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**Subseabed Disposal Program Annual Report
January to December 1978
Volume I**

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Daniel M. Talbert, Editor

Sandia Laboratories

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SUBSEALED DISPOSAL PROGRAM ANNUAL REPORT
January to December 1978
Volume I

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ABSTRACT

This is the fifth annual report describing the progress and evaluating the status of the Subsealed Disposal Program (SDP), which was begun in June 1973. The program was initiated by Sandia Laboratories to explore the utility of stable, uniform, and relatively unproductive areas of the world as possible repositories for high-level nuclear wastes. The program, now international in scope, is currently focused on the stable submarine geologic formations under the deep oceans.

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This report was prepared by Sandia Laboratories, Albuquerque, New Mexico, under contract to the U.S. Department of Energy. The views and opinions contained herein are those of the author and do not necessarily represent those of the U.S. Department of Energy or Sandia Laboratories.

Volume II of this publication contains all principal investigator progress reports referred to in Volume I.

FOR INFORMATION ONLY

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SUBSEA BED DISPOSAL PROGRAM ANNUAL REPORT

Section 1. Introduction

This is the fifth annual report describing the progress and evaluating the status of the Subsea Bed Disposal Program (SDP), which was begun in June 1973. The program was initiated by Sandia Laboratories to explore the utility of stable, uniform, and relatively unproductive deep ocean floor areas as possible repositories for high-level nuclear wastes (HLW).

A critical problem in the development of nuclear power is disposal of the potentially dangerous wastes resulting from the use of nuclear fuels. While the wastes arise from several sectors of the nuclear fuel cycle and are in a number of forms, initially the SDP was limited to consideration of disposal of HLW from the reprocessing of spent fuel from the light water reactor (LWR) fuel cycle. The significance of the source of HLW to the research activities of the program has decreased as studies have progressed and, with the current U.S. policy relating to reprocessing of spent nuclear fuel, considerations of the potentially different burdens that would be placed on repository media and the environment by the disposal of spent fuel elements have been incorporated into the program. Consequently, the term "HLW" in this report and its appendices refers to wastes resulting from any one of many currently realizable reprocessing methods, as well as to unprocessed spent fuel.

Since 70% of the earth's surface is covered by the oceans, it is reasonable that this vast area should be considered in the search for an HLW disposal medium. A number of geological media are being considered for disposal, among them salt, clay, shale, crystalline rocks, and basalt formations on the continental land masses. Similar formations exist beneath the oceans and it is the clay formations in the sea floors that are the focus of this program.

Our current understanding of global geological and climatological patterns, including those of plate tectonics, gives some confidence that disposal of radioactive wastes into the seabed may be both feasible and safe. Some parts of the seafloor have properties that appear to be desirable for a disposal regime: The most seismically stable areas of the earth are under the oceans in the centers of the great oceanic plates; the floors of the major basins are the places most remote from man's normal activities; parts of these floors are severely limited in resources; and processes in deeper parts of the oceans are slow, gentle, predictable, and depositional, as distinct from continental processes which are primarily erosional. It must be understood, however, that our total knowledge of conditions on the ocean floor may not be at the same level as our knowledge of the continents.

On the basis of this reasoning, as outlined in References 1 through 5, and considering present knowledge of the midplate/midgyre (MPG) and continental trailing-edge regions of the oceans, the SDP has been working to provide the information needed to assess the viability of seabed disposal and to develop any new engineering capabilities required. The objectives of the program are to integrate the efforts of several groups of investigators in careful examination of the oceans and the geologic formations beneath them, with the goals of assessing the feasibility of using some portion of these formations for radioactive waste disposal and of possibly developing a safe disposal system.

As the SDP has developed during the past 5-1/2 years, two programmatic elements have evolved. The first consists of developing and conducting a research and engineering program which will yield an assessment of the technical and environmental feasibility of the concept and may offer a demonstrated alternate disposal option to the land-based possibilities currently being studied. A second program element is the development and maintenance of a capability for assessing any ocean disposal scheme proposed or developed by other nations.

At present, attention in the SDP is focused on the unconsolidated deep-sea sediments as a candidate medium for containment of radionuclides from solidified radioactive HLLW. Deep-sea clays that form a large portion of marine sediments have a number of properties that make them attractive:

1. They are extremely fine-grained (most particles are less than one micron in diameter) and consequently have a low permeability, which causes the rate of water migration (natural or induced) to be very low;
2. They have very large surface areas per unit volume of sediment, an important attribute when combined with the ability of the clays to extract (sor) cations from solutions;
3. Their strength is relatively low, thus potentially facilitating subsurface emplacement of waste containers; and
4. They are in a plastic state, do not fracture if disturbed, and tend to flow or "heal" if disrupted.

Section 2. Program Development

Objectives

The primary objective of the Subseabed Disposal Program is to assess the technical, environmental, and engineering feasibility of disposing of processed HLW and/or repackaged spent nuclear reactor fuel in suitable geologic formations under the world's oceans. A secondary objective is to develop and maintain a capability to assess nuclear waste disposal options developed by other nations.

Organization

The direct technical management of the SDP is the responsibility of the personnel of the Seabed Programs Division of the Waste Management & Environmental Programs Department of Sandia Laboratories. Program guidance comes from engineers and scientists working on the program and the appropriate Department of Energy (DOE) program managers.

Individual components of this program are coordinated by using a systems approach designed to deal with the waste from the time it leaves the reprocessing or repackaging facility until it is safely disposed of. The program uses a system engineering technique which couples information derived from the characterization of the natural barriers with the processes required to safely emplace waste in the seafloor sediments.

Inputs to the total systems engineering approach are characterization of the disposal medium, characterization of generic and specific disposal sites, development of system component models, evaluation of transportation and emplacement processes, risk and safety analyses, economic analyses, sociopolitical analyses, legal analyses, and conceptual design of the handling, transportation, and emplacement facilities.

History

In 1973 a group of scientists and engineers was assembled to identify the best geological formation for the ultimate disposal of HLW. It seemed sensible to search for the least valuable piece of real estate on the planet, preferably a region where tranquility and stability are maximized and where no earthquakes, volcanoes, erosive events, glaciers, or humans would be likely to disturb a repository during the time needed for radioactive waste materials to decay to innocuous levels. It also seemed desirable to put the waste in areas where biological productivity and competition for uses and resources would be low. The centers and trailing edges of the tectonic plates were determined to be areas where studies should be concentrated. Such areas that were overlaid by the centers of large surface gyres (great circulating ocean currents where climatological fluctuations are minimized and biological productivity is low) were especially attractive.

Initial program activities were dual: the collection of relevant historical information and the development of important new oceanographic data. To keep the magnitude of data development at a manageable level, initial studies were limited to the central North Pacific MPG area.² This did not imply commitment to that area as the only one deserving of study; the region was chosen because it was a convenient generic site-type study area with the required MPG characteristics.

Oceanographic data acquired during the past decade suggest that the ocean floor is continually being created and destroyed by the dynamic processes of plate tectonics. Knowledge about the direction and speed of the motion of these lithospheric plates has developed sufficiently for us to know that they collide in regions of mountain building or of seismically active deep-sea trenches. These boundaries can be areas where the edges of the crustal plates are destroyed by being thrust under or over other plates.

Placement of HLW into the deep-sea trenches at the leading edges of the subocean plates was rejected.¹ The trenches are unpredictable and unstable, and material from trench bottoms has been thrust up onto the continents in the past. In addition, the trenches are near continents and therefore mankind, and they often lie beneath biologically productive waters.

During 1974 and 1975, efforts and funds were primarily directed at assessment of the water column (the mass of water extending from the surface to the seafloor), the sediment surface, and related dynamics. The water column, including the benthic boundary layer, seemed to be the first logical barrier to the transport of radionuclides that seemed worthy of investigation because of its relative accessibility and the fact that investigative tools and techniques already existed. However, biological samples, surface sediment samples, water samples, photographs of near-bottom fauna, and current-meter data all showed that the energy relations and transformations of the biological, physical, and chemical processes of the water column, including the boundary layer, were more dynamic than expected. Therefore, placement of HLW on the seafloor surface was rejected^{3, 4} because the waste container would in effect be placed directly in the biosphere. Since it is difficult to conceive of a practical manmade waste-form/canister system that would survive for hundreds of thousands of years without releasing nuclides, it must be assumed that radioactive material would eventually enter the ecosystem from such placement. Therefore, the water column should not be considered a primary barrier in the containment system. It will have to be more completely understood, however, as aspects of transportation, safety, and environmental impact are addressed as part of the overall evaluation of the feasibility of a subseafloor waste repository.

As a result of the above conclusion, while program emphasis remained on the North Pacific MPG area, program focus was changed in mid-1975 from studies of the water column to detailed descriptions and studies of the sediments, their properties and chemistry, and the response of the sediment column to chemical and thermal outputs. This emphasis continued through 1976.

The Energy Research and Development Administration (ERDA), now a part of the DOE, conducted two reviews of the SDP in 1975 which confirmed the activities and long-range plans of the program. One of these reviews was by an ERDA consultant; the second was a formal peer review.³ What must be considered a confirming review of the program, its plan, and its goals occurred in early 1976 when the report on the First International Workshop on Seabed Disposal of High-Level Wastes was published.⁶ The workshop essentially approved the seabed disposal concept and developed a plan of research to investigate feasibility of the concept that was very similar in all essential particulars to that of the U.S. Seabed Disposal Program.

In early 1976, ERDA defined a second program element: the development and maintenance of a data base, methodology, and capability for assessing technical feasibility and environmental penalties of ocean disposal systems proposed by other nations. This element of the program, while not diminishing emphasis on the sediment column, precipitated renewed interest in research activities relative to the water column and an expansion of benthic boundary layer studies. Basic understanding of processes, responses, and functioning of the dynamic physical and biological systems of these portions of the environment is necessary if we are to assess the environmental impact of radioactive materials placed on or beneath the floor of the ocean.

The 1977 activities of the program included

1. Development of a number of analytical models as part of the overall system-analysis effort;
2. Continuation of an extensive laboratory program to evaluate sediment sorption with respect to single-specie ions and competition provided by waste constituents;
3. Continued characterization of sediment properties to establish initial conditions and develop a long-term predictive environment model of the sediments;
4. Evaluation of interstitial pore-water movement induced by a heat source;
5. Planning for a major thermal-properties field experiment to obtain quantitative information on thermal processes and material properties;
6. A demonstration of the capability of models and some scoping calculations in an initial investigation of the potential buoyance problem;
7. Continuation of corrosion studies to evaluate candidate canister materials;
8. Further development of biological information necessary to assess the consequences of an accident and to evaluate the environmental impact of seabed emplacement;
9. Development of sampling techniques and specialized instrumentation to provide the capability to obtain requisite samples and needed measurements; and

10. Development of an international program and participation in the international Seabed Working Group.

Emphasis on evaluating the barrier properties of Seafloor Sediments continued through 1978. While the major portion of program funds and effort was applied to this area, activities addressing the overall technical feasibility study, environmental impacts, and international and legal/political considerations continued at a pace commensurate with current SDP priorities and funding.

International Seabed Disposal Program

The SDP has international implications because of its potential contribution to solving the worldwide waste management problem and because of the sensitivities and restrictions established by international treaties with regard to acts which might pollute the world's oceans. These implications are addressed in the SDP by participation in joint international programs, by input to conferences, by discussions of international policies affecting the seas, and by close liaison with international organizations such as the Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA), which deal with both the ocean and nuclear wastes. An international Seabed Working Group (SWG) was organized under the Radioactive Waste Management Committee of the NEA. The active member nations of the SWG as of the end of 1978 are France, Japan, United Kingdom, and the United States.⁷

Program Contributors

To achieve program objectives and to carry out the program plan, a multidisciplinary team of scientists and engineers was assembled early in the program. While a basic core of individuals has remained as team members ever since, the makeup of the total group varies as emphases change and as the need arises for particular specialists and consultants. In Table 1 is a list of individuals who have made important contributions, through either technical activities or critical comment, to scientific work or to program planning during 1978.

Since the inception of the program, it has been the practice to have the current team of participants meet periodically to review and critique the work, to make recommendations about the direction and focus of the program, and to plan future technical activities. During 1976 it became apparent that, with the significant increase in the number of program participants and an increase in the levels of funding, the general maturation of the program required a modification of previous planning procedures. An Executive Planning Group, consisting of an Advisory Group of participating principal investigators, DOE program management, and Sandia Laboratories program management personnel, was established with the responsibility of developing long-range program plans compatible with the waste management goals defined by ERDA (and now DOE) and to make recommendations for research, development, and engineering. Members of the Executive Planning Group during 1978 are indicated on the list of program contributors in Table 1.

Table 1
List of Contributors - 1978

Name	Organization ^a	Name	Organization ^a
Akers, S. A.	URI	Ingram, C. L.	SIO
Allen, G. C., Jr.	SLA	Jackson, D.	Falcon R&D
Anderson, D. H.†	SLA	Janecky, D. R.	U. Minn.
Anderson, V. C.	MPL/SIO	Karnes, C. H.	SLA
Baldwin, K. C.	URI	Kupferman, S. L.	WHOI
Barnford, S. R.	URI	Laine, E. P.	URI
Bennett, J. C.	SIO	Laver, M. B.	SIO
Bowen, V. T.	WHOI	Leinen, M.	URI
Bower, D. G.†	DOE/ECT	Lipkin, J.	SLA
Braithwaite, J. W.	SLA	Livingston, H. D.	WHOI
Bulmer, B. M.	SLA	Marietta, M. G.	SLA
Burroughs, S. N.	SLA	McVey, D. F.	SLA
Burnett, B. R.	SIO	Moran, K. M.	URI
Calnan, D. I.	URI	Morin, R. H.	URI
Carey, A. E.	WHOI	Nuttall, H. E.	UNM
Chavez, P. F.	SLA	Olson, L. O.	APL/UW
Cohen, D.	ANL	Pederson, A.	APL/UW
Criscenzo, S. J.	URI	Percival, C. M.	SLA
Czerniak, T. M.	SIO	Prince, R. A.	URI
Damuth, J. E.	LDGO	Russo, A. J.	SLA
Dawson, P. R.	SLA	Seyfried, W. E., Jr.	U. Minn.
Deese, D. A.	Harvard	Schimmel, W. P., Jr.	SLA
Dietz, A. S.	SIO	Schneider, D. L.	ANL
Dzwilowski, P.	CSI	Schreiner, F.	ANL
Embley, R.	LDGO	Schuler, K. W.	SLA
Epstein, G. R.	URI	Silva, A. J.	URI
Erickson, K. L.	SLA	Sjoblom, R.	ANL
Ewart, T. E.	APL/UW	Smith, C. R.	SIO
Foster, E. L.	BCL	Smith, K. L.	SIO
Fried, S.	ANL	Spies, F. N.	MPL/SIO
Friedman, A.	ANL	Sullivan, J. C.	ANL
Gartling, D. K.	SLA	Sundberg, W. D.	SLA
Gomez, I. S.	SLA	Talbert, D. M.†	SLA
Hadley, G. R.	SLA	Tucholke, B.	LDGO
Hamilton, D. I.	DOE/BER	Van Bostel, R.	SIO
Hayes, D. E.	LDGO	White, G. A.	SIO
Heath, G. R.†	OSU	Yayanos, A. A.†	SIO
Heggie, D.	URI	Zmarzly, D.	SIO
Hessler, R. R.	SIO		
Hetherman, J. R.	URI		
Hollister, C. D.†	WHOI		

Abbreviations:

ANL	Argonne National Laboratory
APL/UW	Applied Physics Laboratory/ University of Washington
BCL	Battelle Columbus Laboratory
CSI	Civil Systems, Inc.
DOE/BER	Department of Energy/Biomedical and Environmental Research
DOE/ECT	Department of Energy/Environ- mental Control Technology

LDGO	Lamont-Doherty Geological Observatory, Columbia University
MPL/SIO	Marine Physical Laboratory/ Scripps Institution of Oceanography
OSU	Oregon State University
SIO	Scripps Institution of Oceanography
SLA	Sandia Laboratories, Albuquerque
UNM	University of New Mexico
URI	University of Rhode Island
WHOI	Woods Hole Oceanographic Institution

†Members of Executive Planning Committee

Reports on the past year's work from many of the team members are given in Volume II of this document; significant results from their scientific endeavors are summarized in this volume. In addition, a number of professional papers and presentations which have been derived wholly or partly from SDP studies by various participants are reproduced in Volume II.

Section 3. Program Research and Scientific Effort

As noted previously, current program attention is focused on the unconsolidated, fine-grained, porous sediments as a potential medium for waste containment. During 1978 emphasis was placed between corroboration and analysis of data to define and characterize generic MFC sediments, initial attempts to winnow suitable portions of the world's oceans in which to identify site-specific areas, intensification of laboratory investigations into the ion-exchange capabilities of clay sediments, laboratory and modeling efforts to define the near-waste thermal and chemical environment, and developing and evaluating a predictive capability for the mechanical response of deep-sea sediments. Other efforts pertinent to the overall technical feasibility study, such as environmental impact considerations, international cooperation, and sociocultural considerations, continued in 1978.

This section is a report of some of the most significant results and conclusions from the activities of the past year. Results are presented in somewhat arbitrary categories: system development and analysis, barrier system characterization and quantification, site characterization and assessment, environmental studies, emplacement, sampling and instrumentation development, and transportation studies. Throughout the text the reader is referred to the appropriate principal investigator's progress report (Volume II) or other reference for more detail.

System Development and Analysis

The basic assumptions of the program are as follows:

1. There exists a system of definable natural barriers that will provide the required containment of waste constituents.
2. A system of man-made barriers can be constructed which will insure the integrity of the waste form for the duration of the credible heat life of the waste.
3. Summation of the containment times provided by the natural and man-made components of the barrier system will be at least an order of magnitude greater than the half-life of the radionuclides of interest.
4. Since the required isolation time is much longer than any man-made experiment, the attributes of each component of the barrier system must be adequately known so that a credible prediction of barrier system integrity can be made.

To compare the rates of decay of constituents of radioactive waste against the rates of migration of the nuclides toward mankind, a formalism based on a set of sequential barriers to that release has been adopted. This formalism, a multiple-barrier concept,⁴ is essentially a system of barriers composed of the waste form, the waste container, any controlled modification of the emplacement media, the seafloor emplacement media, the benthic boundary layer, and the water column. This multiple-barrier concept is the foundation upon which the Subseabed Disposal

Program is that the task of the program is to determine whether any safe and appropriate disposal system can be developed that is cost-effective enough for it to be a technologically feasible concept.

The SSI Program is currently structured as a four-phase program, including (1) Phase I (1973-1975) during which the objective was to determine, in a preliminary fashion, the feasibility of the concept; (2) Phase II (1975-1979) during which the objective was to determine, on the basis of collected historical data, the feasibility of the concept; (3) Phase III (1979-1981) during which the objective was to determine, on the basis of collected historical data, the feasibility of the concept; and (4) Phase IV (1981-1983) during which the objective was to determine, on the basis of collected historical data, the feasibility of the concept. The program is currently structured as a four-phase program, including (1) Phase I (1973-1975) during which the objective was to determine, in a preliminary fashion, the feasibility of the concept; (2) Phase II (1975-1979) during which the objective was to determine, on the basis of collected historical data, the feasibility of the concept; (3) Phase III (1979-1981) during which the objective was to determine, on the basis of collected historical data, the feasibility of the concept; and (4) Phase IV (1981-1983) during which the objective was to determine, on the basis of collected historical data, the feasibility of the concept.

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Details of the subsystem models currently in use and under development are given in the principal investigator progress reports (PIPR) in Volume II:

- Ion transport through porous media (PIPRs E and N)
- Analysis of transient and steady-state fluid flow and heat transfer in porous media (PIPR F)
- Sediment column response to dynamic loading associated with canister emplacement (PIPR G)
- Long-term sediment deformation (creep) using effective stress concepts (PIPR G)
- Paths and rates of biological mobilization and transfer of radioactive ions from sediment to water column and within the water column (PIPR C)
- Predictive environmental model of the sediments of the central North Pacific for the next 10 million years (PIPR A).

A reference disposal system is necessary for study purposes, for development of system models, for simplification of system conceptualization and description, and as a "base case" to tie the developing subsystems of the program together.

The reference subseabed geological disposal system is the emplacement of appropriately treated waste or spent reactor fuel in containers into the red clay sediments in the central area of the oceanic tectonic plate under the central North Pacific in an area overlaid by the hub of a surface gyre (circular water mass). (The selection of such a reference site in this study in no way implies its selection as a candidate disposal site.)

Although several emplacement methods appear feasible, none has yet been developed in detail. For study purposes, the reference method is conceptualized as the use of penetrators to emplace wastes at a suitable depth beneath the sediment surface, in a precisely located and monitored fashion. A specially designed surface ship will transport waste from a port facility to the disposal site and emplace the waste containers in the sediment. A survey/monitor ship, which will have completely surveyed the disposal site before disposal operations begin, will determine the locations and monitor the behavior of individual disposal containers for appropriate lengths of time, and will maintain surveillance of the area surrounding the disposal site.

It is anticipated that the reference system will be modified and updated as the research program progresses and the need for more detail and sophistication in the reference case is established. It is also anticipated that additional "base cases" or reference systems may be developed in the future as other emplacement schemes, sediment types, and site types are investigated and the current reference system described above proves unsuitable or otherwise inadequate.

Barrier System Characterization and Quantification

The effects of the environment on the waste and its container (such as container corrosion and leaching of the waste form) will determine initial migration rates of waste from their emplaced position. These effects will also play a role in the rates of movement of the waste through the disposal medium by such mechanisms as leaching of the waste material, which will generate chemical gradients, adsorption of waste ions onto the medium material, and fixation or transport of isotopes by biological systems.

Results of studies summarized here deal with canister studies; geochemical and geotechnical characterization as it relates to ion migration, diffusion, and advection within the sediments; evaluation of nuclide sorption distribution coefficients; and thermal studies.

The compatibility of candidate HLW canister materials with the geologic environment of the subs seabed is being investigated. Although the waste canister is only one of several physical/geochemical barriers to the dispersal of radionuclides toward the biosphere, it may play a significant role during the first several hundred years after emplacement.

Candidate HLW canister and overpack materials that satisfy appropriate requirements for barrier lifetime, cost, and mechanical properties have been identified. Lifetime objectives generally range from 0 to 5 years for transportation and handling requirements, to 5 to 25 years for waste retrievability constraints, and about 300 years for retardation of near-field, thermally driven interactions such as leaching from the waste form followed by potential radionuclide migration. (PIPR J)

Several series of laboratory tests have been conducted to evaluate the effects of environmental parameters on resultant corrosion rates. Variables tested include temperature (25° to 250°C), pressure, solution composition, oxygen concentration, solution volume/surface-area ratios, and welding and clevice effects.

A principal objective of laboratory studies to date has been to provide preliminary screening data and to select several metals for further comprehensive study from a list of over 20 candidate metals. The listings based on data gathered from tests of all of the candidate metals are summarized as follows:

- The effect of temperature on the initial corrosion rate of 1018 mild steel in deoxygenated seawater was determined using linear and Tafel 100 electrochemical polarization techniques. The temperature range considered was 25 to 200°C. These calculated rates were an order of magnitude higher than measured similar long-term weight loss results. This difference resulted because the electrochemical derived value represents an instantaneous initial rate. However, a useful quantity is the apparent activation energy which was calculated using these initial results. This value equaled 5 kcal/mole for seawater. A more extensive study of temperature effects on the corrosion of selected candidate metals is in progress.
- Most of the coupon experiments were conducted with a solution volume/alloy surface area ratio of 2-3 ml./cm² and a pressure of 5 MPa (700 psia). Lowering the solution volume/surface area ratio by a factor of 10 doubled the corrosion rate of 1018 mild steel. This result was probably due to the lower observed fall of the small-volume experiments (3.2 versus 4). While this effect on the more corrosion-resistant alloys is unknown, it is not expected to be as great. The effect of increasing hydrostatic pressure on a wide range of alloys under deoxygenated conditions was to increase slightly the corrosion rate. This increase, however, was within experimental error and, therefore, the determination of its significance requires further investigation. (PIPR J)
- The effect of a substantial quantity of dissolved oxygen on the corrosion rates of selected alloys in seawater has been studied. A constant partial pressure of 1 MPa oxygen was used during the experiment to maintain a high level of dissolved oxygen. This should represent an overtest of the worst-case effects of oxidizing radiolysis products on corrosion. The oxygenated corrosion rates of all alloys studied increased over the corresponding deoxygenated rates. Many of these metals have been shown not to support an oxygen current at 25°C; this apparently is not the case at 250°C. This effect and the discovery that Hastelloy C-276 pitted in these solutions will be investigated further using electrochemical techniques. (PIPR J)
- Welded coupons with clamped crevices made from 1018 mild steel, SS-304L, and Hastelloy C-276 were exposed to deaerated brine at 70° and 200°C. Crevice corrosion problems were nonexistent in these deaerated solutions. The 1018 steel samples exhibited general corrosion but no weld attack. The SS-304L specimens showed numerous pits around the welded areas at 70°C only, whereas the Hastelloy C-276 samples were virtually immune from attack. Corrosion rates were again unmeasurable at 70°C. Measured corrosion rates at 200°C are as follows: 1018 = 0.1 mm/yr; SS-304L = 0.005 mm/yr; and Hastelloy C-276 = 0.0001 mm/yr. The lack of pitting of SS-304L at 200°C must be due to significant separation between the rest and pitting potentials in deoxygenated high temperature brine. (PIPR J)

Eight candidate alloys have been selected for more comprehensive study. The selection criteria included corrosion resistance under a variety of conditions, also metal cost and availability. The selected prime candidate alloys are as follows (listed in order of increasing corrosion resistance): 1018 mild steel, Corten A steel, lead, 90-10 cupronickel, SS-Ebrite 26-1, Monel 400, Inconel 530, and Ticonel 12.

Comparative reference overpack costs for a variety of metals have been estimated. Overpack costs were calculated for possible 1-, 25-, and 300-year design lifetime requirements under worst-case, brine-inundated, 250°C oxidizing environments. The most expensive (per unit weight) alloys appear to be cost-effective for both the 25- and 300-year lifetime alternatives. Niende 12 appears to be the most cost-effective material studied. (PIPR H)

The near-field environment consists of the waste form, waste canister, and the sediment region immediately adjacent to the canister. For the purpose of the SDP, the near-field is defined as that region contained within the maximum extent of the 100°C isotherm. This region is one of high temperatures and intense radiation, where large chemical and temperature gradients may be expected to have an effect on both the character of the sediment and its barrier properties.

The solubility of the canister and adsorptive capacity of the sediments are functions of the geochemical environment in the near-field of the buried canister--an environment influenced by temperature, pressure, and bulk composition of the system:

- An experimental study has begun in which sediment that is mineralogically and chemically similar to MFG material is reacted with seawater at 300°C and 500 bars, to determine changes in solution chemistry. In general it can be said that, owing to the precipitation of Mg-bearing phases, the solution immediately attains a distinctly acid pH. Concomitantly, Ca, Fe, SiO₂, K, Sr, B, Ba, Mn, CO₃, and Zn are enriched in the aqueous phase, whereas SO₄ and Mg are depleted, relative to the concentrations of these species in seawater before reaction with sediment. Mineralogically the sediment is only slightly modified. Anhydrite is generated in addition to the Mg-mineralization, while the plagioclase and ferromanganous components of the sediment appear to partially dissolve and act as the primary sources of Ca, Sr-Ba-Fe, and Mn-Zn in solution. (PIPR H)
- The removal of Mg from solution as Mg-oxysulfate or talc is strongly temperature-dependent. That is, although Mg is effectively removed from seawater at 300°C, this is not the case at 200°C. At these lower temperatures Mg precipitation is sluggish and, in most systems, dissolution often exceeds precipitation processes so that an alkaline pH results. Clearly, an alkaline pH would be conducive to the preservation of a waste canister. (PIPR H)
- In general, the precipitation of Mg-bearing alteration minerals creates a distinctly acid pH, which is only sluggishly "titrated" by dissolution of the plagioclase component. Furthermore, the low solution pH will undoubtedly affect the stability of a metal canister containing radioactive wastes. Therefore, it must be emphasized that the quantity and type of radioactive waste materials in canisters should be limited to preclude near-field temperatures ≥ 300°C. Whether the low pH also induces radionuclide mobility has not been tested, but this question retains a high priority for future experiments. (PIPR H)
- Results from the same study suggest that, if near-field temperatures are ≥ 300°C, a metal canister will probably undergo appreciable dissolution in a relatively short time. The effect of H⁺ and seawater chemistry at elevated temperatures on the relative mobility of radionuclides is a primary research objective for the coming year. (PIPR H)

- In the future sediment/seawater experiments will be conducted at lower temperatures ($\pm 200^{\circ}\text{C}$). An experiment, in which illite-quartz sediment and seawater were reacted at 100°C and 500 bars, revealed that seawater does not become significantly acid. Apparently the lower temperature significantly limits the formation of Mg-bearing alteration phases. Future experiments will involve reacting Mn-rich sediments with seawater. These sediments are the more probable type to be encountered at the sediment depths currently envisioned for a nuclear waste repository. (PIPR B)
- The mineralogic composition of the sediment is primarily quartz, illite, and chlorite associated with minor plagioclase feldspar. Except for the feldspar these phases are remarkably stable in a fluid of seawater composition, even at 100°C . Therefore, the solution remains acid for a relatively long time, and is only slowly neutralized owing to dissolution of the plagioclase component. (PIPR B)
- The solubility behavior of Sr and Ba is strikingly similar to that of Ca. The Sr and Ba often occur with Ca in plagioclase; the relative similarity of their solubility patterns suggests that these species enter solution from a similar source. (PIPR B)
- Heavy metal solubility during experiments can best be explained by the incipient dissolution of ferromanganese nodules contained in the sediment. These nodules are composed of poorly crystalline or amorphous Fe and Mg oxyhydroxides. It is not surprising, therefore, that while the solution pH is very acid, heavy metals (Fe, Mn, Zn) are dissolved but, as pH rises, concentrations of these species tends to decrease. (PIPR B)

If nuclear waste material is to be deposited within deep ocean sediments, then it must be demonstrated that the system defined by the waste canister, waste form, seawater, and sediment is geochemically closed; i.e., chemical components cannot migrate outside the system. Thus it is apparent that the sorption properties of the sediment enclosing the canister are critically important to the feasibility of subseabed disposal. It has been demonstrated that sediment can retain significant quantities of Eu and Th when interacted with seawater or artificial seawater at 25°C which contained spiked concentrations of these elements.⁵ However, radionuclide sorption by sediments is undoubtedly affected by temperature, the bulk chemistry of the system, and the chemistry of individual radionuclides.

Extensive investigations into the geotechnical characterization of representative deep-sea sediments have been conducted since the SDP began in 1973. During 1978 geotechnical program efforts related to the characterization of the barrier system focused on the stress/strain/time behavior of undisturbed and remolded sediment samples, the permeability and consolidation characteristics of a variety of deep-sea sediments, and the effects of elevated temperatures on geotechnical characteristics:

- The majority of the tests in the quasistatic stress-strain studies are isotropically consolidated, undrained triaxial with pore pressure measurement conducted on both undisturbed and remolded samples from the central North Pacific. Data determined include stress-strain curves, deviator stress at failure, cohesion intercept, angle of internal friction, effect of loading on pore pressure generation, and Young's modulus. (PIPR D)

- Stress paths and Mohr-Coulomb analyses indicate good quality of samples and test results. The effective angle of internal friction for the transition-zone material (transition from predominately illite to predominately smectite) to smectite at a 5-m depth is significantly higher (28.3 deg) than the 2-m-depth illite material (22.9 deg). Cohesion intercepts agree well with undrained shear strengths determined with a vane shear device. (PIPR D)
- A hyperbolic stress-strain model appears to give good results for both undisturbed and remolded samples of Pacific illite and transition material and of an Atlantic carbonate clay. (PIPR D)
- Results of directly measured permeability tests agree well with calculated values from consolidation tests using the square-root-of-time method, but not as well with those calculated using the logarithm-of-time method. The coefficient of permeability in a sample of the top 24 m of the sediment column in MPG-I varies within a narrow range of 3×10^{-7} cm/s to 1×10^{-6} cm/s for a void ratio that varies drastically from three to six. (PIPR D)
- From limited available data, it appears that permeability in remolded and undisturbed samples (at the same void ratio) is about the same. (PIPR D)
- Preliminary investigations into the effects of higher temperatures on the permeability characteristics of marine sediments are underway. In early and incomplete test results, the value of the coefficient of permeability for a sample taken at 80°C is about 2.3 to 2.5 times that of the value taken at 22°C. This is close to what would be expected with a straight viscosity correction for water at that temperature. Detailed analyses should more clearly define the effects of temperature variations on permeability characteristics in the temperature range of 4° to 200°C. (PIPR D)
- Consolidation test results from MPG-I sediment core samples show apparent overconsolidation in the upper few metres followed by normally consolidated conditions at depth. It appears that the sediment column is fully consolidated under existing overburden conditions and, therefore, there is no excess pore water pressure and no upward migration of water due to natural stress effects. (PIPR D)

Dominant mechanisms for radionuclide sorption and migration must be reasonably well understood and their mathematical descriptions formulated, solved, and verified experimentally to support the development and subsequent use of models to simulate the rates of migration of nuclides in the emplacement medium.

Studies of pore fluids from cores support the belief that the only advection of interstitial waters in deep-sea pelagic clays overlying old (> 80 million years) oceanic crust results from sediment deposition. In the central North Pacific study areas (MPG-I and -II), this upward movement of pore fluids is at velocities of less than 10^{-11} cm/s. Since the seafloor grows upward at about the same rate, such advection is unimportant as a mechanism for transporting ions from a buried waste canister to the overlying ocean. (PIPR B) Preliminary models of the effect of a localized heat source on this advection suggest that the convection induced by such a source increases the total movement of pore fluids by a trivial amount (less than 50 cm displacement in central North Pacific clay during the thermal lifetime of a waste canister).⁵

The present working hypothesis is that the major potential method of ion migration away from the waste form will be primarily molecular diffusion. The simpler mathematical analyses of diffusion which yield analytical solutions show that, to a first approximation, the migration rate of an ionic species should be inversely proportional to the magnitude of its sorption distribution coefficient, K_d , which is the ratio of sorbed to dissolved ions in a given volume of material. For a given material, K_d is a function of temperature, pressure, concentration of the species of interest and concentrations of all other competing species.

Early in the SDP a series of sorption experiments were initiated using Th and Eu as test elements in batch sorption experiments.^{3,4} Numerous sorption studies have continued during 1978 using the:

- Concentration dependence of K_d has been shown to increase linearly on a log-log plot with decreasing solution concentration. This implies that the amount of sorbed ion decreases more slowly than the amount of dissolved ion as the concentration of the ion is increased. (PIPR B)
- Temperature dependence of K_d has been shown to increase with increasing temperature (Figure 1). From the viewpoint of ion migration, this trend has the important effect of opposing the increases in diffusion coefficients that also accompany an increase in temperature. (PIPR B)
- Observed K_d values for a range of deep-sea sediments (siliceous ooze, calcareous ooze, smectite- and illite-rich clays) span about an order of magnitude under experimental conditions. Siliceous ooze values are consistently lowest, and smectite clay and calcareous ooze consistently highest. (PIPR B)
- The effect of sediment lithology on K_d has been investigated for a continuous 24.38-m core taken from the MPG-1 area. Data from this core (Figure 1) illustrate the range of values and systematic variations found in this pelagic clay environment. The range for K_d in this one core includes the range of all deep-sea sediments tested to date except siliceous oozes. (PIPR B)
- Uptake of Eu by North Pacific smectite-rich clay as a function of time under experimental conditions (Figure 2) suggests that sorption is a two-stage (at least) process. The initial stage occurs very rapidly (in a few minutes) and is assumed to reflect ion exchange on exterior and highly expanded interlayer surfaces. The second stage occurs more slowly (over at least a few months) and is assumed to result from migration of Eu ions into sites within the material lattice. These data show that short-term (~ 24 h) K_d results reported in the past^{3,4,5} do not reflect true equilibrium. However, deviations are comparable to the lithologic variability at a single level in a sediment core, so no useful purpose is served by vastly increasing the duration of experiments. This kinetic effect means that K_d values reported from past Eu sorption experiments are conservative. (PIPR B)

Sorption of the actinide elements is generally considered to be of principal concern. Before pursuing an extensive experimental program involving the actinides, a preliminary investigation has been conducted to examine the sorption of several nuclides having relatively much less complicated solution chemistries. The generalizations being developed to describe the sorption of the preliminarily investigated nuclides will be used in developing an efficient program for investigating the sorption and complex chemistry of the actinide elements.

Figure 1. Downcore Variation in Distribution Coefficient of Eu Relative to 0.68N NaCl in MPG-1 Sediment Sample. Profiles show the effects of lithologic, temperature, and solution concentration variations on K_d values.

Figure 2. Rate of Uptake of 0.002M Eu in 0.68N NaCl by Smectite Rich Sediment From Central North Pacific. Note apparent two-stage reaction.

The preliminary investigation examined several aspects of the behavior of the equilibrium distribution coefficients for the sorption of rubidium, cesium, strontium, barium, silver, cadmium, cerium, promethium, europium, and gadolinium from aqueous sodium chloride solutions at low temperatures (4° and 11°C). For the nuclides selected, values of K_d were determined as functions of the concentration of the species in the equilibrium solution and to a limited extent as functions of solution pH.

- For the nuclides studied, the distribution coefficients generally vary from about 10 mL/g at solution-phase concentrations of the order of 10^{-2} M, to 10^4 mL/g and greater at concentrations of the order of 10^{-7} M and less. These data appear to be reasonably consistent with related data for similar oceanic sediments and related clay minerals found within the continental United States. (PIPR K)
- For each nuclide studied, the sorption distribution coefficients appeared to result from a minimum of two separate mechanisms. In all cases, one mechanism appears to be an ion-exchange phenomena associated with the silicate phases and appears to have a relatively much larger sorption capacity than the other mechanism. In the case of cesium (and probably rubidium) the second mechanism appears to also be related to the silicate phases and may or may not be an ion-exchange phenomena. However, for the other elements studied, the second mechanism appears to be related to the hydrous iron and manganese oxides and again may or may not be an ion-exchange process. (PIPR K)

As a result of the preliminary investigations, additional experiments were conducted: (1) single-component experiments involving technetium, molybdenum, uranium, plutonium, americium, and curium in 0.68N NaCl solutions, and (2) preliminary multicomponent experiments involving cesium, barium, cerium, europium, and americium. Preliminary principal results from these experiments are summarized below (from PIPR K):

- For the initial actinide experiments, the oxidation states of the Pu, Am, and Cm were not determined. However, as supplied from the manufacturer, the oxidation state of the Pu was initially probably (IV) and of Am and Cm (III).
- At comparable solution-phase concentrations, the magnitude (10^4 mL/g and greater) and strong pH-dependence of the distribution coefficients for Am and Cm were very similar to those observed for the lanthanide elements.
- The experiments involving Am and Cm were also apparently affected by competing solution-phase reactions similar to those observed for the lanthanides.
- At comparable solution-phase concentrations, the magnitude of the distribution coefficients for Pu appear to be somewhat less (about 3×10^3 mL/g) than for Am and Cm and for the lanthanides. Furthermore, the pH-dependence of the distribution coefficients for Pu did not appear to be as pronounced as for Am and Cm.
- Based on the hydroxide solubility products for both Pu(IV) and Pu(VI), several orders of magnitude more Pu apparently remained in solution at pH 8.3 than would have been expected.
- For the technetium experiments, ^{99}Tc was used and was initially added as the pertechnetate anion. The distribution coefficients for Tc were found to be essentially zero at pH values of 2.6 and 8.2.

Since ionic charge may greatly affect migration rates because of its influence on self-diffusion or on ion exchange, preliminary experiments were begun to determine the stability of a given oxidation state of various actinide ions in sea water and sea-water/sediment slurries under various oxygen concentration and temperature conditions:

- Observations were carried out on a sealed, evacuated sample of PuCl_3 in water for 418 days. It was found that the concentration of Pu(III) decreases with a 3.6-year half-life while at the same time Pu(IV) and some small quantity of Pu(VI) are formed. The reaction is probably caused by radiolysis of the water solvent. Other samples of plutonium compounds in the IV and VI states were made up in samples of sea water and in sea-water/sediment slurries. All of these samples were contained in evacuated sealed spectro-photometer tubes so that the absorption peaks due to the several oxidation states could be monitored. In this way changes in concentrations of the various states could be observed. (PIPR I)
- Complications were encountered in some of these samples because of the fact that the intensity and position of the various absorption peaks may change with pH. Since it is not possible to monitor pH in a sealed vessel such as a spectrophotometer tube, the only pH measurement that can be made is at the termination of the experiment when the tube is opened. A different approach to the problem will be attempted in the future using atmosphere boxes in which pH can be controlled. (PIPR I)
- When the sample tube was opened after 418 days, the pH was found to be 1.87. As measured by the optical density some 77% of the Pu was still in solution as Pu(III) . The remainder of the Pu was in the precipitate. When the precipitate was dissolved in HCl, it was found that 22% of the Pu was still in the III state (probably adsorbed on the surface of the precipitate) and the rest was Pu(IV) with a small amount of the Pu (0.5%) being present as Pu(VI) . (PIPR I)
- A plausible explanation for these changes from the original Pu composition is that the Pu(III) was radiolytically oxidized and that the peroxide formed during the radiolysis of the solvent was the oxidizing agent. This experiment suggests that, in the immediate neighborhood of a repository containing HLW canisters, it is likely that radiolysis would cause oxidation of lower valent plutonium ions and consequently affect mobility and migration. (PIPR I)

Thermal studies during the past year included several scoping studies, development of computer programs for detailed analyses, laboratory experiments, and development of an in-situ experiment:

- A closed form analytical solution was used to compute maximum temperature for a waste canister 3 m long by 0.3 m in diameter buried below 10 m. For typical 10-year cooled wastes (high level and spent fuel), the maximum temperature increase above ambient was found to be about 140°C per kilowatt of initial thermal output of the waste. Chemistry data at this time indicate the desirability of keeping the maximum temperature in the range of 200° to 250°C. Thus the waste thermal power is limited to 1.4 to 1.8 kW. (PIPR F)
- As an aid in experiment design and data interpolation, scaling parameters were derived for conduction/convection, canister buoyancy, and sediment erosion problems. (PIPR F)
- The problem of sediment erosion due to a thermal plume caused by coupling of the sediment temperature field into the water column was investigated by a scoping analysis. The induced convective velocities for reasonable waste thermal outputs and burial depths were found to be small compared to threshold velocity required to induce erosion. Therefore, convectively induced erosion

should not represent a threat to the integrity of the sediment barrier.
(PIPR F)

- Two computer codes were developed, the first, MARIAH, to solve the coupled heat transfer fluid flow problem, the second, IONMIG, to address the radionuclide migration problem. Both codes are in the checkout stage. It is anticipated that they will be made fully operational in 1979. Verification experiments also will begin in 1979. (PIPR F)
- Experimental apparatus to measure thermal properties of deep sea sediment has been designed and constructed. An initial test in which the thermal conductivity and thermal diffusivity of illite were measured over the temperature range of 25° to 420°C has been completed. The illite, from the MP-G-1 study area, was consolidated and maintained at a lithostatic pressure of 0.32 bar. Pore pressure was maintained at 600 bars during the test. The values for both conductivity and diffusivity were found to remain almost constant up to 300°C at 1.0 W/m-K and $2.75 \times 10^{-7} \text{ m}^2/\text{s}$, respectively, and then to decrease by about 20% at 420°C. (PIPR F&L)

Planning for a major thermal-properties field experiment was begun during 1977.⁵ This experiment, the in-situ heat transfer experiment (ISHTE), is a test which may require more than one fielding to obtain quantitative information on thermal processes and material properties; it is not intended to be a simulation of an emplaced waste container.

The ISHTE studies during 1978 included further development of experiment plans (PIPR D, L, F, and M), thermal and fluid analysis efforts (PIPR F), initiation of hardware and instrumentation development (PIPR E), an investigation of a possible field-test site (PIPR D), laboratory investigations of thermal conductivity at in-situ conditions (PIPR D, F, and L), and design of a heat source. (PIPR M)

- The first ISHTE test will be for one year with a peak heater/sediment interface temperature of about 400°C. This is long enough for the heater and sediment to approach thermal equilibrium and allows for a long observation time for any unforeseen or nonlinear effects. The peak temperature is higher than anticipated for actual seabed emplacement and will provide verification that there are no unexpected responses near the proposed operating temperature. (PIPR M)
- Thermal analyses have aided in selecting power requirements (maximum power 0.4 kW thermal), instrumentation location and types, and developing various operational aspects. (PIPR F)
- Detailed plans have been developed for the structure, heat source, sensors, samples, control system, tracking and telemetry systems, power source, handling equipment, and fielding procedures for deployment of the ISHTE system. (PIPR E)
- ISHTE power will come from radioisotopic sources. A radioisotope heat source will be placed in the sediment and a radioisotopic thermoelectric generator (RTG) will provide the basic electrical power. The HTG chosen for use is the SNAP-21 system, designed for deep-sea applications. (PIPR M)

Site Characterization and Assessment

Site characterization and assessment activities were focused primarily on four areas of effort during 1978: (1) continued development of site-suitability criteria for submarine geologic formations, (2) completion of the geologic assessment of the generic central North Pacific study site, MPG-I, (3) assessment of initial data from a western North Atlantic study site, MPG-III, and (4) initiation of a project to winnow suitable portions of the world's oceans in which to identify site-specific areas.

The development of criteria for site suitability has essentially been ongoing since the inception of the SDP.^{1 2 3 6} These efforts continued during 1978 and are discussed in PIPR A. Basically, suitability criteria that evolved early in the development of the SDP have remained unchanged with primary efforts directed at refinement and clarification.

The midplate, midgyre region of the central North Pacific (MPG-I) was chosen as an study site primarily because of the (relatively) abundant existing data on bathymetry, red clay consistency, low energy bottom circulation, relatively unproductive overlying waters, and the presence of red clays which possess the following desirable characteristics:

- Very high sorption properties for heavy metals that tend to inhibit movement of radionuclides
- Low permeabilities (typically 10^{-6} to 10^{-7} cm/s) that cause the rate of water migration to be very low
- Low shear strengths that could facilitate subsurface emplacement of waste containers
- The plastic state of the sediments that inhibits fracturing if disturbed and leads to "healing" or flow if disrupted.

Using the MPG-I study area as a generic representative of the central North Pacific, early established objectives of the SDP were to (1) describe the present-day environment, processes, and their rates within the area, and (2) determine the paleoenvironmental conditions that influenced this site during its geologic evolution. This information is necessary in determining the past stability of the region and is critical to the credible prediction of future environmental characteristics.

A significant body of data and associated analyses of this data relative to the geologic assessment of MPG-I have been given in previous SDP annual reports.²⁻⁵ During 1978 these data and significant conclusions were pulled together into one comprehensive report (PIPR A). Significant conclusions in that report were as follows:

- The MPG-I area in the central North Pacific is marked by low abyssal hills, water depths between 5000 and 6000 m, red clays with slow (3 mm/1000 yr) sedimentation rates, and low velocity (less than 5 cm/s) bottom currents. The sediment thickness varies between 20 and 50 m, with the thickest sediments found in the southern portion of the region in low rolling swales.

- Sedimentological and stratigraphic data have been examined from one giant piston core, GPC-3, and have been used to construct a paleoenvironmental history from which the future stability of the region has been assessed. Palaeomagnetic stratigraphy shows sedimentation rates for the upper part of the core decrease from 2.5 mm/1000 yr at the surface to 1.1 mm/1000 yr at a depth corresponding to two million years before present (mybp). Ichthyolith stratigraphy shows sedimentation rates between about 65 and 5 mybp to be constant at 0.2 to 0.3 mm/1000 yr.
- A sedimentation model based on the NNW movement of the Pacific Plate moving through different sedimentation provinces accounts for most of the sedimentological variations seen in GPC-3. The geotechnical properties do not vary monotonically with depth because of downcore mineralogical variation in the sediment.
- The presence of manganese-encrusted ash layers in GPC-3 suggests either a bottom-water circulation change occurring sometime between 30 and 20 mybp or manganese precipitation on the ash layers caused by a change in Eh of the sediment due to the ash falls. If a hiatus did occur, the duration of the nondeposition is inferred to be less than 4 to 5 million years (m.y.) based on the ichthyolith stratigraphy. The lack of large hiatuses indicates this region has been relatively stable during the Cenozoic in comparison to other regions in the Pacific where large hiatuses exist in the sediment record.
- North hemisphere glaciation has little effect upon the MPG-I area other than to increase the sedimentation rates by a factor of 2.
- Future environmental conditions at the MPG-I area are estimated for the next 10 m.y. based on the paleoenvironmental data presented here. The environmental conditions are projected to be essentially identical to the present environment during this time interval. Large-scale bottom-water circulation changes resulting from changes in polar climatic conditions and reorganization of the plates are difficult to predict in the future. It is unlikely, however, that a major reorganization of the plates will occur in the next 10 m.y. which would significantly alter bottom-water circulation.

Evaluation of a western North Atlantic study area was begun. The area, designated MPG-III, is located in the vicinity of 35.3°N, 61.2°W. Several cruises were conducted in the area during 1978 to collect data for an initial evaluation of the geological, geophysical, geotechnical, and chemical characteristics of the area. (One of these cruises was a joint U.S.-France geophysical expedition aboard the French ship Resolution, conducted as part of the multinational participation in the International Seabed Disposal Program.) Reports covering cruises EN-023 and EN-024 aboard the R/V Endeavor are given in PIPR D and PIPR B, respectively.

- Extensive 3.5 kHz and airgun seismic profiling programs in the MPG-III area suggest that considerably more erosion has taken place within the past several million years than inferred from historical data. (PIPR B)
- Bottom current measurements confirm that erosion is occurring today, although the reason for such a dynamic deep circulation system is unclear at this time. (PIPR B)
- Preliminary stratigraphic studies show that the discontinuous sedimentation suggested by the profiler records is reflected in marked hiatuses and mixing of sediments in recovered cores. Even in cores taken in an area where the acoustic profiler records do not indicate erosion, a significant hiatus is evident in the stratigraphic data. Core to core variations in accumulation rates

exceeds factor of 8 (Figures 3 and 4), more than four times the range of variation measured in MPG-I. (MPR B)

Figure 3. Age vs Depth Plots for EN-024 Cores From MPG-III With Continuous Records of Deposition. Ages based on changes in foraminiferal assemblages. Note 8-fold variation in accumulation rate.

Figure 4. Accumulation Rates of Cores EN-024 PC2, LPC2, and LPC3 Relative to PC1, Showing Roughly 8-Fold Variation Within MPG-III Area

- An assessment of the redox conditions of the interstitial waters from MPG-III shows that they are strongly reducing at depths of more than a few metres. (PIPR B)
- Because of geological factors, current feeling is that the MPG-III site on the North Bermuda Rise may not be a suitable study area for the SDP. However, a geochemical appraisal of sediment samples taken from that area in the summer of 1978 shows no obvious reason why these sediments should be excluded. The acoustically laminated sediment deposits are fine-grained, probably have low permeability, and have relatively high water content and low shear strength, so that there would be little problem in attaining deep penetration into the sediment column. The fine-grained soft abyssal plain sediments east of the Bermuda Rise indicate that this area may also be of interest as a possible study site. (PIPR D)
- The data and samples obtained from MPG-II will be useful to the SDP because the type of sediment in the area is prevalent over large areas of the western North Atlantic, thus representing a generic type. (PIPR D)
- Overall, the results of the MPG-III and ancillary surveys are disappointing from the standpoint of establishing an SDP generic study area for the western North Atlantic. The region is much more dynamic than implied by the historical data or predicted from a general consideration of the deep circulation of the North Atlantic. (PIPR B)

A major task during 1978 was to compile a series of maps for both the North Pacific (0°-60°N; 110°W-130°E) and the North Atlantic (0°-45°N; 5°-85°W) that show the various site-suitability criteria defined by the SDP. The major suitability criteria defined by the maps are:

- Political boundaries (200-mile limits)
- Location of earthquake epicenters and seismicity
- Thickness and acoustic character of sediments
- Types and distribution of sediments
- Variations in roughness of seafloor and basement morphology
- Bathymetry
- Distribution of polymetallic nodules
- Distribution of bottom currents and nepheloid layers
- Distribution of heat flow and thermal conductivity.

The resulting maps are given in PIPR C.

The geological and geophysical data that were considered in the preparation of the above-mentioned maps, while not representing an exhaustive collection of all such data on these oceans, do, however, provide an adequate reconnaissance base to allow focusing evaluations on manageable areas.

Based on the information contained in these maps, a selection was made of the most promising study areas of each ocean (those which appear best to satisfy the most exclusion criteria). The areas chosen for each ocean area (see Figures 5 and 6) are listed below:

North Pacific (in order of priority)

- (1) 20°-40°N, 145°-180°E (east of Japan)
- (2) 20°-35°N, 140°-160°W (east of Hawaii)
- (3) 20°-35°N, 115°-130°W (west coast of North America)
- (4) 35°-50°N, 160°-180°E (east of Japan)

North Atlantic

- (1) 20°-29°N, 58°-69°W (distal Nares Abyssal Plain)
- (2) 29°-34°N, 52°-58°W (distal Soken Abyssal Plain)
- (3) 15°-32°N, 25°-35°W (Great Meteor Seamount area)

These areas collectively represent about a million square kilometres for future study in detail, rather than the many tens of millions of square kilometres represented by the entire oceans. These areas represent the best-qualified, based upon existing and available oceanographic data. While it is recognized that there may be other equally qualified areas as yet unidentified because of a lack of data or funds to acquire extensive new data, it is felt that no generic type of area of potential interest has been missed.

Environmental Studies

The processes of the water column and the benthic region must be understood to address the problems of environmental impact, transportation, waste emplacement, monitoring, safety, and risk analyses.

One of the critical questions that is being addressed concerns potential pathways back to man of radionuclides which may be accidentally introduced into the benthic region. Potential vectors are either biological agencies or physical mass transport in the water column. Organisms might metabolize a radionuclide and excrete it into solution, allowing it to be moved by currents. Currents might also transport organisms which have incorporated radionuclides. The mobility of organisms themselves will also result in the transport of radionuclides. The potential pathways and the rates of transfer present complex problems.

Of primary interest within the context of the nuclide migration problem is an assessment of the consequences of a mishap in the process of transportation or emplacement and the consequences of leakage from a poor emplacement. Vertical and horizontal transport of material through the water column must be understood. Mobilization, immobilization, and transport of materials by the biota, currents, sediments, and chemical gradients in the benthic boundary layer and mid- and upper-water layers of ocean systems must be evaluated. In general, an understanding of processes, responses, and the functioning of the dynamic physical and biological systems of these regions is necessary to assess the impact of the introduction of radioactive materials.

Figure 5. Black Boxes Outline Areas for Future Study of the North Pacific

Figure 6. Black Boxes Outline Areas for Future Study of the North Atlantic

One of the basic assumptions of the program is that the study areas upon which efforts have been concentrated are typical of much broader areas of midplate, midgyre regions and are typical of abyssal oligotrophic areas. This allows studies to be pursued without having to conduct specific site selection first, and has allowed maximum use of limited manpower and funds by giving first priority to studies of processes, rather than diluting efforts by doing everything at once. The complexity of the total problem, however, can be appreciated when one considers that the introduction of radionuclides into the benthic region by a release due to failure of the containment system at the disposal site is only one problem, and that a shipping accident could introduce the problem to the benthic region almost anywhere.

A variety of research activities were continued during 1978 which addressed the biological characterization of the benthic region, chemical response of the benthic region to radionuclide input, potential transfer pathways in the biological system, and the development of a model for nuclide transport in marine ecosystems. These research activities are reported in PIPRs C, D, Q, R, and S.

- The ocean ecosystem model discussed in the 1976 annual report⁴ has been further developed and work on the mathematical and numerical aspects of the water column and biological migration model was begun during 1978. This model traces the migration of radionuclides through the upper few centimeters of the sediments, water column, and marine biota to man. (PIPR Q)

The magnitude of biological pathways in the potential return of waste radionuclides to man is a function of the standing crop of the transporting organisms, the rate of activity of these organisms, their mobility, the nature of their interactions with other organisms, and their interaction with specific radionuclides likely to be introduced into their environment.

Progress has been made in characterizing the fauna present in and on the sediment in the central North Pacific. This includes the microbiota, meiofauna, macrofauna, and abyssopelagic scavengers. In looking at these various biotic components, focus is on their potential for dispersing or concentrating radionuclides.

- In a benthic community the infauna could mediate radionuclide transport by moving sediment, and by moving pore water in and out of the sediments. Through burrowing and feeding activities, a particular grain of sediment could be exposed to overlying waters many times before actual burial. In addition to mechanically exposing radioactive material, benthic organisms would be likely to incorporate such material through feeding and respiratory activities. Assuming normal trophic level relationships, it is reasonable to expect a concentration of radionuclides as the trophic levels increase. (PIPR Q)
- A characterization of the distribution and density of the macro-infauna is fairly complete, but relatively little is known of the meiofauna and especially the microbiota. These are important because they are the most abundant portions of the infauna, are at the base of the food chain, and are likely to be the first organisms to come into contact with leaked radionuclides. (PIPR Q)

- Of the mobile scavenger species, a shrimp was made to focus on amphipods. They are a large component of the benthic community and are highly mobile, cosmopolitan organisms. A number of aspects of their generalized life-style suggest that they may be very important in potential mobilization of radionuclides. They appear to feed on the bottom, which would allow incorporation of radionuclides present in the sediment, and they are very mobile, allowing direct biological transport. The fact that they live in the water column not only means that this is where they excrete their wastes, but that they may constitute the first step in a pelagic food chain leading ultimately to man. (PIPR Q)
- Height records are very important as an indicator of amphipod mobility. It is not unusual to find *E. Gryllus* large distances above the bottom. Reasons for their being trapped at these heights are not known, but it is likely that they are foraging and are subject to predation while in the water column. Findings such as these also emphasize the active upward transport component to which benthic materials are subject, and make it more important to understand the role of *E. gryllus* in this scheme. (PIPR Q)
- Primary library work has been completed for the literature search on the bioaccumulation of those radionuclides with potential deep-sea biotic impact. A bibliography of approximately 325 references on the modes, mechanisms, and extent of the accumulation of those radionuclides in the biota was also compiled with primary emphasis on crustaceans, mollusks, and polychaetes. Articles pertaining to radionuclide marking techniques have been collected. All of this information, along with a summary of the various factors which affect the uptake and concentration of radionuclides by the marine biota in general, is being incorporated into a single bioaccumulation source book. (PIPR Q)
- Metazoa of the central North Pacific abyssal benthos are mostly concentrated in the upper 10 mm of sediment with some microcores showing substantial numbers (of nematodes) to 15 mm. The nematodes extend to the 40 to 45 mm layer with a rare individual being found in the 50 to 55 mm layer. (PIPR Q)
- Harpacticoids are much less abundant than the nematodes and appear to be mostly concentrated in the first 5 mm of sediment. Harpacticoid numbers rapidly drop off beyond the 0 to 5 mm layer and none have been found in the 10 to 15 mm layer. (PIPR Q)
- Manganese nodules occupy some surface of virtually every core taken in the central North Pacific. There is an abundance of life associated with the nodules so that they may ultimately be considered as "coral reefs" of the deep-sea benthos. As possible centers of biological activity, an ecological study of the abyssal benthos on the central North Pacific would not be complete without including the manganese nodules. (PIPR Q)
- Sediment community respiration measurements were made in the MPG-1 area in 1978 by using a free-vehicle grab respirometer.⁴ Sediment community respiration was found to be comparable in magnitude to rates obtained in the Sargasso Sea at similar depths. (PIPR S)
- Nutrient exchange rates across the sediment/water interface are of the same order of magnitude as those measured at shallower stations in the northwest Atlantic but significantly lower than rates obtained in more eutrophic deep waters off southern California. (PIPR S)
- Attempts to characterize the abyssopelagic fauna are underway using a free-vehicle gill net, baited trap, and hook array, with interesting preliminary results. The abyssobenthic macrourid *Coryphaenoides armatus* has been caught at depths from 50 to 685 metres above the bottom in the central and eastern North Pacific, showing that this ubiquitous fish is a likely transport mechanism between the bottom and midwater. (PIPR S)

● An important recent finding has been that the physiological state of the cells of deep-sea bacteria is a significant determinant of their adenosine triphosphate (ATP) content. The amount of ATP per cell can be increased 10- to 30-fold over that normally present by placing the cells at a hydrostatic pressure which is inhibitory to their growth. This means that the ATP content of a sample from the deep sea may be an overestimate of the number of cells capable of functioning at the depth of the sample. It has been shown that the inhibition of growth (cell division) by both excessively low as well as high pressures leads to the accumulation of ATP. (PIPR R)

● Much effort was expended this year in establishing a collection of deep-sea microbial cultures and maintaining them. Several deep-sea microbes have been isolated in pure culture using the silica gel pour-tube method.⁵ Mixed populations of microbes are also growing in liquid culture media of various kinds. The inocula for the enrichment and isolation procedures came from the water column, from sediments, and from putrefaction processes in pressure-retaining amphipod traps following the death of undecompressed amphipods. As far as sampling procedures are concerned, the maintenance of low temperatures is of paramount concern. No evidence exists that the strict avoidance of brief decompressions in the sampling and handling of inocula and cultures is a necessary precaution. The most interesting deep-sea bacterium isolated to date, a barophilic (pressure-adapted) organism, is not affected by temporary decompressions to the extent that it loses its viability. (PIPR R)

● The carbon content of sediment samples from the central North Pacific has been determined. The data from these GPC-3 core samples is given in Figure 7.⁴ (PIPR R)

Figure 7. Results of ATP and Total Carbon Analyses. The samples collected from a giant piston core (GPC-3) are described in the Annual Report of 1976.

even though concentration factors, defined as the ratio of the concentration of a radionuclide in an organism to that in the environment, have been used to help predict man's intake of radionuclides through the consumption of food, there are no formalized tables of data set on bioenvironmental concentration of radionuclides by aquatic organisms usually consumed by man. Analysis of environmental substances in aquatic environments is so laborious and time-consuming that there have been few determinations under natural conditions of the capacity of aquatic organisms (especially marine organisms) to accumulate various radionuclides as measured by the concentration factor. (PIPR C)

Concentration factors for many radionuclides have been determined by performing uptake experiments in aquaria containing water in which the radioactivity of a nuclide has been accurately measured. The accumulation of the radionuclide by the aquatic organisms and its simultaneous removal from the water are then determined using appropriate assay procedures, even though concentration factors strictly refer to the steady-state condition resulting from a continuous release. Concentration factors have been determined for many species of aquatic organisms and vary by many orders of magnitude because of the metabolic characteristics of these species, the peculiarities of their aquatic environment, and the procedures employed to measure the concentration factors. (PIPR C)

Since there are few or no bioenvironmental data for many radionuclides in the marine environment, metabolic equivalence classes of radionuclides have been constructed to model the radiobiological effects of radionuclides in the HAW inventory that may be important contributors to the radiation dose to man. Each radionuclide has been placed in one of three metabolic equivalence classes: the plutonium class, the strontium class, and the cesium class. Assignment of each radionuclide to a class is based on human dosimetry considerations. All radionuclides in a class are considered to exhibit the same radiobiological effects as the principal nuclide of that class. This scheme will be revised as more data become available. (PIPR O)

The chemistry of fallout nuclides and their dispersion and redistribution on earth has been the object of ongoing studies reported previously.^{2 3 5} These studies continue with the objective, for this program, of elucidating pathways and rates by which radionuclides move through the ocean, their rate of penetration into the benthic sediments, and the effectiveness of the sediments in immobilizing them.

To make useful predictions of environmental distributions in (and the effects on) the oceans of radionuclide wastes that may be released, it is essential that each identifiable release to the marine system be studied to extract as much information as possible. Detailed results of radionuclide distributions observed in submarine sediments of areas which the U.S. has used in the past for the dumping of low-level solid wastes, both in the Atlantic and the Pacific, are given in PIPR P.

Emplacement

The reference subseabed geological disposal system was described in an earlier section, System Development and Analysis. As was noted, none of several apparently feasible emplacement methods has been developed in detail. However, the simplest system conceived, a penetrator has been established as an interim reference method for emplacement.

Knowledge of the deformations of seabed sediments, not only during emplacement of waste containers but also for times long after emplacement, is needed for evaluation of both emplacement techniques and long-term waste isolation. The cavity formed during emplacement must close and form a continuous sediment barrier, both mechanical and chemical, around the emplacement waste container.

- Several aspects of evaluating and developing predictive capability for the mechanical response of deep ocean sediments were investigated. The effort encompassed methods for analyzing sediment response ranging from the very slow creep deformations related to long-term stability to the dynamic motion resulting from penetrometer emplacement. Computer simulations were made using finite-element and finite-difference codes to assess each code's ability to predict stresses and deformations occurring during dynamic emplacement of penetrometers and to interpret the results of lab emplacement experiments. Development of governing differential equations and corresponding finite-element formulations for the analyses of fully saturated, deformable, porous media was continued. (PIPR G)
- A significant portion of the overall effort to develop predictive capabilities was devoted to activities related to providing constitutive models required by the computational techniques being studied. Existing literature was reviewed for dynamic, quasistatic, and creep properties of fine-grained clays. (PIPR G)
- Dynamic analyses were performed to simulate the entry of penetrometers into sediment columns. Initial efforts were directed toward simulating the laboratory test conditions associated with the hole-closure studies previously reported.⁵ Both one- and two-dimensional analyses indicated that the qualitative rebound behavior of sediments after projectile penetration was strongly influenced by proximity to the tank walls. Further work concentrated on modeling penetration of a projectile and subsequent sediment response for in-situ conditions. (PIPR G)
- Development of a deformable porous media model based on effective stress principles was continued. After a detailed review of numerical formulations for solving the governing equations reported in the literature, it was decided to modify an existing code to solve the governing equations appropriate to subseabed applications. (PIPR G)
- Sediment response must be determined for the mechanical and thermal loadings that result from the emplacement of heat-producing wastes. Implementation of the finite-element equations (representing the governing differential equations that describe the features of the sediment response) into a computer code has been started. An effective means of formulating the finite-element equations is being studied to solve the governing equations with compressibility of the fluid included. (PIPR G)

Laboratory hole-closure experiments are in the final phase of testing. These experiments were designed to allow experimental verification of computer models and to provide insights into

sediment behavior during and subsequent to emplacement of projectiles by either quasistatic or dynamic methods. Two Sediment depths (9 and 18 metres) have been simulated for three types of oceanic sediment (Atlantic carbonate, Pacific illite, and Pacific smectite). Further details and results of these tests are given in Reference 5 and PIPR D.

Sampling and Instrumentation Development

Much of the capability to make needed measurements and to obtain requisite samples is either unavailable or in need of specialized modifications. As in the past, part of the effort and available funds of the SDP have been directed toward the development of needed instrumentation and sampling techniques and equipment.²⁻⁵ The major development efforts of 1978 are discussed briefly below and the reader is referred to the appropriate part of Volume II for details.

- Design of a seafloor work vehicle got under way during 1978. In brief, the vehicle is 2.5 m long x 2 m wide x 2 m high and is designed for handling over the side of an oceanographic ship equipped with an articulated crane and a suitable winch and accumulator system. In operation, 9000 m of double-armored coaxial cable will transmit 15 kW of power to the vehicle and transmit information back to the surface at a 1.25 megabit/s rate. The standard configuration will include a track-propulsion system, thrusters, TV cameras, lights, manipulator, compass and acoustic navigation, instrumentation, and side-looking sonar. Modularity of design will provide ready adaptability to a variety of scientific instrument packages. (PIPR T)
- A project was begun to develop a Long Coring Facility to obtain high-quality, large-diameter (more than 10 cm), long (more than 50 m) cores from the deep oceans. An Engineering Workshop on Deep Sea Coring was conducted in 1977.⁵ A follow-up Workshop on Long Undisturbed Sediment Cores from the Deep Seabed was held in early 1978 and is reported in PIPR E. Subsequently a joint project between Sandia Laboratories and the National Science Foundation was started in late 1978 and is reported in PIPR U.
- Accumulating evidence suggests the importance of abyssopelagic animals in the active transport of food from the sediment/water interface into the water column. To quantify this exchange rate, there is a need to know population densities and mobility rates along with individual animal metabolism. Conventional techniques using dredges, trawls, and camera surveys are not adequate to determine such population parameters. Therefore a feasibility study has begun to develop a free-vehicle acoustic array for making such measurements. The study has shown that such measurements can be made by applying sonar techniques and data processing to a large remote sampling scheme of long duration. (PIPR S)
- Equipment has been developed to measure the in situ metabolism of abyssopelagic animals at various distances off the bottom using a free-vehicle baited trap respirometer system. Individual animal measurements of metabolism will be made in the MPG-I area in 1979. These measurements, when combined with population size and mobility rate estimates as determined by the above equipment, plus tagging experiments, can then be used to predict the rate of transfer of food and radionuclides into the water column from the bottom. (PIPR S)
- A large free-vehicle conical net is being developed to capture the more active pelagic fauna such as squid and large predatory fishes that escape towed nets or the gill net/baited trap/hook array. The system is in final development and will be tested off southern California early in 1979. (PIPR S)

- As part of the in situ heat transfer experiment (ISHTE), a wide array of instrumentation and equipment developments are currently underway and are reported in PIPRs E, I., and M.

Transportation Studies

Transportation studies for the SDP were begun in 1978. The objective of the transportation activities is to ensure that operational hardware for transporting waste is designed, licensed, fabricated, tested, and available for use in a manner that is consistent with the overall objective of the SDP.

A program plan has been developed and system interface, logistic, institutional, environmental, design, licensing, and construction tasks were identified. Major transportation-related expenditures are projected to commence in 1983. During 1979, a final program plan will be developed. (PIPR V)

Section 4. International and Legal/Political Aspects

The radioactive waste disposal programs of most countries remain focused on investigation of continental geologic formations as possible waste-containment sites. It has been noted previously that several countries have initiated programs to investigate the possibilities of using the seabed and the geologic formations in the subseafloor for the disposal of H.W.⁵ Aside from the numerous technical advantages and disadvantages involved, use of the international seabed and subseabed for radioactive waste disposal raises a multitude of social, economic, political, legal, institutional, and ethical issues.

The technical aspects of seabed H.W. disposal are being addressed on an international level by the multinational International Seabed Working Group (ISWG) and by participation in the series of international workshops conducted by the ISWG. The results of the first three workshops conducted through 1978 are discussed in References 4, 6, and 7. Late in 1978, arrangements were being made for a fourth international workshop to be held in February 1979. Present official participation in the ISWG is by France, Japan, United Kingdom, and the United States.

Past and continuing marine disposal practices complicate the political and institutional aspects of an inherently controversial concept; this is especially the case on the international level. Containment within natural subseafloor geologic formations forms the basis of the SDI.⁶ All past marine disposal practice was based on dilution and dispersal in the oceans. It is clear that the feasibility of eventually implementing some form of subseabed disposal program will be directly related to the extent to which it is perceived as similar to, or different from, past ocean dispersal practices. Since almost everyone confuses the distinct concepts of disposal in the oceans, on the seabed, and in the subseabed, it becomes legally and politically crucial to carefully differentiate between past or proposed dumping into the oceans and carefully controlled emplacement of waste containers into the subseafloor.

Actual H.W. disposal in the subseabed is far enough off that many aspects of the social, legal, and political situations could change significantly in any direction. However, it seems reasonable to do legal and political research now in order to identify important problems and guide development in the interim.

As part of the SDI,⁶ research continued in 1978 on domestic and international political policies and trends relevant to subseabed disposal of H.W. These items are discussed in PHWR.

Section 5. Status

During the first year of this program, 1974, generic ocean areas were identified for consideration for seabed disposal concepts, and initial investigations were undertaken to evaluate early thoughts by program participants. From this first year came results and conclusions, based upon evaluation of collected historical data, preliminary analytical calculations, and initial new data derived from field work, that the water column (the mass of water extending from the seabed to the surface) should not be considered as a primary barrier or as an emplacement medium for H.W.

Program emphasis during the second year shifted from the water column to the characterization of mudflats, mudgyre sediments, their natural processes, and processes that are altered or imposed by the presence of radioactive wastes. Further analysis of available data, including supplemented historical data and new laboratory and field information, reinforced the initial impression that the water column was unsuitable for consideration as a disposal medium. Peer reviews of the program found that conclusion to be technically sound.

Many results from the second year of research proved to be the beginnings of complex investigations that must be completed to allow realistic assessment of ocean-bottom sediments as a disposal medium and a primary barrier to the migration of radionuclides. During 1976, emphasis was divided between continuing to collect data with which to characterize the midplate mudgyre sediment cover, initial laboratory investigations into the ion-exchange capabilities of the clay sediments, and analytical and modeling efforts to define the near-waste thermal environment. The acquisition of a long, large-diameter core from the MPC-1 study area of the central North Pacific provided samples of a major portion of the sediment column for geotechnical, chemical, and microbiological laboratory analyses, gave a firsthand look at the geologic history of the region, and provided an opportunity to correlate remotely acquired geophysical data with the realities of the geologic structure. Analysis of these data indicated long-term stability of the region and produced no surprises or anomalies that would preclude use of the sediment column as a disposal medium. Initial laboratory work with samples of abyssal red clays and selected ions that might be expected to result from dissolution of waste showed a high affinity of the clays for the ions, suggesting very favorable ion-exchange properties for the deep-sea sediments.

The broad spectrum of research investigations begun in 1976 continued in 1977, the fourth year of the program. The activities focused on (1) development of a number of analytical models as part of the overall system-analysis effort, (2) continuation of an extensive laboratory program to evaluate sediment sorption with respect to single-specie ions and competition provided by waste constituents, (3) continued characterization of sediment properties to establish initial conditions and develop a long-term predictive environment model of the sediments, (4) evaluation of interstitial pore-water movement induced by a heat source, (5) planning for a major thermal-properties field experiment to obtain quantitative information on thermal processes and material properties, (6) scoping calculations in an initial investigation of the potential buoyance problem, (7) corrosion

studies to evaluate candidate canister materials, (b) continuation of the biological information data base necessary to assess the consequences of an accident and to evaluate the environmental impact of subsurface emplacement, and (c) development of an international program and parties; action in the International Seabed Working Group.

The 1978 activities of the program included:

- Development of an analytical capability to assess ion transport through subsurface media
- Development of an analytical and numerical capability to analyze transient and steady-state fluid flow and heat transfer in porous media
- Further development of computer models to evaluate sediment column response to emplacement and heat burden
- Initial development of a biological transfer model to address paths and rates of ion transport
- Completion of a predictive environment for the central North Pacific
- Completion of an initial set of short-term corrosion tests to obtain scoping/instrumentation/modeling data
- Assessment of a variety of potential canister overpack materials for relative costs and economic impact
- Initial investigations into the chemistry of waste canister, waste form, pore water, and sediment interactions near the emplaced waste
- Continued characterization of the geochemical and geotechnical properties of deep-sea clay sediments
- Initial laboratory investigation into the effects of high temperatures on geotechnical properties of sediments
- An initial assessment of thermal properties at supercritical conditions from laboratory investigations
- Continuation of an extensive laboratory program to evaluate the ion sorption properties of sediments
- Continued development of the in situ heat-transfer experiment and initial design of various hardware subsystems and deployment/recovery methods
- A synthesis of existing western North Atlantic geological and geophysical data and an initial evaluation of a potential western North Atlantic study area
- Compilation of an extensive geological and geophysical data base for the North Pacific and selection of areas for more detailed study based upon current site-suitability guidelines
- Further development of the data base necessary to assess environmental impact and the complex pathways back to man through both the physical and biological ocean systems
- Completion of a feasibility study for the development of a seafloor work platform

- Initiation of a joint study with the National Science Foundation to develop a Long Coring Facility to enable acquisition of high-quality deep sea sediment cores
- Continued participation in the International Seabed Working Group,

The attention of the SDP remains focused on the waste form and canister for short-term (several hundred years) containment and on the sediments for long-term containment. Data thus far suggest that normally slow diffusion of ions through the highly impermeable deep-sea clay is further reduced substantially by the sorptive properties of clay sediments. Additionally, the low permeability of the clay strongly inhibits thermally driven convection of pore water. These results from sorption and thermal studies encourage optimism, but further extensive laboratory and in-situ validation is required.

At the conclusion of the fifth year of the SDP, it can again be stated that no technological or environmental reasons have been identified that would preclude the possibility of successful disposal of H W or spent fuel in selected, stable, sedimentary formations beneath the abyssal floors of the deep oceans.

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