16. There are several important features in the curves. First, the time required for 100% of primary consolidation to occur is 13.0 minutes for the sample at 294 degrees and 48.0 minutes for the sample at 277 degrees kelvin. Therefore, primary consolidation occurs more rapidly at higher temperatures in this temperature range. Second, the slope of the secondary compression curve is greater for the 277 degree sample than for the 294 degree sample. Therefore, secondary compression occurs more rapidly at low temperatures in this temperature range, and the overall effect appears to be self-compensating. Third, there is an

Strain Control

- 1.) $Q = kiA$
- 2.) Flow control reg. keeps constant head differential between points A & B.
 $\therefore i = \text{constant}$
- 3.) $A = \text{constant}$
- 4.) Metered valve controls k , & hence flow rate, which results in constant strain rate.

Figure 13. Oil Bellofram Loading System
Using Flow Control

Stress Control

- 1.) 3-way valve shuts off strain control system, & stress may be controlled directly by air-oil pressure system.

Key

R	= Regulator	G	= Gauge
R ₀	= House Line	G ₁	= Panel Gauge
R ₁	= Top Back Press.	G ₂	= NBS Calibrated Wall Gauge
R' ₁	= Oil Reservoir Press.		
R ₂	= Bottom Back Press.		
R ₃	= Cell Press.		

*See detailed schematic showing flow control system

Figure 14. Low Temperature Triaxial Compression
System Assembly

Figure 15. Wiring Schematic

Figure 16. Consolidation Curve for an Undisturbed Sample

initial axial strain of 2.05 per cent in the 277 degree sample. This results from a preload placed on the sample by the equipment used in the 277 degree room. This preload is insignificant and should be ignored.

The effect of temperature on the rate of primary consolidation can best be illustrated by a plot of Coefficient of Consolidation versus Effective Stress as shown in Figure 17. The significant features of this plot are that the Coefficient of Consolidation is higher at 294 degrees than at 277 degrees for all values of effective stress, and that there is an increase in the Coefficient of Consolidation with effective stress at both temperatures investigated.

The effect of temperature on the rate of secondary compression is shown in Figure 18. The values of the Coefficient of Secondary Compression are two to three times higher for the sample at 277 degrees kelvin than they are for the sample at 294 degrees kelvin.

The shear strengths of the remolded and undisturbed samples were measured using a laboratory vane shear device. The undisturbed sample was tested at an effective stress of 52 kPa and at a strain rate of 1.2×10^{-4} % per minute. The axial strain rate which results from a one-dimensional consolidation test decays exponentially. This strain rate would affect the measured strength values were it different for the two samples. Therefore, care was taken to remove and test the samples at identical axial strain rates. The strain rates given for the test are the strain rates of the consolidation test at the time of removal and not the strain rates of the laboratory vane shear device. The shear strength at 277 degrees was 26 kPa while the shear strength at 294 degrees was 29 kPa. This represents an increase in shear strength of 11% with an increase in temperature from 277 degrees kelvin to 294 degrees kelvin. The remolded sample was tested at an effective stress of 13 kPa and at a strain rate of 3.5×10^{-5} % per minute. The shear strength of the 277 degree sample was 48 kPa while the shear strength of the 294 degree sample was 53 kPa. This represents a net increase of 11%. It should be noted that it is difficult to calibrate a vane shear device. Therefore the absolute values of vane shear strength may not coincide precisely with triaxial results. However, the relative values can be relied upon to show percentage increase or decrease, which was the object of these measurements.

The effect of temperature and effective stress on the permeability are shown in Figure 19. The permeability is unaffected by temperature in the low pressure range but the permeability of the 294 degree sample is substantially higher at higher effective stress.

An increase in temperature in the soil regime has four important effects. First, there is a viscosity effect on the pore water and the adsorbed water. As the temperature is increased the viscosity and shearing resistance of the pore water and adsorbed water decrease. This decreases the strength of the soil and also causes a decrease in void ratio. Second, the pore fluid and soil particles expand with increasing temperature. This causes a decrease in strength and an increase in void ratio. Third, there is a reduction in yield strength of the soil particles at the soil to soil contact points. This causes a decrease in void ratio and a decrease in shear strength of the soil skeleton. Fourth, the thickness of the double layer is affected by the temperature. However, as the temperature increases, which would increase the thickness of the double layer, the dielectric constant of the pore water decreases, causing a decrease in the thickness of the double layer. These effects tend to be self-compensating.

The combined effect of these four effects for the field drainage conditions is two-fold. First there is a decrease in void ratio, or the sample tends to consolidate under load. This densification of the soil increases the shear strength. The second effect is a decrease in shear strength due to a change in viscosity of the pore water and adsorbed water. In the temperature range investigated the effect of consolidation is greater than the viscosity effect and the result is an increase in strength with increasing temperature. However, this may not be the case at higher temperatures where the effect of decreasing yield strength at the contact points would have a more dominant effect.

Figure 17. Coefficient of Consolidation

Figure 18. Coefficient of Secondary Compression

Figure 19. Permeability vs. Pressure
Remolded Samples

CURRENT AND FUTURE WORK

The work to be completed under the 1981 contract is as follows:

- 1) Calibrate thermocouples at 323, 373, and 473 degrees kelvin.
- 2) Calibrate load frame for different strain rates.
- 3) Calibrate the LVDT used to measure axial strain.
- 4) Perform an axisymmetric Finite Element Analysis of the soil sample and sample membrane to determine an appropriate correction factor. Include the effect of folds in the sample membrane.
- 5) Deair the Volume Change Device and calibrate the wheatstone bridge for the desired weight range.
- 6) Deair the salt water lines and introduce salt water into the system.
- 7) Mount a trial sample in the system.
- 8) Run a preliminary test at the fast and slow strain rates.
- 9) Evaluate the performance of the system.
- 10) Make any required modifications to the system.
- 11) Begin the testing program for the soil samples at elevated temperatures.
- 12) Design, fabricate, and assemble another HITT.

It is anticipated that trial tests on soil specimens shall begin on or before March 1, 1981. The design or assembly modifications would then be made and tests on real specimens would begin.

The variables considered to be of primary importance in the HITT testing program are strain rate, temperature, lateral pressure coefficient, and vertical effective stress. Two strain rates shall be used in the HITT testing program, a fast and a slow strain rate, with tests being run to 20% to 30% total strain. Tests shall be run at two temperatures on the HITT, 373, and 473 degrees kelvin. Two lateral pressure coefficients shall be investigated, 1.0 and 0.6. A vertical effective stress of 32 kPa shall be used for essentially all of the tests.

It is recommended by the University of California at Berkeley that another HITT be fabricated so that more tests can be run during a given period of time. A second HITT could be fabricated for the following cost:

MATERIALS

1) Stainless Steel	\$1500.00
2) Load Rod	\$25.00
3) Tie Down Rods	\$25.00
4) Seals	\$100.00
5) Valves and Fittings	\$900.00

6) Instrumentation	\$1950.00
7) Heating System	\$1500.00
8) Bottled Nitrogen Gas	\$15.00
9) Tubing	\$100.00
10) Volume Change Device	\$300.00
11) Ball Bushings	\$40.00
12) Valve Mount Panel	\$100.00
13) Sliding Crane	\$100.00
14) Miscellaneous	\$2345.00
TOTAL =	\$9000.00

LABOR

Machinist	\$5000.00
Research Assistant	\$1500.00
TOTAL =	\$6500.00

The total cost to fabricate would be approximately \$15,500.00. This cost includes all materials and labor required to fabricate and assemble the system but doesn't include the labor required to deair the system and make it operational.

RESULTS AND CONCLUSIONS

The results of the research program for 1980 may be summarized as follows:

- 1) The design, fabrication, and assembly of the HITT is complete with the exception of the Volume Change Device Containment Cubical.
- 2) The Low Temperature Triaxial Compression Equipment has been renovated and reconditioned and resumption of testing of soil specimens is eminent.
- 3) For the HITT apparatus, the internal Load Cell in the specimen base has been calibrated and checked and it appears to be accurate, reproducible, and reliable. The calibration curve is linear for all temperatures tested and the zero shift effect can be quantified. The slope of the calibration curve is not greatly affected by the temperature.
- 4) Membrane Compliance Tests have been conducted but further investigation is required before a correction factor or equation can be determined. The Finite Element Method, an elastic approach, and an empirical method are being investigated to determine an appropriate correction factor.
- 5) The pressure transducers have been isolated from temperature and calibrated on-line. The calibration curves are linear and reproduceable.

6) The data resulting from one dimensional consolidation tests at different temperatures is useful and interesting. Further tests shall be conducted at elevated temperatures to extend the range of the results.

7) A Quality Assurance Program has been developed and a Quality Assurance Officer has been appointed to ensure compliance.

REFERENCE

Henkel, D. J., and Gilbert, G. D., (1952), "The Effect of the Rubber Membrane on the Measured Triaxial Compression Strength of Clay Samples," *Geotechnique*, vol. 3.

Appendix O
Physical Simulations Using
Centrifuge Techniques

H. J. Sutherland

PHYSICAL SIMULATIONS USING CENTRIFUGE TECHNIQUES

by

Herbert J. Sutherland

INTRODUCTION

The long-term mechanical response of deep ocean sediments to the emplacement of waste canisters and to the temperature gradients generated by them involve phenomena that are driven primarily by the force of gravity. This driving mechanism involves body forces interacting with the geometry of canister emplacement and temperature gradients to create an overburden stress distribution which, in turn, interacts with structural configurations, material properties, and tectonic activity (which defines boundary conditions) to produce horizontal stress states. This complicated stress state may be duplicated in a reduced-scale model if the body force (apparent force of gravity) acting on the model is increased in the same proportion that the scale is decreased.¹ A centrifuge can be used to increase the body force in the model. Thus, with equal material densities, the stress field that occurs in the actual structure is reproduced in the scaled model. And, if sediments from the field site are used to construct the centrifuge-loaded scale model, then regardless of the complexity of the materials' stress-strain behavior the displacement and strain field will be reproduced in the model as well.

A relatively simple example (slope stability) of this physical scaling is given in Figure 1. For this case, the nondimensional stress N can be written in terms of the specific gravity γ , the height H , and the cohesion C . The design safety factor F can then be posed in terms of N , the shear angle ϕ , and the geometry of the slope. In this simulation, all linear dimensions are reduced by the scaling factor n ($n = 100$ in Figure 1) and the body force is increased by the same factor. As seen in this figure, this technique keeps the stress distributions in the model equal to that in the prototype, and by using materials from the site, all material constants remain the same. Thus, all parameters in the model duplicate those in the prototype, and the design of the structure may be verified.

The scaling factor n carries over to the other parameters.² Some of these scaling relations are shown in the table. Of prime importance are the relations for time. These relations vary depending on the physical processes involved. As an example, diffusion processes scale as n^2 ; i.e., one hour on the centrifuge at $n = 150$ is equivalent to approximately 2.6 years for the prototype structure. Thus, time scaling may provide a technique for "accelerated-life-testing" of full-size prototype structures.

Table: Scaling Constants

<u>Parameter</u>	<u>Symbol</u>	<u>Scaling</u>
Length	L	n
Area	A	n^2
Volume	V	n^3
Stress	σ	1
Modulus	E	1
Time	t	1, n, n^2
Force	F	n^2
Moment of Inertia	I	n^4
Weight of Explosive Charge	C_e	n^3
Period of Oscillation	T	n

As summarized in Figure 2, centrifuge simulations provide the experimenter/designer with a method for predicting large-scale field events. And, when this technique is combined with computer simulations, the field event can be predicted by two independent methods. Moreover, the centrifuge simulations with their closely controlled models and boundary conditions can be used to refine and/or verify computer models, and the computer models with their versatility can be used to identify all important features of the prototype which must be modeled in the physical simulations. Thus, more confidence in the predictions of both models is obtained.

To accurately simulate the mechanical response of the canister/sediment system requires (1) a large centrifuge with the necessary fixtures for testing geotechnical structures, and (2) an understanding of the laws that govern the scaling of all phenomena pertinent to the problem. Both areas were addressed during the past year.

CENTRIFUGE SIMULATIONS

Modifications to the Sandia-25 Centrifuge

Sandia's 25 ft-radius centrifuge is currently being modified to permit the testing of scale models of geotechnical structures. The modifications include: (1) a medium-scale 2-D specimen box, (2) a large-scale 2-D specimen box, (3) a swing platform, and (4) a mirror system. The two specimen boxes are designed to test two-dimensional (slab geometry) models to 150 g's. The medium-scale box will accept specimens 20.5 in x 13.5 in x 3 in

and the large-scale box will accept specimens 5 ft x 3 ft x 8 in. The medium-scale box was designed to be used with fixturing already available on the centrifuge, while the large-scale box was designed to be used with the swing platform. This platform facilitates the construction, testing, and post-test examinations of models constructed from materials that flow under the influence of gravity, e.g., ocean sediments, by keeping the total acceleration vector acting on model always perpendicular to its base. This platform will accept a variety of specimen holders, including the two boxes mentioned above. Photographic coverage of the side view of the 2-D boxes is obtained via the mirror system.

The medium-scale specimen box has been used in the preliminary set of hole-closure experiments (discussed later).

The design and fabrication of the large-scale components are complete; however, before they may be used on the centrifuge they must be qualified statically to full design loads. The large-scale specimen box and the mirror system are currently being qualified at Sandia. The swing platform requires special handling in that a 1.2 million pound testing machine is required to qualify this component. This test will be conducted in Los Angeles during March, 1981. After static qualification, they will be mounted on the centrifuge and checked dynamically. Then large-scale simulation experiments can begin.

Hole-Closure Experiments

Before the thermal/mechanical interactions of the canister and the sediment can be investigated using centrifuge simulation techniques, the scaling relations for all pertinent phenomena must be understood. This understanding may be achieved from theoretical considerations (discussed later) or from a series of centrifuge experiments. In the latter case, a single prototype is modeled at several scaling factors. The results are then cross-correlated to obtain the scaling relations.

To begin the experimental investigation of scaling relations for the canister/sediment system, a hole-closure experiment is being conducted. This experiment, which was designed to investigate the mechanical scaling relations for the sediment, is shown schematically in Figure 3. Using the medium-scale specimen box, a sample of sediment is first packed against a weir assembly. Then at g , a pin is pulled allowing the moveable weir to fall, thus creating a hole in the sediment. The movement of the sediment into this cavity is observed using a video camera, high-speed motion picture cameras, and pore-pressure and total-pressure measurements at selected sites. The thickness of the wier (dimension a in Figure 3) will be 0.5 in, 0.375 in and 0.25 in for loadings of 75 g , 112 g , and 150 g , respectively.

Initial tests with this apparatus showed that the slider mechanism was not balanced properly in the original design, causing the wier to stick during its downward movement. This problem is currently being rectified with minor modifications.

When reliable operation of the wier is obtained, the instrumentation will be set up and calibrated using kaolinite to simulate ocean sediment. Then, the actual tests on the sediment will begin.

SCALING RELATIONS

The interpretation of the results from a centrifuge simulation of the canister/sediment problem is not straightforward because the stress and strain states produced in the sediment are functions of time. In particular, these states change with pore pressure buildup and dissipation, thermal gradients, and flow of the sediment, to name a few. Thus, to relate the time of a particular measurement on the model to a homologous (equivalent) time in the prototype requires an understanding of the time scaling laws for all of the phenomena involved in the problem. Moreover, if the scaling laws are not the same for all the phenomena, then a homologous time for the prototype may not exist.

As mentioned earlier, the scaling relations that are pertinent to the canister/sediment problem may be developed along experimental and/or theoretical lines. In addition to the experimental investigation of these relations, a parallel development has been pursued along theoretical lines. As discussed in the 1979 annual report, the theoretical development of scaling relations may be obtained directly from the solution of the different equation(s) that describe the particular process(es) of interest. The obvious limitation to this technique is that closed-form solutions are not available for all processes of interest in the canister/sediment problem. An alternative theoretical approach to this development is the dimensional analysis techniques that are based on the Buckingham Pi Theorem. This theorem states that if a physical system is described by m independent parameters, such that:

$$F(q_2, q_3, \dots, q_m) = 0, \quad (1)$$

and that this parameter set is complete, then its solution has the form

$$f(\pi_1, \pi_2, \pi_3, \dots, \pi_{m-k}) = 0, \quad (2)$$

where the π terms are independent products of the parameters $q_1, q_2, q_3, \dots, q_m$ and are dimensionless in the fundamental dimensions (which are k in number).

The importance of this theorem is that it permits the determination of the scaling parameters (modeling laws) for physical processes without the necessity of being able to describe them mathematically. And, the application of this theorem to a particular problem is relatively simple; the implication being that very difficult problems involving many processes may be analyzed successfully and with relative ease.

However, the theorem is not a panacea. These benefits are gained at the loss of important information about the physical processes involved in the problem. The first area of loss concerns the list of q parameters. This set must be composed of independent elements and it must be complete. Although this statement sounds almost trivial, it is not because this theorem does not provide any insight into the physical processes involved. And, thereby, it does not offer any technique for correcting mistakes in the q parameters. The result of the addition (loss) of a q parameter is the gain (loss) of a π term, which can obscure the relationships between other π terms and may lead to erroneous conclusions about their inter-relationships.

The second area of loss, and the most important, concerns the π terms obtained from a valid set of q parameters. The complete set is not unique. This result is in sharp contrast to other techniques which provide a unique set of nondimensional variables; each of which usually can be associated with a physical process or to a "cross-term" between processes. The implications of this information loss are many, but the major one is that once a set of π terms is obtained for a problem, they may have to be manipulated to put them in a more "appropriate" form. Again, the theorem offers no insight into this process.

To apply this technique to the canister/sediment problem, the list of pertinent variables must be constructed first. The physical processes that effect the movement of a canister after its emplacement include "dead weight" effects (ρg), thermal conductivity effects (k), heat capacity effects (ρC_p), kinematic viscosity effects ($\nu = \mu/\rho$), and the thermal energy release (Q) as a function of time (t). The responses will include the displacement of the canister (X), temperatures (θ), and the sediment velocity (u), all as functions of time. And, the geometry of the container (r) must be modeled as well as other geometric aspects of the problems. The latter being written as a series of nondimensional geometric ratios (r_i). Thus (1) becomes

$$F(\rho g, k, \rho C_p, \nu, Q, t, X, \theta, u, r, r_i) = 0 \quad (3)$$

with fundamental dimensions, which include force (F) length (L), time (T), and the temperature (θ).

One set of π terms that can be generated from these parameters is:

$$r_i, \frac{x}{r}, \frac{ut}{r^2}, \frac{ur}{u}, \frac{Q}{(\rho g)r^4}, \frac{(\rho C_p)\theta}{(\rho g)r}, \frac{(\rho C_p)u}{k}. \quad (4)$$

In this form, the first two terms can be interpreted as the geometric scaling; the third and fourth terms as viscous flow; the fifth as the heating term; the sixth as the "cross-term" between heat capacity and dead weight; and the seventh as the "cross-term" between heat capacity and conduction.

Using the techniques discussed by Sutherland in the 1979 annual report to evaluate the scaling relations from these terms, we will take

$$r_m = nr_m,$$

$$g_m = ng_p,$$

$$\rho_m = \rho_p,$$

$$u_m = u_p,$$

$$(\rho C_p)_m = (\rho C_p)_p,$$

and

$$k_m = k_p. \quad (5)$$

where the subscript m refers to the model and the subscript p refers to the full scale prototype. Terms 1, 2, and 7 in (4) are satisfied automatically. For term 3, we have

$$\frac{u_m t_m}{r_m^2} = \frac{u_p t_p}{r_p^2},$$

$$\frac{t_m}{r_m^2} = \frac{t_p}{n^2 r_m^2}.$$

Solving,

$$t_p = n^2 t_m. \quad (6)$$

For term 4,

$$\frac{u_m r_m}{u_m} = \frac{u_p r_p}{u_p} ,$$

$$\frac{u_m r_m}{u_m} = \frac{u_p n r_m}{u_m} ,$$

$$u_m = n u_p .$$

For slow motion

$$u_m = \frac{x_m}{t_m} \quad \text{and} \quad u_p = \frac{x_p}{t_p} ,$$

then

$$\frac{x_m}{t_m} = n \frac{x_p}{t_p} ,$$

$$\frac{x_m}{t_m} = n \frac{n x_m}{t_p} ,$$

$$t_p = n^2 t_m . \tag{7}$$

For term 5,

$$\frac{Q_m}{(\rho g)_m r_m^4} = \frac{Q_p}{(\rho g)_p r_p^4} ,$$

$$\frac{Q_m}{n(\rho g)_p r_m^4} = \frac{Q_p}{(\rho g)_p n^4 r_m^4} ,$$

$$Q_p = n^3 Q_m . \tag{8}$$

And for term 6,

$$\frac{(\rho C_p)_m \theta_m}{(\rho g)_m r_m} = \frac{(\rho C_p)_p \theta_p}{(\rho g)_p r_p},$$

$$\frac{(\rho C_p)_p \theta_m}{n(\rho g)_p r_m} = \frac{(\rho C_p)_p \theta_p}{(\rho g)_p n r_m},$$

$$\theta_m = \theta_p. \quad (9)$$

Thus, (6) through (9) predict that time scales as the scaling factor squared, thermal energy scales as the scaling factor cubed, and that the temperature fields scale one to one.

These results are consistent with previous work, and imply that the canister/sediment simulations will have a consistent n^2 scaling on time.

CONCLUDING REMARKS

Centrifuge techniques offer a method for doing physical simulations of the long-term mechanical response of deep ocean sediment to the emplacement of waste canisters and to the temperature gradients generated by them. Theoretical investigations of the scaling laws for pertinent phenomena indicate that the time scaling will be consistent among them and equal to the scaling factor squared. This result implies that this technique will permit "accelerated-life-testing" or proposed configurations; i.e., long-term studies may be done in relatively short times.

Medium-scale simulation experiments that are designed to investigate the mechanical response of the sediment are currently in progress. Large-scale simulations can be started in the near future with the completion of the modifications to the Sandia-25 centrifuge.

REFERENCES

1. P. B. Bucky, "Use of Models for the Study of Mining Problems," Am. Inst. of Mining & Metallurgical Engineers, Tech. Pub. No. 425, (1931), 3-28.
2. G. I. Pokrovsky and I. S. Fyokonov, Centrifuge Model Testing in the Construction Industry, 2 vols, draft translation, Building Research Establishment Library, England (1975).

Fig. 1. Slope Stability Analysis

Fig. 2. Numerical and Centrifuge Simulation Techniques

all dimensions in inches

Fig. 3. Schematic Diagram of the Hole-Closure Experiment

Appendix P
In-Situ Heat Transfer Experiment
L. O. Olson and T. E. Ewart

IN-SITU HEAT TRANSFER EXPERIMENT (ISHTe)
WASTE MANAGEMENT RESEARCH DIVISION, SUBSEABED DISPOSAL PROGRAM

Progress Report
for
January 1, 1980 - December 31, 1980

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INTRODUCTION

A group within the Ocean Physics Department of the Applied Physics Laboratory, University of Washington, is developing systems to measure the in-situ thermal conductivity of deep ocean sediment. The initial experiment plan was to implant a 400 watt isotope heat source into the sediment at MPG-I and monitor the thermal field around it at distances of up to 2 m for one year. The temperature data were to be recorded on a seabed platform along with photographs and vane shear values. Upon command, digital data in storage would be sent to the surface acoustically. At the end of the year, corers would be driven in by the platform to take samples of heat affected sediment. These were to be recovered along with the platform for laboratory analysis. Work was progressing well on the design of the various systems until mid-1980 when higher sediment shear strengths were estimated for in-situ MPG-I and more experiments for the platform were added. Also, more emphasis was placed on the accuracy of location for the thermal sensors.

These perturbations have caused considerable rethinking for the entire experiment. By year end, firm designs had not been made for any of the add-on experiments and a formal ISHTE definition had not been established. However, with rough ideas of what is wanted by the scientific participants, APL has started re-evaluating component designs for compatibility with the more complex experiment.

Another addition to the ISHTE program this year is an ISHTE simulation (ISIMU) to be performed in the Ocean Environment Chamber at NSRDC in Annapolis, Maryland, during October and November 1981. The purpose of this test is to look for unexpected phenomena in the heat affected sediment -- mainly looking for unexpected sediment reactions to the heat, but there are other aspects to consider. For example, since the experiment will use an approximately 1/4 scale model heater exposed to full ISHTE temperatures, there could be severe corrosion problems unique to this experiment.

Ideally, APL would want to evaluate materials from a corrosion standpoint for the ISIMU. Time and money constraints, however, are preventing this. Some "best guess" substitute materials will have to be used, with a possible risk of component failures during the month-long test. Our plan is to obtain a reliable commercial heater to maintain the temperature so that the failure of some thermal sensors doesn't stop the experiment. Corrosion problems in ISHTE hardware really can't be verified in ISIMU because the stagnated salt water system employed in the chamber will probably be much different than the real ocean environment.

This report covers the major work performed by APL during 1980 for the ISHTE. The expanded scope of ISHTE hasn't affected the work performed on the designs discussed. Design of the platform and the control system will be affected the most; they have been delayed until next year, when more details on the add-on experiments will be available. The locational accuracy of the thermal probes and the predicted higher sediment shear strength have affected the development of the probes and their implantment mechanisms. This has prolonged the

completion of their manufacture. The ISHTE simulators hasn't had any major impact on this year's work, but will delay some of the work planned next calendar year.

The two major systems developed this year for ISHTE have been the acoustic tracking and data telemetry system and the hydrostatic sediment corer. Both systems are highly successful and are described in detail in this report.

The last section of this report covers APL's proposed hardware for performing ISIMU. For a general description of the ISHTE platform and fielding plans, see last year's Subseabed Disposal Program Report, Volume II (Ref. 1).

OPEN OCEAN ACOUSTIC TRACKING SYSTEM

The ISHTE project plan requires an accurate underwater tracking system to monitor and display the location of the launch ship along with the experiment platform during deployment and recovery. A method is also required to reposition the ship over the platform for acoustic communications and data transmission. Also, if the primary and backup recovery systems malfunction, a tracking system will be necessary for guiding a manned submersible or a grapnel to the seafloor platform.

Since it is important to obtain platform status during handling in the ocean, coded signals are used as tracking pulses in the acoustic system. This also allows acoustic units to be addressed individually, thus eliminating the need for multiple acoustic frequencies in the system. For a general description of the tracking system, see Ref. 1. For specific details, see "A Deep Ocean Acoustic Tracking and Telemetry System," Ref. 2.

In 1979, APL designed the basic tracking system and assembled prototype units. During 1980, APL tested components of the system in Puget Sound and then in the deep ocean off the coast of Hawaii. Next, a complete tracking system was assembled and test tracking was performed in Puget Sound (see Ref. 3). Finally, during July 1980, a complete open-ocean tracking test was successfully performed at MPG-I from the USNS De Steiguer.

The remainder of the year was used in refining the acoustic hardware and the software for the displays. Considerable effort was spent in improving and testing the surface transducer which is suspended on a cable below the ship. This system is a vulnerable link in rough weather testing at sea.

General System Characteristics

Figure 1 illustrates the ISHTE platform on the seabed along with the long-baseline tracking array. The transponders will be planted in a roughly square pattern 2000 m on a side, and tethered 100 m above the seabed. Any three of the four transponders can be used for tracking. The fourth is a spare in case one transponder malfunctions or is in a

bad terrain acoustically. The tracking and telemetry system has been designed to provide an acoustic communication range of 10 km from the farthest transponder. Thus a surface ship can be tracked in an area of approximately 150 sq. km. The tracking system can simultaneously track both a surface ship and a submerged experimental platform with respect to the bottom mounted transponder array. It is anticipated that additional objects (launch and recovery line, backup recovery line) will be tracked in a round-robin fashion.

Each of the bottom mounted transponders has its electronics and battery (capacity for two years) mounted inside a 43 cm diameter glass pressure housing manufactured by Benthos. One assembly weighs about 30 kg in air and has 14 kg of buoyancy in water. It can be easily handled by one person during launch. An "anchor last" launch is used with a 32 kg anchor clump.

The shipboard computer (Fig. 2) is an LSI 11/03 with a teleprinter terminal and Hewlett-Packard cathode ray tube displays employing intelligent drives with memory. One display shows the tracking of both the ship and the tracked object in x and y with a depth printout. The other large display shows telemetered information. A third, smaller display is used on the ship's bridge as a slave off the tracking screen.

Status information from the experiment platform will be embedded in the tracking ping returns from the platform. This status information will be monitored and displayed in real time along with the location of the launch ship and the platform. At three month intervals during the experiment, the tracking system will be used to reposition the ship over the experiment platform. The platform will then be commanded to telemeter to the ship the approximately 2 megabits of data that have been gathered and stored on the platform during the interim. The system is capable of locating the position of the ship and a tracked object to an accuracy of better than 10 m with position updates every 15 to 20 sec. Although the basic acoustic data rate is 2 kilobaud, the net acoustic data rate for data telemetry is lower because of the overhead required for correlation and error detection codes and for gaps between pings. A final implementation of the data telemetry link has not yet been made, but we anticipate a net acoustic data telemetry rate of approximately 1.5 kilobaud.

Tracking Array Deployment

The launch site for the first transponder is established using conventional shipboard navigation. With the ship traveling at 2 to 3 knots, the buoyant transponder sphere is placed into the water and the 100 of mooring line is fed out under light tension. When the line is out to full length, the anchor is attached and dropped over the fantail of the ship. The ship continues on a steady course while the second transponder is lowered into the water and the mooring line is payed out similar to the first transponder. On this unit, the anchor is held until the ship has moved approximately 2 km (20 to 30 minutes depending on speed). At the correct elapsed time, this second unit's anchor is gently dropped into the ocean. At MPG-I, where the water

depth is about 5800 m, the transponders take about 90 minutes to touch bottom. A transponder in a moored orientation is shown in Fig. 3.

After both transponders have had ample time to reach the bottom, they are commanded to measure the acoustic travel time between themselves and telemeter this information to the surface. Using this information and the known depth from the fathometer, the LSI 11/03 computer uses a two-transponder tracking program to show ship position for launch of the third and fourth transponders. This two-transponder tracking is accomplished at a much reduced accuracy and has an ambiguity problem as to which side of the base line the ship is located, but it is very adequate for planting transponders.

After the transponders have reached bottom, the tracking computer commands each transponder to measure the travel time between it and the remaining three transponders. These intertransponder distances are used to make an initial estimate of the relative transponder locations.

Once the intertransponder distances have been obtained, the ship survey is begun. At 14 to 18 positions distributed over the transponder array, the tracking computer sends a ping to which all four transponders reply. The four travel times are automatically stored in a file on disk. To aid in navigating the ship over the desired survey pattern, the survey program uses the self-survey data and the four travel times to make a least squares estimate of the ship's position. The ship's current position, previous positions, and the estimated locations of the transponders are plotted on a CRT display. These estimates of the ship's location are typically within 100 m of the actual location.

The transponder location program uses all intertransponder travel times, ship survey travel times, and estimates of ship and transponder locations to minimize the differences between travel times given by estimated locations and the measured travel times using a conjugate gradient method. Because the accuracy of conversion from travel times to distances is the main limitation on the absolute accuracy of the tracking system, an accurate sound velocity profile is needed. If a reasonable survey geometry is followed, the program will locate the transponders to within 1 m of their relative positions.

The program SURSUM is used to determine how well the location program has fit the transponder locations to the travel time data. For each ship survey point, SURSUM computes the four ship locations given by the measured travel times to four distinct sets of three transponders. The accuracy of the transponder locations is indicated by the differences in ship location given by the different sets of transponders. SURSUM prints out the standard deviations in x, y, and z for each ship location and the average standard deviation for the complete set of ship survey locations. If a particular location exhibits much larger standard deviations than the rest, it is assumed to be bad, is removed from the survey data, and the location program is rerun. A successful survey will have average standard deviations in ship location of less than 0.5 m.

At this point, the tracking is oriented from one transponder selected as the origin with the x direction parallel to the ocean surface and passing through a vertical projection of a second transponder. The y direction is also parallel to the ocean surface and 90° clockwise from x. The z dimension is the vertical depth below the ocean surface.

To orient the array in an earth referenced coordinate system, simultaneous ship positions given by satellite navigation and acoustic tracking using SIMTRA are entered into a program called NECORD. Once two or three such positions have been obtained, NECORD makes a least squares fit to the data to rotate the transponder array into north-east coordinates and to determine the latitude-longitude of the transponder array. As more satellite navigation data become available, they are entered into NECORD so that the rotation of the array into earth coordinates and the latitude-longitude location of the transponder array are continually improved and updated. A sample of the tracking display is shown in Fig. 4.

The transponder array is recovered by sending a special command sequence to the transponders to actuate a Benthos titanium wire corrodible release. To facilitate recovery, each transponder has a flashing light and radio transmitter (purchased from Ocean Applied Research). These units are mounted upside down on the transponder when it is in its moored position, but when the anchor is released, the transducer's moment causes it to flip over and hold the radio and light out of the water when on the surface. These units have both tilt and submergence switches to shut them off under water. At night, the light is reputed to be visible from the deck of a ship at a range of about 10 km under good conditions. The homing range on a CB frequency radio with an antenna mounted on the ship's mast should be at least that good with reasonable radio signal conditions.

Error Estimates

The ability to return to the same position, assuming that the sound velocity profile does not change, is limited by the timing accuracy of the tracking system. The use of a correlation code gives the transponders a ± 15 μ sec timing resolution of the arrival of tracking pulses with modest (6 to 10 dB) signal to noise ratios. A round trip ping is timed at four points: real time clock to bottom mounted transponder to acoustic transmitter-receiver to real time clock. Thus the one way travel time resolution of the tracking system is ± 30 μ sec, which at most could produce an error in slant range of about 5 cm. Ignoring the problem of holding the ship transducer steady at sea, the tracking system should have little difficulty in returning to any given point to within 1 m.

Relative tracking accuracy is defined as the degree to which point to point distances calculated by the tracking system agree with the actual distances. Relative tracking is affected by:

- a. Errors in measuring sound velocity profile
- b. Fluctuations in the sound velocity profile
- c. Errors introduced by the average velocity approximation
- d. Errors in locating the transponder array
- e. Errors in slant range travel time measurement
- f. Movement of the ship transducer during the round trip travel time.

The most significant errors are those caused by errors in measuring the sound velocity profile.

Because there are so many potential sources of error, an accurate analytic estimate of typical relative tracking accuracy is difficult to derive. The best indication of typical relative tracking accuracy has been obtained by placing a tracked object below an SVSTD probe and comparing the depth of the object computed by the tracking system with the depth read out by the SVSTD probe. Results obtained from these tests indicate that the relative accuracy of the tracking system is good to approximately 10 m if the ship is within 6 km horizontal range from the origin of the transponder array. Further tests of the tracking system will provide more information on the relative tracking accuracy.

Absolute tracking accuracy (the degree to which latitude-longitude positions calculated by the tracking system agree with the actual positions on the earth) is even more difficult to estimate. Absolute tracking accuracy is affected by all the errors that affect relative tracking plus errors in determining rotation angle and latitude-longitude location of the transponder array from relatively inaccurate satellite fixes. In general, absolute accuracy is limited by relative accuracy, the number of satellite fixes, and the accuracy of each one.

Testing

Initial tests of components of the tracking system were conducted in Puget Sound and then in deep water near Hawaii. Several tests of the complete tracking system were made in Puget Sound at depths to 200 m. Finally the complete tracking system was tested in the deep, open ocean to evaluate its operation in an environment similar to that planned for ISHTE. The major tests are described in the following section.

A preliminary deep water checkout of transponder operation in a nontracking field test was conducted in March 1980, approximately 15 miles west of Kailua-Kona, Hawaii, in 4000 m of water. Acoustic pings were sent and received with the deck transponder; a portable timer/counter was used to obtain round trip travel times. Communications were tested by mooring a transponder 100 m off the bottom and then conducting a range test to 7500 m slant range in sea state 4. Communications were perfect and the transponder was successfully recovered. The self-survey feature of the transponders was tested by mooring two transponders 100 m off the bottom approximately 1600 m apart. This test was conducted closer to shore in 1500 m of water to avoid rough weather. Communications to both transponders were reliable, and the transponders were able to measure the travel time between themselves. Transponders were

recovered with the aid of an OAR radio direction finder. A Texas Instruments 9000 series Loran C receiver was used for navigation.

The full tracking system was first tested in Puget Sound, May 1980, from APL's barge in 200 m of water. The transmit power of the transponders was reduced to lessen reflections due to the relatively shallow water. The transponder array was planted in a roughly 150 m square. Tracking of the ship was tested inside and outside the transponder array. Simultaneous ship and object tracking was tested with the object suspended at different depths below the APL barge and suspended from a small boat some distance from the barge. The tracking tests went smoothly except that surface reflections caused some bad tracking data points. (Software has been added to the tracking program to screen out most of the surface reflections.) Three independent ship surveys were made to obtain an indication of how accurately the program XPLOC was locating the transponder array. The transponder locations given by the three independent surveys all agreed to within 0.12 m. The average standard deviation in ship location computed by the program SURSUM was 0.28 m.

A deep water tracking and telemetry test was conducted in July 1980 approximately 600 miles north of Oahu, Hawaii, off the USNS De Steiguer in 5800 m of water (Ref. 3). Figure 5 shows the test site in the area, referred to as MPG-I. The transponder array was planted in a roughly 2 km square. Tracking of the ship and a tracked object was tested inside and outside the transponder array. The ship was tracked to a slant range of 11.4 km from the center of the array with no lost replies or bad data points. The tracked object was tracked from the surface to the bottom by lowering it on a nylon line from the ship. The tracked object was also suspended below the ship's SVSTD probe so that the depth of the object computed by the tracking system could be compared with the depth read out by the SVSTD probe. The transponder array was located in earth referenced coordinates using a least squares fit to 10 pairs of simultaneous satellite and tracking fixes. In general, all the performance specifications of the tracking system were met or exceeded.

Deep ocean acoustic data telemetry was tested by sending 256-bit data pulses from a source 4 m off the ocean floor. Errors in the received data due to ship noise and surface reflections prevented establishment of an error rate for the data telemetry pings. Errors caused by bottom reflections and distortion through the water column seem to be nonexistent, but cannot be positively ruled out on the basis of the test data obtained. We hope to solve problems with surface reflections and ship noise by using a more directive surface transducer. A more extensive data telemetry test is planned for April 1981 at MPG-I.

COMMERCIAL ACOUSTIC RELEASES

ISHTe will use commercial acoustic releases at three locations in the fielding. Auxiliary handling lines to lower the platform from the ship into the water will be released acoustically within a few hundred feet of the surface. A long-term mooring of a release at 5700 m depth will be made for the anchor of the backup recovery-line. The lowering

lines on both the platform and the backup recovery mooring will be separated acoustically just above the floats of the taut moorings after deployment. The release units must be able to lift 4600 kg and should be easy to handle in a mooring line.

In July 1980 at MPG-I, APL made some tests (at 5850 m depth) of two release systems on hand and one newly developed release borrowed from Benthos, Inc. The units used were two squib charged AMF model 322 releases obtained from Sandia, one recockable InterOcean release, model 1000 DR-12 on hand at APL, and a new Benthos 865-A recockable release.

The performance of all units tested, even at minimum range, was seriously affected by ship noise. Digital ranging didn't work on any of the units near the seabed. Because the AMF unit has the most power, it could be heard the best. The acoustic returns from the AMF units could be heard quite well from the audio output of the AMF receiver. Acoustic returns from the InterOcean release near bottom were not discernible from the background noise using headphones on InterOcean's deck box receiver. We knew the InterOcean release was transmitting because its signals were heard faintly with headphones on the ship's PDR receiver. When the release command was sent to the InterOcean release, the proper pulses indicating that the unit had responded to the command were observed on an oscilloscope connected to an APL receiver. Dual AMF releases are securing a 9-month-long test mooring at MPG-I that will be recovered in April 1981.

The newly developed Benthos release appears to be an ideal package from the standpoint of size, weight, capacity, corrosion resistance, and the ability to rearm the unit without opening the pressure case. The test unit was deployed in an "anchor last" mooring at MPG-I. Ranging on the release with the Benthos deck box was good to about 2.5 km, after which the digital ranging meter started to become somewhat erratic. Valid ranges were obtained intermittently to about 4.0 km. Beyond this range the returns could not be detected using the Benthos deck unit, even with headphones. We know the signal was present because it was picked up on an oscilloscope monitoring the output of an APL receiver.

When sufficient time had elapsed for the mooring to be on the bottom, a release command was sent, and the proper response was observed on the oscilloscope. The mooring floated up and was successfully recovered. We were able to stay in the area of the mooring without the ranging ability because the ship was navigated by the APL acoustic tracking system. The Benthos unit was an easy package to handle at sea. Benthos representatives report that they are working on increasing the transmit power to solve the range problem we had.

In summary, if the range problem can be solved by Benthos, their units would be ideal for ISHTE. The AMF units currently have more power than the others tested and their new units are smaller, recockable, and reputed to be better acoustically than the units we are using on the long-term mooring. However, even their new units have a serious corrosion potential because of the aluminum cases. Another drawback is that an auxiliary release bar is required to carry the ISHTE loads of 4600 kg.

SEDIMENT THERMAL PROBES

More than 70 thermal sensing elements are required in probing the sediment. This does not include specially packaged items such as the line source conductivity probe or probes located on the heater surface. The sensing elements consist of platinum resistance temperature sensors and thermistors. The sensor package should allow insertion into the sediment with minimum disturbance, reliable and accurate thermal sensing during the one year experiment, and reliable recovery for post-calibration. The initial design and construction phase for the sediment thermal probe package was completed in 1979 (Ref. 1).

During the early spring of 1980, the program manager requested that APL delay the construction of the thermal probes because of possible changes in the sensor spacing and because of concern about the drive accuracy of the long, slender tubes. There was considerable discussion at the 1979 Annual Seabed Meeting about optimum sensor positions in the thermal field because of the possibility of sediment layering. More discussions on this topic have taken place, but a change has not been formally decided on by SNL program personnel.

When APL tried to determine the straightness of the glass tubing in the probe, it was found that there was no uniformity in either the bends or the diameter along the length. APL took several of the glass tubes and evaluated the general curvature of the first 20 cm, which had a radius of approximately 83 m. Assuming that sediment lateral support would cause the probe to follow that curvature, we estimated locational errors for each depth. Steve Burchett of SNL was asked to calculate the length of straight rod that would have to precede the glass tube into the sediment to establish a straight path. In a memo presented at the 11th ISHTE meeting, he recommended a 10 cm straight section. Unfortunately, this value was based on a 1 mm wall thickness for the tube instead of the 2 mm specified in the ISHTE quartz probe design. A quick calculation by Burchett led him to believe this difference would have a negligible effect, but he will check further.

Another concern at APL has been the reliability of the quartz tube with respect to breakage during handling and to cracks propagating from the ground end. An ideal glass surface is flame-polished to remove microscopic cracks. The optimum configuration for a straight drive is a flat end to preclude unequal lateral forces which would cause a curved path. However, the quartz tube's flame-polished end is not flat and the ground end has microscopic cracks. Thus it is likely that stress and the presence of water will cause crack propagation (Ref. 4). To use the present design, a straight section of plastic rod should be bonded to the flame-polished end of the sensor tube. This design is detailed below, along with an alternate metal-sheathed design which appears to be a better choice if a prototype can be successfully manufactured.

Design Description

The sediment thermal sensor assembly consists of an electronics housing, a sensor probe, and the interface seal housing and seals that facilitate the making of the electronics and probe. A cross-sectional view of the entire assembly is shown in Fig. 6. The following description will be limited to the probe subassembly.

The probe consists of the sheathing material, the temperature sensors with their respective electrical leads, and the fillers and potting material to fix the sensors in place. The probe subassembly is specified by APL Dwg. D-37308. The number of sensors installed within each probe ranges from three to eight. Each sensor has two lead wires that must be routed through the seals of the interface to the electronics housing. There are nine probes containing a total of 51 Rosemount platinum resistance temperature sensors. The remaining four probes contain a total of 20 Thermometrics, Inc., thermistors. The lead wire is solid conductor, TFE Teflon insulated, AWG 28 hookup wire.

The sheathing material is clear fused quartz tubing with a 4 mm inside diameter and an 8 mm outside diameter. The properties of this material are listed in Table 1. One end of the sheathing tube is fused closed and cut off flat. The other end is left open and also is cut off flat to provide a good bearing surface.

Table 1. Properties of clear fused quartz

PHYSICAL	
Density.....	2.2 g/cc
Hardness.....	6 mohs
Tensile Strength.....	7000 psi
Compressive Strength.....	160,000 psi
Young's Modulus.....	11.1×10^6 psi
Rigidity Modulus.....	4.85×10^6 psi
Bulk Modulus.....	5.6×10^6 psi (approx.)
Poisson's Ratio.....	0.14
THERMAL	
Coefficient of Thermal Expansion..... (between 20°C and 350°C)	$0.55 \times 10^{-6}/^{\circ}\text{C}$
Thermal Conductivity.....	$0.0033 \text{ (cal)(cm)/((sec)(cm}^2\text{))} (^{\circ}\text{C})$
Specific Heat.....	0.18 cal/g
Fusing Point.....	1750°C (approx.)
Softening Point.....	1670°C (approx.)
Annealing Point.....	1140°C (approx.)
Strain Point.....	1070°C (approx.)

The sensors are fixed inside the quartz tubing with an RTV silicone rubber compound, ECCOSIL® 4952, manufactured by Emerson & Cuming. Typical properties for this compound are given in Table 2. Note that it is formulated to give a thermal conductivity approximately midway between that of water and the quartz tube.

Table 2. Typical properties of ECCOSIL 4952 RTV silicone rubber

Color.....	red
Viscosity, cps.....	30,000
Shelf Life, months.....	6
Specific Gravity.....	2.28
Durometer, Shore A.....	70
Tensile Strength, psi (kg/cm ²).....	650 (46)
Elongation, %.....	>100
Tear Strength, lb/in. (gm/cm).....	>25 (4,460)
Compression set, %.....	90
Thermal Expansion, /°F(/°C).....	90 x 10 ⁻⁶ (162 x 10 ⁻⁶)
Thermal Conductivity, (Btu)(in.)/(hr)(ft ²)(°F).....	7.5
(cal)(cm)/(sec)(cm ²)(°C).....	0.031
Dielectric Strength, V/mil (kV/mm)...	550 (21.6)

ECCOSIL 4952 (formerly designated ECCOSIL 4852) is a red, pourable, RTV silicone-based material that has a higher thermal conductivity than the more conventional silicones. It can be cured at room temperature or at elevated temperature to a flexible silicone rubber capable of withstanding temperatures of 500°F (260°C) continuously, and up to 600°F (315°C) for short periods. It is particularly recommended for potting and encapsulating components from which heat is to be dissipated.

Between the sensor positions inside the tube, the space is filled with Emerson & Cuming hydrospace grade "microballoons." These are thin-walled, hollow glass spheres approximately 10 to 175 microns in diameter. This material reduces heat transfer between sensors; its characteristics are given in Table 3.

Design Discussion

Two aspects of the temperature probe design that bear on the performance of the ISHTE are the dimensional irregularity and the susceptibility to brittle fracture of the quartz tubing. The variation from specified dimensions for the quartz tubing causes an uncertainty in the placement accuracy of the sensors.

The quartz tubes are neither straight nor of constant diameter. For implantment, the quantitative effect of this lack of straightness is not entirely clear. However, it seems reasonable to assume that the straighter the tube is, the more accurate will be the sensor location radially from the heater. The diametral variation over the length of the tube is the primary consideration for design of the clearance between the outside diameter of the tube and the inside diameter of the bearing that guides the probes into the sediment. Larger diametral variations will increase the uncertainty in placement of the temperature sensors.

In addition to the placement uncertainty introduced by the curvature and diametral variations of the quartz tubing, there is an uncertainty introduced by the possible installation of the sensor in a

Table 3. Characteristics of Emerson & Cuming
FTD 202 microballoons

Bulk Density,	
lb/cu ft.....	9.6
g/cc.....	0.155
True Particle Density	
lb/cu ft.....	14.8
g/cc.....	0.238
Particle Size Range, microns	% by wt.
>175.....	0
149-175.....	4
125-149.....	3
100-125.....	7
62-100.....	51
44- 62.....	23
<44.....	12
Packing Factor.....	0.651
Thermal Conductivity	
(Btu)(in.)/(hr)(ft ²)(°F).....	0.70
(cal)(cm)/(sec)(cm ²)(°C).....	0.0029

NOTES:

Bulk Density: Weight of a tamped sample in air divided by its bulk volume.

True Particle Density (TPD): Weight of a sample divided by the volume of liquid displaced by the sample. Thus, it is the weight of the average particle divided by its volume.

PACKING FACTOR: Volume of liquid displaced by a sample divided by volume of the tamped sample in air. (It is the ratio of True Particle Density to Bulk Density.)

THERMAL CONDUCTIVITY: Measured on a tamped sample in air.

location other than on the axial centerline of the probe. Because the probes are free to rotate as they are implanted, any deviation from the central axis will be equal to one-half of the radial positional uncertainty after the probe is implanted.

The advantages of using the quartz tube over other alternatives are: it is very strong in compression; virtually impervious to corrosive attack; has very good dielectric and thermal properties for this application; and affords visual inspection of the temperature sensor installation.

Design Alternative

In an attempt to reduce the positional and reliability uncertainties mentioned above, consideration of other sheathing materials has led to the study of alternate thermal sediment probe designs. An alternate design has evolved that is not completely specified, but is considered workable. Figure 7 shows the alternate design schematic.

The sheathing material is a nickel-chromium-molybdenum type alloy that has excellent corrosion resistance in sea water. The alloy would probably be Hastelloy alloy C-276. The sheath would be fabricated as a tube with an 8 mm outside diameter and a 1 mm wall thickness. One end of the tube would be plugged by welding a light press fit plug of the same alloy in place using a TIG welding process. Table 4 compares the specified fabricating tolerances on dimensions for the metal tubes and the quartz tubes.

Table 4. Manufacturing dimensional tolerances for tubing

	<u>Fused Quartz</u>	<u>Metal (commercial)</u>	<u>Metal (special order)</u>
Outside Diameter, total variation (mm)	0.960	0.102	0.051
Straightness* (mm per meter length)	1.0	0.833	0.43

* Straightness is measured as the largest gap between a flat surface and the outside diameter of the tube within the length specified.

Each sensor is potted in an RTV silicone rubber compound inside a sensor holder made from a short brass tube. The sensor holder has the midsection of its outside diameter machined so that there is room for a small piece of thin, beryllium-copper spring strip to be placed between the holder and the inside diameter of the sheathing tube. The spring strip will provide good thermal contact between the holder and the sheathing, and will prevent unwanted movement of the holder assembly. Characteristics of the RTV potting compound, ECCOSIL 4954, are shown in Table 5. This compound is similar to ECCOSIL 4952, but has twice the thermal conductivity.

Table 5. Typical properties of ECCOSIL 4954 RTV silicone rubber

Color.....	red
Viscosity, cps.....	40,000
Shelf life, months.....	6
Specific Gravity.....	2.33
Hardness, Shore A.....	78
Tensile Strength, psi (kg/cm ²).....	525 (36.9)
Elongation, %.....	85
Tear Strength, lb/in. (kg/cm).....	85 (15.2)
Thermal Expansion, /°F.....	87 x 10 ⁻⁶
/°C.....	(156.6x10 ⁻⁶)
Thermal Conductivity,	
(Btu)(in.)/(hr)(ft ²)(°F).....	15
(cal)(cm)/(sec)(cm ²)(°C).....	0.062
Dielectric Constant at 1 MHz.....	5.03
Dissipation Factor at 1 MHz.....	0.002
Dielectric Strength, volts/mil (kV/mm)...	520 (20.4)

Tubular insulating spacers made of mullite are placed between the sensor holders. Wires from the sensors pass through the center of these spacers and through the sensor holders along the probe. Microballoons are then used to fill the voids (similar to our previous design). In segments where 10 or more wires pass, it may not be practical to backfill with microballoons.

Discussion of Alternative

The alternate probe design has evolved as a result of specifying a metal sheath in lieu of the fused quartz sheath. The metal sheathing can be manufactured to closer diametral and straightness tolerances, and has a greater resistance to breakage during handling and deployment. The materials available for metal sheathing are sufficiently inert for an ISHTE deployment of one year.

One concern about using the metal sheathing is the increased stem conduction of heat from sensor to sensor. It should be noted, however, that the resistance to radial heat flow will also be decreased. Thus there is still the same relationship between radial heat conduction and heat conduction along the stem to the adjacent sensors. For instrumentation using multi-sensor probes with metal sheathing, the temperature measurement industry's rule-of-thumb for spacing the sensors is ten diameters. Applying this to the present design, the minimum spacing between sensors in a probe would be 8 cm. As presently specified in the ISHTE, the spacing is at least 20 cm.

Sensor Implantment System

The initial ISHTE design called for small diameter probes to be driven just past the bottom of the heater. The sediment shear strength was estimated to be 36 g/cm^2 . This required a drive force of a few kilograms, which was to be generated by gravity on the electronics housing. When multiple probes in a common tube were specified, the diameter was increased, and the desired length became 185 cm. The drive force per probe was then estimated by A. J. Silva of the University of Rhode Island to be 6 to 8 kg. Gravity could still drive most of the probes, by adding some ballast to the electronics case or assisting with a linear spring, so a prototype implantment tube assembly was manufactured and displayed at the 10th ISHTE meeting.

At the same meeting, Burchett of SNL presented computer studies, based on a new in situ sediment shear strength value of 110 g/cm^2 (from Silva), that estimated required drive forces of 20 to 30 kg per probe. This value, even with the caution that laboratory tests may prove it to be high, requires that the implantment system generate forces higher by a factor of 2 or 3.

APL started evaluating designs using an electrically powered hydraulic pump at ambient pressure to drive all the sensors like hydraulic cylinder stems. The system being designed uses batteries to drive an oil flooded, pressure balanced dc motor and hydraulic pump. This will build up pressure above the 600 bars ambient pressure to force the sensors, which are sealed inside a metal implantment tube, to extend like a hydraulic

cylinder and be pushed into the sediment. Current plans are to reverse the system at the end of the experiment and suck the probes back out of the sediment. If metal sheathed probes are used, it will not be so important to retract the tubes for recovery. The use of glass probes requires retraction for protection during recovery.

THERMAL CONDUCTIVITY PROBE

Under the guidance of Dave McVey of SNL, two thermal conductivity probes were designed, built, and tested. These probes are capable of withstanding the 10,000 psi ambient pressure of the deep ocean while making a direct in situ measurement of the thermal conductivity of the sediment during the ISHTE experiment. The "business end" of the probe is a 2.16 mm o.d. Inconel tube with an 11 cm long heater coil inside (see Fig. 8). At the center of the coil are three thermistors spaced 1 cm apart. Each is capable of an independent measurement of thermal conductivity. By measuring the rate of temperature rise when the heater is turned on, it is possible to calculate the thermal conductivity of whatever nonconvective medium the probe is embedded in. The theory of how this works is contained in two memoranda from D. F. McVey to C. M. Percival: "Design of Thermal Conductivity Probe for ISHTE," dated 13 June 1980, and "Analysis of Thermal Conductivity Data from ISHTE," dated 10 September 1980.

Design Details

The 2.16 mm o.d. tube (17 cm long) is attached to an 8 mm o.d. Inconel tube (71 cm long) as shown in the sketch. The 8 mm tube is connected to an electronics housing designed for the ISHTE quartz rod thermal probes. Inside the electronics housing is a Sea-Bird Electronics RC oscillator similar to those used for the sediment temperature probes. The oscillator generates a frequency inversely proportional to the square root of the output of whatever resistive element is connected to its input. Mercury-wetted relays are used to connect the thermistors and a stable reference resistor sequentially to the input of the oscillator. These relays require that the probes be operated within $\pm 30^\circ$ of vertical. The electronics housing has a four-pin underwater connector for +11.5 volt, ground, signal, and synchronization lines. A positive pulse on the synchronization line causes the relay multiplexer to switch to the next position.

The heater coil (resistance = 150 ohms) is #37 Manganin resistance wire wound on the outside of a 19-gauge stainless steel mandrel (1.07 mm o.d., 0.81 mm i.d.). One end of the coil wire passes through the inside of the mandrel, which also contains the three thermistors. The mandrel, heater, and thermistor assembly fit inside the 2.16 mm o.d. tube. The mandrel extends from the closed end of the 2 mm tube to a position flush with the outside end of the threaded fitting at the opposite end of the 2 mm tube. This assembly is then immersed in transformer oil (Shell DIALA 3AX63702) and evacuated to remove all air. The end of the threaded fitting is then sealed with Dow 734 RTV silastic. (The threaded fitting and the eight protruding wires are first carefully cleaned, and then primed with Dow 1200.) Twisted pairs (four) of #26 copper wire are used

to make the connections through the 8 mm tube to the multiplexer board in the electronics housing.

Calibration and Testing

After final assembly, it was found that a thermistor lead was open on one of the probe assemblies. We proceeded with calibration and testing of both probes without repairing the defect because two of the three thermistors are redundant. Both probes were calibrated by the Northwest Regional Calibration Center (NRCC). The heater coils were not powered during calibration. The calibration process generated the constants for the following equation relating frequency to temperature:

$$T = \frac{1}{A+B \ln(f_0/f) + C \ln^2(f_0/f) + D \ln^3(f_0/f)} - 273.16 ,$$

where T is the temperature in degrees Celsius, f is the instrument frequency in hertz, and f_0 is the instrument frequency at the lowest calibration temperature. This equation fits the instrument output to actual temperature within a few millidegrees Celsius.

To evaluate their performance, both probes were frozen into separate blocks of ice, with the ice boundaries at least 15 1/4 cm from the center of the probes. Auxiliary temperature probes were also frozen into the ice blocks to determine the far-field ice temperature. Unfortunately, we were not successful in creating homogeneous blocks of ice with no air bubbles. Thus the measurements of the thermal conductivity of the ice should be lower than the theoretical values because of entrained air bubbles. The ice temperature at the beginning of the test was -6.4°C. The test was run for 276 minutes, during which time the auxiliary temperature probe indicated that the ambient temperature of the ice increased to -6.25°C. Probe #1 exhibited the expected linear relationship between temperature and $\ln(\text{time})$; however, the lower, middle, and upper thermistors indicated thermal conductivities of 0.0286, 0.0294, and 0.0329 W/°C cm, respectively. These readings are higher than the theoretical conductivity of ice, which is 0.0225. One explanation for the high readings is error introduced by stem conduction. Another factor is that part of the heater coil resistance is in the electrical leads to the coil, so that the power actually dissipated in the 11 cm coil was 8% less than originally assumed. If this correction is made, the indicated readings are 0.0263, 0.0270, and 0.003 W/°C cm, respectively. It was also noted that the absolute temperature readings of the three thermistors in Probe #1 did not agree well with each other when the heater was on. This is believed to have been caused by the method of construction--one lead to the heater coil passes through the center of the mandrel, adjacent to the three thermistors. Different proximities of the thermistors to this heated wire are probably the reasons behind the temperature discrepancies.

Probe #2 never achieved the expected linear relationship between temperature and $\ln(\text{time})$; instead, the thermal conductivity increased with time. Also, a second test in ice was run on Probe #1 several days later, and the performance was similar to that observed for Probe #2. No explanation for this nonlinearity has been found, nor for the change in the test results for Probe #1.

After the previously described tests had been run, it was discovered that the electronics housings for both probes were not connected to electrical ground because some internal parts had been inadvertently anodized. Correcting this condition resulted in much quieter outputs from the probes ($<0.001^{\circ}\text{C}$ rms noise). Also, the 8 mm tube was not electrically connected to the electronics housing, which probably caused an offset of about 0.3°C between readings during the calibration at NRCC (in which the stem was effectively grounded to the case by salt water) and the readings during the APL ice test (in which the stem was ungrounded).

Conclusions and Proposed Modifications

- (1) Another test needs to be run with the probe in a substance of known thermal conductivity. Ice is not recommended because of the difficulty in obtaining a large pure sample, and because of uncertainties about uniform thermal contact between the probe and the ice. McVey has recommended that a block of Teflon be used.
- (2) Prior to further testing, the probes should be rebuilt so that the Manganin wire is confined to the outside of the mandrel and within the 11 cm length of the coil (e.g., by using copper leads everywhere except in the coil itself).
- (3) If analysis by D. F. McVey shows that stem conduction is introducing errors, the 2 mm o.d. portion of the probes should be lengthened.
- (4) The electronics should be modified so that the heater coil can be turned on and off independently of the oscillator electronics. Presently, heater power is on whenever the oscillator is on, unless the heater is manually disconnected.

HYDROSTATIC CORER DEVELOPMENT

One of the requirements of ISHTE is to recover samples of the sediment at the end of the experiment. To meet this requirement, six piston corers will be sequentially driven into, and removed from, the sediment. Five of the corers will be hydrostatically actuated whereby the ambient sea pressure will provide the driving force. The sixth corer (heater canister overcorer) will be attached to, and driven by, the nearest hydrostatic corer. The corer locations, penetration depths, and structural arrangements have been discussed in previous program progress reports.

The hydrostatic corers are completely self-contained, except for a specific electrical initiation signal, and are special designs for ISHTE. The hydrostatic actuation concept is modeled after units developed for the MANOPS program (Ref. 5). For ISHTE, the corer designs are identified by the sediment sample length desired: 120 cm, 140 cm, and 160 cm.

Over the past year, one 160 cm hydrostatic corer has been designed, built, and locally field tested. This 160 cm hydrostatic corer is shown in Fig. 9 and the specifications are listed in Table 6. The 160 cm hydrostatic corer has been field tested in Puget Sound with two actuations. Both actuations agreed with the expected performance. Additional field testing is planned for April 1981 at the MPG-I site.

Table 6. Specifications for the 160-cm corer

SIZE

Diameter, outside	11.43 cm	4.5 in.
Diameter, sediment sample	10.16 cm	4.0 in.
Length, collapsed	245 cm	96.5 in.
Length, extended	438 cm	172.6 in. (14 ft - 4.6 in.)

WEIGHT, in air	92 kg	203 lb
OPERATING DEPTH, maximum	6100 m	20,000 ft
SAMPLE LENGTH	160 cm	63 in.
CORING FORCE	770 kg	1700 lb
CORING PRESSURE	3.25 MPa	471 psi
CORING VELOCITY	10 cm/sec	4 in./sec

WORKING FLUID

Low temperature hydraulic oil,
Tellus 10 (Shell Oil Company)

FLUID VOLUME	4.4 liters	270 in. ³ (1.17 gal.)
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CORER ACTUATION

Electrically initiated gas
pressure cartridge,
Holex #3602

PRESSURE RELIEF VALVE	520 kPa	75 psi
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SHIPPING CONTAINER

L x W x H	244 x 18 x 18 cm	96 x 7 x 7 in.
Volume	0.077 m ³	2.72 ft ³
Weight, gross	100 kg	220 lb

Corer Description

Figure 10 shows a cross-sectional representation of a corer incorporating a hydrostatic actuator which generates the hundreds of kilograms of force required to drive the corer tube into the sediment. Operation of the system is similar to that of a standard hydraulic cylinder employing a meter-out control valve. When a load rests on a hydraulic cylinder, the working fluid trapped within the cylinder is pressurized. A metering control valve is used to release this pressurized hydraulic fluid to a reservoir at atmospheric pressure, thus allowing the cylinder to actuate and the load to move.

In the hydrostatic actuator shown, the corer piston and rod will be fixed to the platform. With the initiation valve closed, the working fluid will be trapped between the piston and the core barrel. Since the core barrel will be free to move, the ambient sea pressure on the outside will balance the pressure of the trapped fluid inside. An electrical signal will open the initiation valve to actuate the corer. Then the high-pressure trapped fluid will be forced through the valve and control tube to the low-pressure reservoir within the piston stem. As the pressure on the trapped fluid is relieved, the sea pressure will drive the core barrel to maintain a pressure balance. Since the control tube will be a long, small-diameter tube, it will generate a velocity-dependent back pressure on the trapped fluid, thus controlling the rate of corer actuation by turning the available energy into heat. As the core barrel meets resistance from the sediments, the rate of actuation will slow. The velocity in the control tube will drop, thus reducing the back pressure on the trapped fluid, and more of the energy will be expended in driving the corer.

Corer Design

Particular attention was given to the core barrel and cutter dimensions during design so as to provide a corer that minimizes disturbance of the sediment sample. Figure 11 shows recommended core barrel characteristics (Ref. 6). The comparable ISHTE values are within the recommended ranges except for the area ratio, Ca. However, the 160 cm corer has a fixed position and a sharp cutter, and therefore has the appropriate prerequisites to fulfill the recommendation.

The corer inside diameter of 10 cm was chosen by A. J. Silva of URI to fit existing extrusion equipment. The corer length was determined by D. F. McVey of SNL for the sampling depths required in the thermal field of the heat canister. The combination of the two dimensions in the length to width ratio, $C = 16$, shows good agreement with the recommendations in Fig. 11.

Due to the length requirements of the core nose, core catcher, and working fluid volume changes (from temperature and pressure), the piston placement must be many centimeters above the sediment. Figure 10 shows a plastic plug inside the core tube just above the sediment surface. The purpose of the plug is to reduce the dead water volume on top of the sediment sample.

Current plans call for the ISHTE to last for one year which means the corers will be in the structure on the ocean floor for one year before actuation. Several features have been included in the corers to minimize the problems associated with exposure to the corrosive environment and the high pressure for such a long period of time. These features include the special initiation valve design, choice of corer materials, corer inherent operation, seals, and choice of working fluid.

The initiation valve is a minor adaptation of a valve developed for MANOPS by Oscar Kirsten of Scripps. The valve uses an electrical signal to fire a gas pressure cartridge. The gas pressure impulses a rupture piston which pierces a solid metal disc that normally blocks the working fluid. This allows the working fluid to flow to the low pressure reservoir.

Two important considerations in the valve design were: that the valve always opens upon command, and that the working fluid does not leak through the valve before actuation. The gas pressure cartridge provides the reliability for valve opening. It is a commercially available electro-explosive device (from aerospace technology). The particular device used has two independent bridge wires that are simultaneously fired by separate firing circuits. The metal disc provides the leak free condition until rupture. It uses a metal-to-metal seal along with an O-ring.

Several test firings of the complete valve assembly have been accomplished with no failures. The MANOPS program has conducted six firings at the design pressure. The ISHTE tests have included five firings, one of which was at design pressure.

The corer itself is corrosion resisting through choice of materials. It is entirely constructed of 17-4PH stainless steel and type 316 stainless steel. The core tube and core nose are made from type 316; the remaining pieces are all made from 17-4PH. The 17-4PH pieces in contact with sea water are heat treated to condition H1150. Pieces not in long-term contact with sea water are heat treated to condition H900 for increased strength and hardness.

Even though the above materials resist corrosion in sea water, they are somewhat susceptible to pitting and crevice corrosion. In a galvanic couple, mild steel provides sufficient cathodic protection to reduce corrosion. We plan to construct the platform from mild steel with the corers mounted in direct contact with the platform. Also, mild steel anodes will be installed on top of the core tube and on the bottom of the piston to protect critical sealing areas.

The design of the corer is such that it inherently protects the dynamic sealing surfaces from the sea water. The sealing surfaces are bathed in oil while the corer is in its collapsed state. Upon actuation, the corer extends and only then do the surfaces come in contact with sea water.

The working fluid has moderate corrosion-inhibiting properties for both ferrous and nonferrous metals. This enhances the corrosion

resistance of the corer in the event of water leakage. Even if corrosion should occur under the sliding seals, any leakage would allow the seal to move toward a new surface.

The working fluid is a petroleum-based, low-temperature, hydraulic oil. It is marketed by Shell Oil Co. as a proprietary fluid called Tellus 10. The viscosity is satisfactory for both atmospheric pressure and room temperature, as well as the design pressure at depth and the associated temperature.

The core tube is free to move either up or down to compensate for the working fluid's volume changes due to temperature and pressure variations. Based on room temperature and atmospheric pressure, the core tube will move up 7.6 cm if the fluid temperature reaches the upper design limit of 71°C. The core tube will move down 7.6 cm from the room temperature position when the corer reaches the design depth and temperature. At design depth, the core cutter attached to the bottom of the core tube will clear the sediment by 5 cm.

The corer fluid circuit has four built-in passages. A fluid circuit diagram is shown in Fig. 12. The passages, except for the control tube, are drilled openings in the outer shell and piston. The control tube is a piece of stainless steel tubing. It is sized to achieve a certain amount of pressure drop at design flow and operating depth. In the 160 cm corer the tube is 0.64 cm o.d., 0.31 cm i.d., and approximately 4 m long. At the operating depth, 5.5% of the hydrostatic pressure is used for driving the core tube, 83.5% of the pressure is dissipated in the control tube, and 11.0% of the pressure is dissipated in the initiation valve and other portions of the drilled passages.

After the corer has been actuated, the working fluid displaces a considerable volume in the low pressure reservoir. This raises the reservoir pressure above atmospheric. Prior to corer servicing, the pressure (estimated to be 310 kPa absolute) needs to be bled off. The VENT port allows for discharge of this excess pressure in the low-pressure reservoir.

The pressure relief valve is a safety feature that automatically accomplishes excess pressure discharge to limit the reservoir pressure to 520 kPa. If some seals failed at depth and allowed sea water to fill the low-pressure reservoir, the reservoir pressure could be dangerously high upon corer retrieval.

The DUMP passage directs the working fluid from the initiation valve through the check valve to the low pressure reservoir after the initiation valve has been activated. This volume of oil increases the internal pressure in the low-pressure reservoir. During retrieval, the check valve blocks the flow of this pressurized fluid into the corer annular space as the pressure on the outside of the corer is reduced. Without the check valve, this release would partially extrude some of the sediment sample out of the core barrel.

The FILL port is the external connection whereby the working fluid can be injected into the corer's annular space. The DRAIN port allows

for fluid removal from the low pressure reservoir without corer disassembly.

The sediment sample is currently expected to be extruded from the corer and then processed in accordance with ISHTE requirements. Extrusion from the corer will be the reverse of the direction that the sediment entered the corer. By attaching a pump to the FILL port and injecting oil into the corer, the outer core tube containing the sediment will retract over the corer piston to extrude the sediment.

Corer Test Equipment

A coring test frame has been built to hold the corer and other equipment for in-water tests. Figure 13 shows the coring frame with the equipment installed. The frame is a pyramid shaped structure that is 1.83 m square on the base and 2.90 m high to the tip of the lifting bail. The frame is ballasted with railroad wheels in each corner to provide an air weight of about 5.12 kN. This weight was calculated as that necessary to provide the resistance for the corer penetration force at MPG-I.

In addition to the corer which is the long, vertical device in the center of Fig. 13, the coring frame contains the following:

- a. a tracked object
- b. a watertight electronics housing
- c. a pressure sensor
- d. an underwater camera system
- e. two bottom contact switches.

The tracked object is in the spherical plastic housing in the near foreground with its attendant transducer on a long, white standoff. The electronics housing is the spherical housing to the left of the corer and in the center of the figure. The housing contains the corer firing circuit and corer pressure data system in addition to being an electrical junction box.

The pressure sensor is a Paroscientific digiquartz pressure transducer with a 0 to 69 MPa operating pressure range. The gauge is contained within a pressure case attached to the coring frame. (In Fig. 13, this case is between the corer and the middle of the transducer standoff.) A 0.64 cm o.d. tube connects the gauge to the FILL port on the corer. An electrical cable connects the transducer in the pressure case to the data recording components in the electronics housing.

The pressure recorder is activated by a pulse from the corer firing circuit about 15 seconds before firing. The Paroscientific pressure transducer provides an output signal whose frequency is proportional to pressure. The electronics count N_1 periods of the signal while at the same time counting N_2 periods of a 3MHz reference (f_R). The frequency f_p of the pressure transducer output can then be determined by

$$f_p = \frac{N_1 f_R}{N_2}.$$

Since N_1 and f_R are predetermined, only N_2 need be recorded to allow subsequent calculation of the pressure. The data are recorded at intervals of 0.1 sec on erasable programmable read-only memory (EPROM). The EPROM's utilized have 2K bytes of storage (2048 data points). In the field, data recorded on the EPROM's can be selectively read out using a portable microcomputer (Intel SDK 85) and converted to pressure with a programmable calculator. A complete printout of pressure versus time is obtained using an Intel microprocessor development system with a universal PROM programmer. A PL/M program reads the EPROM's, calls a FORTRAN subroutine to compute the pressure, and writes the result to a line printer.

A Benthos 35 mm deep-sea camera system with a flash unit is mounted on posts attached to the base on the left side of Fig. 13. A trip switch (not visible) for the camera system initiates the picture-taking sequence. A second trip switch (also not visible in Fig. 13) operates off the same trip weight and initiates the timing circuit in the corer firing electronics.

Corer Test Procedure

A typical sequence of events for a field test of the corer follows.

The corer frame with all equipment installed is launched and lowered on a nylon line. As the frame approaches the sea floor, the weight on the camera trip switch touches bottom and releases the load which allows it to actuate. The camera then begins a sequence of 10 pictures to photograph the character of the sea floor prior to touchdown and to photograph the frame landing.

A second switch is actuated simultaneously to start a timer circuit. This circuit provides an adjustable delay between frame touchdown and corer firing of up to 30 minutes. At the end of the delay period, the timer circuit initiates the corer firing circuit. This circuit starts the camera for a second set of pictures, starts the pressure data recording, and sets the "squib fired" (gas pressure cartridge) indicator circuit. About 15 seconds after the corer firing circuit is turned on, it fires the corer initiation squib. There are two squib firing circuits, one for each bridge wire in the cartridge, and both are ignited during corer firing.

The corer firing circuit can also be initiated by an acoustic command message from the tending ship. The message is sent to the tracked object which in turn initiates the corer firing circuit. The "squib fired" indicator is telemetered back to the ship when the corer firing circuit is initiated by either the contact switch or the acoustic command message.

The second set of pictures shows the corer penetrating the sediment. This sequence runs the camera out of film. The number of exposures is determined by the film length. Since this length is known, the time interval between frames can be adjusted to ensure a complete record of the corer drive sequence.

Corer Field Test

Two corer actuations were made in Puget Sound. The first was an actuation just above the bottom for baseline operational pressure measurements. The coring frame, however, was placed on the bottom to initiate the first 10 pictures with the trip switch. After a short hold period on the bottom, the coring frame was hoisted about 20 m above the bottom, and the corer was actuated by an acoustic command message from the ship.

During the second actuation, the coring frame was lowered to the bottom at a depth of 223 m. The corer was acoustically commanded from the ship to fire. The "squib fired" response was then received at the ship over the acoustic link. After retrieval, the corer showed full penetration and brought back the full sediment sample.

The corer pressure recording system allowed the corer actuation time to be measured which then allowed the corer penetration velocity to be computed. The corer actuation times were 172 seconds for the water column test and 188 seconds for the bottom sediment sample test. This gives a coring rate of about 1 cm/s. Calculated time estimates were 135 and 188 seconds, respectively, which compare favorably with the test times. The penetration velocity for ISHTE is expected to be 10 cm/s. This increase in velocity will be caused by the higher pressure available at MPG-I depth.

MATERIALS EVALUATION

Various combinations of materials are going to be used in the hardware and platform structure on the ocean floor for the ISHTE test. The choice of these materials is based on the strength, deflection and corrosion resistance requirements. In general, our plan is to make the structure from mild steel and the hardware from 316 stainless steel, 17-4PH stainless steel, Inconel 625, or Hastelloy C276.

The canister housing and implant assembly will be made from Inconel 625. The Inconel choice was made by the heater manufacturer and SNL engineers. In the literature, Inconel 625 is reported to be inherently one of the better metals for sea water applications. In our design of the implant assembly, the Inconel will be coupled to the mild steel structure. The mild steel galvanically protects the Inconel so no serious corrosion problems with the metal combination are anticipated in sea water. The structure's area will be large compared to the canister system. Effects on those components in heated mud will be another matter and must be addressed separately.

In other hardware applications where corrosion resistance is a design requirement, 316 stainless steel will be used. The galvanic couple with mild steel is favorable to maintaining corrosion free 316 without generating large hydrogen overvoltages. Once again the structure is considered large with respect to the amount of 316 used, so corrosion of the mild steel is expected to be small for the galvanic protection provided.

Pressure vessel applications require a material with greater strength than 316 stainless steel, and thus 17-4PH stainless steel will be used.

This alloy, if used with a heat treatment that provides aging at 1025°F or above, can be used effectively in sea water according to the literature. Passivity is maintained in high velocity sea water, similar to austenitic grades; however, cathodic protection to control pitting and crevice corrosion is recommended in quiet sea water. In general, the 17-4PH alloy's characteristic performance in sea water is much like that of types 304 and 316.

Neither the specific corrosion performance of alloy 17-4PH nor the relative performances with respect to type 316 was noted in the literature searched. Consequently, the long-term mooring installed in MPG-I during July 1980 provides an opportunity to compare the corrosion performance of 17-4PH in the actual environment planned for ISHTE.

Corrosion Test Objectives

For the long-term mooring, our corrosion test objective was to determine the corrosion resistance of the typical materials planned for ISHTE (except for Inconel 625). This includes specimens of

- a. 17-4PH in the annealed Condition A
- b. 17-4PH in the aged form, heat-treated for 4 hours at 1050°F (H1050)
- c. Type 316 stainless steel
- d. Type "18-8" stainless steel fasteners
- e. Rubber cable seal disks in contact with type 316 stainless steel.

Experiment Specimen Set

Figure 14 is an assembly sketch of a specimen set to be attached to the long-term mooring. From left to right, the specimens are as listed in Table 7. Disks and washers, as well as the rod and mounting fasteners, are being corrosion tested. The rod is made from 316 stainless steel and the fasteners are "18-8" stainless steel from laboratory stock. The rod was clamped to a mild steel bracket with the fasteners. This mounting system allows an evaluation of a typical bolted joint on the platform structure. Three replications of the specimen assembly set were installed on the long-term mooring.

Pre-Test Procedure

Our pre-test procedure was as follows.

- a. Make corrosion test specimens in machine shop
- b. Clean specimens
 - i. Sandblast all surfaces
 - ii. Scrub and rinse with mixture of acetone and alcohol to remove grease and oils
- c. Weigh specimens
- d. Assemble specimens into test configuration
- e. Photograph typical disk, washer, and assembly
- f. Package in dessicant packed bags and ship to Hawaii
- g. Install specimen assembly in long-term mooring
- h. Photograph installation in mooring
- i. Launch long-term mooring.

Table 7. Listing of assembled specimen set

<u>Specimen No.</u>	<u>Specimen Material</u>
1	17-4PH Condition A disk, isolated
2	17-4PH H1050 disk, isolated
3	17-4PH H1050 disk coupled to 17-4PH Condition A washer
4	17-4PH Condition A disk coupled to type 316 washer
5	17-4PH H1050 disk coupled to type 316 washer
6	Mild steel disk coupled to 17-4PH Condition A washer
7	Mild steel disk coupled to 17-4PH H1050 washer
8	17-4PH Condition A washer with surface weld bead, isolated
9	17-4PH H1050 washer with surface weld bead, isolated
10	Rubber cable seal sandwiched between type 316 washers

Post-Test Field Procedure

Our planned post-test procedure is as follows.

- a. Recover long-term mooring
- b. Photograph specimen sets in long-term mooring
- c. Remove each specimen assembly from mooring
- d. Photograph each individual specimen assembly
- e. Rinse and scrub with a bristle brush each specimen assembly in fresh water, being careful to remove all organic matter
- f. Bake in oven at 105°C to remove all moisture
- g. Package in bags and ship back to laboratory.

Post-Test Laboratory Procedure

- a. Disassemble each assembly
- b. Photograph each test specimen
- c. Clean corrosion from each test specimen
 - i. Mechanical treatment, such as scrubbing with bristle brush, scraping, wire brushing, or sandblasting
 - ii. Chemical treatment, such as 10% nitric acid solution at 60°C
- d. Weigh each specimen, determine corrosion loss, and calculate in terms of corrosion rate per year
- e. Determine average depth of 10 deepest pits and the depth of the deepest pit
- f. Evaluate test results according to ISHTE requirements.

Long-Term Mooring

The mooring (Fig. 15) was deployed in the MPG-I area to evaluate some ISHTE hardware and some material test samples exposed to sea water and pressure 100 m above the bottom (5720 m depth) for approximately nine

months. The mooring used glass Benthos spheres for buoyancy, mainly nylon line, dual AMF model 322 acoustic releases, and 145 kg of railroad wheels for an anchor. The mooring is located at 30°19.10'N 157°52.37'W near the GPC-3 site in 5800 m of water. This system will be recovered by APL next spring on a planned cruise with the De Steiguer.

The transponder at location #4 (see Fig. 5) was recalled from the tracking array after operating for three days at 5700 m depth. The lithium battery pack was replaced with a double lithium battery pack which is adequate for over a year. The stainless steel (type 316) vacuum ports in the transponder's glass pressure housing were replaced with titanium parts. The seal housing of the transducer was replaced with a seal housing that protected all unanodized aluminum parts of the transducer's base from sea water. This transponder, with a recovery package consisting of an OAR flashing light and an OAR radio transmitter, was attached to the top of the mooring.

A 3 m length of 1 1/4 cm diameter braided polypropylene line was attached to 7 m of galvanized chain. Along this chain were attached four 43 cm diameter and one 25 cm diameter Benthos glass floats, plus one 43 cm diameter glass instrument housing containing 40 single-pin electrical connectors and two vacuum ports.

Twenty meters of plaited nylon line attached the chain to a fiberglass frame, which contained the components listed below (a-j) plus an InterOcean recockable acoustic release. This release was not a crucial link, but was attached so that the unit could be evaluated acoustically at rated depth and range. Also, the mooring will test the corrosion resistance and pressure resistance of this release for the nine month period at 5700 m depth. The ISHTE hardware and test samples are:

- a. One Sea-Bird Electronics 3-02 deep ocean thermistor probe
- b. One 17-4PH stainless steel pressure housing for the ISHTE thermal sediment probes
- c. Four 43 cm diameter Benthos glass floats
- d. One Benthos titanium wire burning release
- e. Some protective greases on metals
- f. One EnviroCon four-pin bulkhead connector
- g. Three sections of jacketed 2.3 mm diameter Kevlar line
- h. One section of unjacketed 1.6 cm diameter braided Kevlar line
- i. One Marsh Marine three-pin bulkhead connector
- j. Three corrosion test assemblies (mentioned in detail previously).

The remainder of the mooring consisted of plaited nylon line, two AMF releases (rigged so that either unit will release the mooring), and the 145 kg anchor. The mooring has enough buoyancy that any two glass pressure cases or the InterOcean release and one glass case can flood without preventing a buoyant recovery.

After the anchor hit bottom, the mooring was accurately surveyed into the ISHTE tracking array with the APL transponder located at the top of the mooring. Later, this transponder stopped replying. Since

the main tasks for this transponder were to survey the mooring geographically and to test the hardware for pressure and corrosion effects during a long period of time, the transponder's failure at this point didn't warrant recalling the mooring. Long-term electrical testing can be performed better in the laboratory under controlled conditions than in a one-shot test in the ocean. We hope the cause of this transponder's failure can be determined next year upon recovery. The failure should not have much effect on the recovery unless the unit has flooded, which will prevent operation of the OAR recovery radio and flashing light for location on the surface. Because it may be flooded, the recovery team will have to range on the AMF releases during ascent.

Nylon Line Testing

APL has used many nylon lines to moor and lower packages into the ocean over the past 20 years with good success. However, with the long lengths planned for ISHTE and the criticality of the terminations, APL has been doing some field testing on immersed tensile strength, soaked splices and terminations, elongation under load in the saturated condition, and shrinkage of new and aged lines. The testing has shown some apparent discrepancies between laboratory test results reported in the literature and results from our field testing. The tests have also taught us some lessons about line splicing and the assembly of terminations. We plan to continue testing on terminations at a low level of effort next year.

ISHTE SIMULATION

The ISHTE simulation (ISIMU) is a scale-model test employing a tub of consolidated ocean clay to represent the sediment at the ISHTE site. A fresh water pressure chamber will be used to create the high pressure of the deep ocean. A bath of pressurized salt water will be contained over the clay sediment in an attempt to simulate the ocean environment. A heat source will be located in the center of the tub and thermocouples placed in the surrounding sediment to monitor the thermal field.

Charles Hickox, the prime investigator for ISIMU, has stated that the main purpose of the simulation is to check for unanticipated thermal phenomena in the sediment. We also want to investigate instrumentation and materials problems which may occur in ISHTE. However, it should be pointed out that such things as corrosion will be impossible to simulate in the closed environment even if the time and money were available.

One of the greatest unknowns involved with both ISHTE and the simulation will be the effect of salt water and sediment on materials at elevated temperatures and pressures. Little information on these effects is available in the literature, even for laboratory tests, and practically nothing is known of the effects at the bottom of the ocean.

Because of limited time and funds, SNL program personnel are requesting APL to use standard off-the-shelf hardware for the heater and thermocouples, not the actual materials to be used in ISHTE. This is

probably reasonable in light of the following: the salt water tank will be a stagnated system and not very representative of the ocean; miniaturization of the ISHTE hardware would be both expensive and difficult; and many of the materials for ISHTE in the hot sediment areas will be exotic. Special mill runs will probably be required to obtain the Inconel 625 or Hastelloy C-276 materials. Special milling is expensive, considering the small quantities needed, and requires long lead times.

With less than the optimum materials in ISIMU, some components in the sediment may fail rather rapidly and not last the 30 days. We plan to make the heater system as reliable as possible so that even if other components corrode severely, the thermal field will be maintained. After the first few days, sensors in the cooler sediments (where corrosion should be less rapid) will be able to monitor the thermal field. Inconel 600 will probably be the sheath material chosen for the thermocouples because it is readily available. It should be suitable in the salt water when coupled with mild steel as an anode. The performance of Inconel 600 is difficult to predict in the sediment because there will probably be marked changes in the pore water's pH.

Proposed ISIMU Instrumentation

The 115 watt dc heater for the sediments will have four 2 mm diameter thermocouples attached to the surface: one near the bottom, two at mid-depth, and one near the top. Two other thermocouples will be located in the implant tube with a vertical separation to allow an estimate of the thermal gradient in the tube. These thermocouples will have their analog voltage signals converted to a digital signal in the electronics package borrowed from the ISHTE electric heat source (EHS). This will not only be an accurate system, but it will test some ISHTE hardware at pressure. These serial digital strings of data will be cabled out of the pressure chamber into an APL readout package and then converted to temperature and recorded in an HP 85 desktop computer.

Sediment thermal sensors will be chromel-alumel thermocouples with cold junction chambers in the saltwater bath. The low-level analog voltages will be carried from the cold junction chambers over jacketed copper wires to a Fluke data logger outside the pressure chamber. The associated cold junction temperature will be measured in the salt water bath area by Sea Bird Electronics thermistor probes. These probes convert the temperature signal to a frequency in a Wien bridge oscillator. The frequency will be cabled out of the pressure chamber to the APL readout unit used for the heater thermocouples. This value is sent to the HP 85 computer and used with the thermocouple value from the data logger to obtain a temperature reading. Most of this monitoring hardware exists for the ISHTE and will only require minor modifications. The real work is involved in the software to make the system automated.

Selected thermocouple records from the simulation will be continuously displayed on an HP 7225A plotter hooked to the HP 85 computer. These plots will be a good monitor on the experiment. All of the thermal data will be printed out and will be stored on the computer's 210K byte cassette cartridge. After the experiment, these data can be transferred from cassette to nine-track tape, if desired.

APL's involvement in ISIMU was to be minimal, but our part has grown, justifiably, because the simulation will allow us to begin testing some of the ISHTE hardware, at least electronically. This involvement can also give us valuable knowledge on thermocouple technology, which will relate to the ISHTE heater monitoring system. APL will use about 18 engineering man-months in support of the simulation and the pressure testing of ISHTE hardware in the chamber.

REFERENCES

1. "Subseabed Disposal Program Annual Report," Vol. II, Sandia National Laboratories, Albuquerque, NM, 1980.
2. J.L. Roberts-Backes, B.M. Bell, W.E. Nodland, and L.O. Olson, "A Deep Ocean Acoustic Tracking and Telemetry System," APL-UW 8015, Applied Physics Laboratory, University of Washington, Seattle, WA, December 1980.
3. L.O. Olson and J.L. Roberts-Backes, "ISHTE System Tests at MPG-I, July 1980, APL-UW TN 12-80, Applied Physics Laboratory, University of Washington, Seattle, WA, 1980.
4. S.M. Widerhorn, E.R. Fuller, and R.M. Thompson, "Micromechanisms of Crack Growth in Ceramics and Glasses in Corrosive Environments," Internal Report 80-2023, National Bureau of Standards, May 1980.
5. O.H. Kirsten and R.F. Weiss, "A Hydrostatically Actuated Piston and Hydraulic System for Deep-Sea Free Vehicle Applications," in OCEANS '78 Conference Record, paper 26D, pp. 596-598, Marine Technology Society and Institute of Electrical and Electronics Engineers, 1978.
6. A.M. Rosfelder and N.F. Marshall, "Obtaining Large, Undisturbed and Oriented Samples in Deep Water," Marine Geotechnique, Adrian F. Richards, Editor, University of Illinois Press, 1967.

Figure 1. ISHTE platform deployed.

Figure 2. Tracking computer system.

Figure 3. Simulated transponder mooring.

Figure 4. Sample of tracking display.

Figure 5. Test site in MPG-I area.

Figure 6. Sediment thermal sensor assembly.

Figure 7. Metal sheathed sediment probe.

Figure 8. Thermal conductivity probe.

Figure 9. 160 cm hydrostatic corer.

Figure 10. Cross-sectional representation of a hydrostatic corer.

Characteristic	Equation	Recommended Design Value	ISHTE Value
Inside clearance	$C_i = \frac{D_s - D_e}{D_e} (100)$	0 to 0.5 for very short corers 0.75 to 1.5 for current corers	1.2
Outside clearance	$C_o = \frac{D_w - D_t}{D_t} (100)$	0 for noncohesive sediments <2 or 3 for cohesive sediments	0
Area ratio	$C_a = \frac{D_w^2 - D_e^2}{D_e^2} (100)$	<10 unless corer has stationary piston and sharp cutter	16
Safe length/width ratio	$C = \frac{L}{D_s}$	<10 in dense to loose noncohesive sediments <20 in stiff to very soft cohesive sediments	17
Cutter sharpness		$\alpha < 10^\circ$ and preferably $\alpha = 5^\circ$	5°

L = maximum sampling length
 D_s = barrel inside diameter
 D_t = barrel outside diameter
 D_w = cutter outside diameter
 D_e = cutter inside diameter
 α = cutter angle

Figure 11. Core barrel characteristics.

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Figure 14. Assembly sketch of ISHTE corrosion test specimen set.

Figure 15. Long-term corrosion mooring.

Appendix Q

Design and Development of Deep-Water
Piezometer for the
Sandia Subseabed Disposal Program

R. H. Bennett, J. J. Burns, and D. N. Lambert

DESIGN AND DEVELOPMENT OF DEEP-WATER PIEZOMETER FOR THE
SANDIA SUBSEABED DISPOSAL PROGRAM (SDP) (Status Report for 1980)

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The National Oceanic and Atmospheric Administration (NOAA), Atlantic Oceanographic and Meteorological Laboratories (AOML), Marine Geology and Geophysics Laboratory (MGGL) contracted with Sandia Laboratories, Subseabed Disposal Program (SDP) to prepare initial design and to begin development of a piezometer for the In Situ Heat Transfer Experiment (ISHTe). General design specifications and material types were established by mutual agreement between AOML and Sandia during planning meetings. ISHTe experimental objectives were considered of paramount importance in arriving at the piezometer specifications and on the types of materials to be used. AOML's objectives for the design and development of the piezometer in 1980 included:

- (1) Preliminary design of the mechanical components of the piezometer probe,
- (2) Purchasing of basic materials for fabrication of the initial probe,
- (3) Purchasing of a few selected pressure sensors for high-pressure testing,
- (4) Installation of a high-pressure test facility at AOML for testing pressure sensors, and
- (5) Initiating preliminary testing of pressure sensors.

Each of the objectives (1-5) were completed successfully in 1980. In addition, AOML constructed a prototype piezometer probe which was tested for mechanical performance in situ in submarine sediments on the U.S. Atlantic continental slope aboard the DSRV ALVIN in October 1980 during NOAA allocated ALVIN time. The mechanical performance test was successful.

ACTIVITIES

Design of Piezometer Probe

Preliminary design of the mechanical components of the piezometer probe was completed in 1980. Working drawings with specifications and detailed dimensions of components of the probe were completed. The piezometer probe consists of an 8 mm diameter titanium tube that attaches to a tip having a cone angle of approximately 5.3° . Details regarding the choice of probe tip design can be found in Bennett and Faris (1979). A porous stone, which allows

pore water pressure to be transmitted to the pressure sensors, is fastened between the titanium tube and the probe tip (Figure 1). Pore pressure is transmitted through the porous stone to an internal tube to the pressure sensor. The differential pressure sensor is pressure balanced by a similar internal tube that runs from the pressure sensor to the top to the porous stone retainer (Figure 1). The pressure sensor is enclosed in a stainless steel housing which will be pressure compensated to in situ hydrostatic pressure (Figure 1). The stainless steel pressure sensor housing is physically separated by high dielectric polycarbonate material. The total lengths of the piezometer probes will depend upon the experimental design objectives for ISHTE. Only one pore pressure measurement at a preselected depth below the sediment-water interface (mudline) will be possible with each piezometer probe. These limitations were imposed on the design of the probe because of the requirement to limit the maximum size of the probe diameter (8 mm). Additional details of the piezometer probe materials and design are indicated in Figures 1 and 2.

Mechanical Performance Test of Piezometer Probe

During NOAA-allocated DSRV ALVIN dives off the U.S. Atlantic continental slope, October 1980, the prototype piezometer probe was tested in situ for mechanical performance in submarine sediment. The piezometer was attached to a newly developed geotechnical platform designed by NOAA (D. N. Lambert) for use on the ALVIN. The site where the test was conducted was located at 38°19.7'N, 73°21.6'W and in close proximity to a NOAA piston core site where geotechnical studies have been carried out (Bennett *et al.*, 1977). Water depth was 1450 m at the piezometer site. The piezometer probe was driven into the surficial submarine sediments at a rate of 0.25 m/minute in three increments (0.3 m, 0.6 m, and 1.0 m of penetration). Each increment of penetration was made in one smooth motion using a high torque, 38.42 N-m (340 in-lbs) 1/8 HP permanent magnet DC motor connected to a drive mechanism. A sediment cone penetrometer measurement was also made at the piezometer site (Figure 3) and one miniature vane measurement of shear strength was carried out on the sediment core recovered at the site. The profile of cone resistance with depth below the sediment-water interface showed a variable but steady increase to 1.2 m. During insertion of the piezometer the probe responded well with no observable hesitation through the sediment to each selected depth. The pressure sensor used during the test was a differential semiconductor transducer. The pressure sensor responded to insertion; however, useful engineering data of the pore pressure were not obtained due to suspected malfunctioning of the sensor. After returning the sensor to the shore-based laboratory and repressurizing to 68.9 MPa (10,000 psi), the sensor failed completely. Limited pressure testing was carried out in 1980 at NOAA using this type of sensor and testing showed that the particular type of sensor would not be suitable for use in future high pressure experiments. The probe length used (1.46 m plus length of sensor housing) during the ALVIN dives was considerably longer than will be used in the ISHTE simulation tests and the deep water experiment but its additional length provided a good test for rigidity and penetration performance. Insertion performance was considered excellent in the silty clay sediments.

Installation of High Pressure Test Facility and Initial Test Results on Selected Sensors

A high-pressure test facility was installed at AOML in 1980 for testing pressure sensors in an effort to determine if any currently available sensors would be suitable for the deep-water piezometer system. The high pressure chamber can be pressurized to a maximum of 103.35 MPa (15,000 psi) which is well above the projected in situ ambient hydrostatic conditions for ISHTE. Pressure sensors can be stressed to desired levels while monitoring their electrical output. Stress conditions can be maintained at high pressures for extended periods of time in order to observe any potential long-term changes in the pressure sensors.

Two differential pressure transducer types (semiconductor and variable reluctance) were initially tested at 68.9 MPa for: (1) mechanical integrity; (2) electronic integrity; and (3) stability of electronic output under high stress conditions. Four National Semiconductor Corporation pressure sensors (LX-1604D and LX-1611D) and two Validyne Engineering Corporation sensors (DP-78 and DP-195) were electronically "burned in" for two hundred hours prior to stress testing. All four of the semiconductor transducers failed electronically during high pressure testing to 68.9 MPa. The Validyne differential sensors (DP-78 and DP-195) were stressed to 82.68 MPa (12,000 psi) then brought to 68.9 MPa and held at this pressure for 24 hours. No failure was observed in either of the variable reluctance pressure sensors while under test conditions. On this initial high pressure test, pre and post calibrations of the sensors indicated good agreement. Further high pressure testing will be carried out to determine possible long-term effects and characteristics of variable reluctance sensors.

Plans for 1981

AOML plans to continue high pressure testing of pressure sensors during 1981. Two piezometer probes will be fabricated for use in the ISHTE simulation experiment. As testing and evaluation of the piezometer progresses during the year, the system and components will be modified as required to meet the requirements of the ISHTE experimental objectives.

References Cited

- Dennett, R. H., D. N. Lambert, and M. H. Hulbert, 1977, Geotechnical properties of a submarine slide area on the U.S. continental slope northeast of Wilmington Canyon: Mar. Geotech., 2:245-261.
- Bennett, R. H., and J. R. Faris, 1979, Ambient and dynamic pore pressures in fine-grained submarine sediments: Mississippi Delta: Applied Ocean Res., 1:115-123.

ISITE DEEP WATER PIEZOMETER		
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Date: 7-7-80		
JOINT SANDIA - NOAA PROJECT		
NOAA CONTACTS:	47483-1-11	
R. H. BENNETT, J. T. BURNS		

- NOTE: 1. TITANIUM IS TYPE CP TITANIUM
2. STAINLESS STEEL IS TYPE 316 STAINLESS STEEL
3. ALL DIMENSIONS ARE DIAMETER AND LENGTH (DXL) IN mm

FIGURE 2. Drawing of piezometer probe showing type of material and approximate dimensions(in mm) of components.

FIGURE 3. Cone penetrometer profile at the ALVIN miniature piezometer site in Wilmington Geotechnical Corridor. A standard cone was used with a 60° apex and a 10 cm² base area.

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