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Seabed Disposal Program Annual Report January to December 1977 Volume I

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ABSTRACT

[illegible] which [illegible] Sandia Laboratories [illegible] relatively [illegible] high-level nuclear wastes. The program [illegible] international [illegible]

*Volume II of this publication contains the Appendices referred to in Volume I.

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Volume I

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SEABED DISPOSAL PROGRAM ANNUAL REPORT

SECTION 1

INTRODUCTION

This is the fourth annual report describing the progress and evaluating the status of the Seabed 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 Seabed Disposal Program 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 with respect to the 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 scenarios, as well as to unreprocessed spent fuel.

Since 70 percent 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 seafloors that are the current focus of this program.

Recent improvements in our understanding of global geological and climatological patterns, including the description of plate tectonics, which are due in part to recent advances in oceanographic research techniques, give some confidence that seabed disposal 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 resource limited; and processes in deeper parts of the oceans are slow, gentle, predictable, and depositional, as distinct from continental processes, which tend to be 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, 2, 3, and 4, together with present knowledge of the mid-plate/mid-gyre (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 possibly developing a safe disposal system.

As the SDP has developed during the past 4 1/2 years, two programmatic elements have evolved. The first consists of the developing and conducting of 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.

Although the seabed disposal of HLW has been considered an alternative to other more extensively studied concepts in the U.S., it is a more main-line project in the international arena. Since the seabed may be a viable option for ultimate waste disposal and since there are many international implications of such a system, basis for cooperation and exchange of information has developed with other countries, such as Japan, France, and the United Kingdom. It is anticipated that through mutual involvement a more complete and timely assessment of concept feasibility can be made.

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 HLW. 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 (sorb) 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

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 the data development at a manageable level, initial studies were limited to the central North Pacific MPG area.[4] 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 suboceanic 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[2,3] because the waste container would be effectively placed directly in the biosphere. Since it is difficult to conceive of a practical manmade waste-form/canister system that would survive without releasing nuclides for hundreds of thousands of years, 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, when transportation, safety, and environmental impact have to be considered in relation to a sub-seafloor 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.

In early 1976, the Energy Research and Development Administration (ERDA), now a part of the Department of Energy (DOE), 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.

Emphasis on evaluating the barrier properties of seafloor sediments continued through 1977. While the major portion of program funds and effort was applied to this area, activities relative to the overall technical feasibility study, environmental impacts, and international and legal/political considerations continued at a pace commensurate with current SDP priorities.

International Seabed Disposal Program

The SDP has international implications because of its potential contribution to solving the worldwide waste management problem and also 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. More specifically, an international Seabed Working Group (SWG) has been organized under the Radioactive Waste Management Committee (RWMC) of the NEA (see Appendix A, Volume II).

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 I 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 1977.

The objectives of the SDP as outlined in the first-year report[4] remain unchanged. To provide a basis from which to view the critical scientific decision points in the overall program plan, a Barrier System Logic and Decision Diagram was developed and is described in Reference 2.

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

A significant group of presentations to the nuclear community by program participants occurred at a special session of papers invited on "Methods for Seabed Disposal of Nuclear Waste" held in the 1977 annual meeting of the American Nuclear Society. Abstracts of these presentations are given in Appendix B.

TABLE I

List of Contributors - 1977

D. R. Anderson*	SLA	C. E. Hickox	SLA
K. Baldwin	URI	C. D. Hollister*	WHOI
S. R. Bamford	URI	C. L. Ingram	SIO
V. T. Bowen	WHOI	C. H. Karnes	SLA
D. G. Boyer*	DOE/ECT	E. Laine	URI
J. W. Braithwaite	SLA	M. Leinen	URI
B. R. Burnett	SIO	H. D. Livingston	WHOI
D. J. Calnan	URI	R. E. McDuff	SIO
P. F. Chavez	SLA	J. A. McGowan	SIO
J. Damuth	LDGO	D. F. McVey	SLA
P. R. Dawson	SLA	L. O. Olson	APL/UW
D. A. Deese	Harvard	A. Pederson	APL/UW
A. S. Dietz	SIO	R. A. Prince	URI
P. S. Doyle	SIO	P. B. Rhines	WHOI
A. R. Driscoll	WHOI	W. P. Schimmel, Jr.	SLA
J. C. Dunn	SLA	A. J. Silva	URI
R. Embly	LDGO	C. R. Smith	SIO
G. B. Epstein	URI	K. L. Smith	SIO
K. L. Erickson	SLA	F. N. Speiss	MPL/SIO
T. E. Ewart	APL/UW	K. D. Sundberg	SLA
D. H. Hamilton	DOE/BER	D. M. Talbert*	SLA
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T. L. Hayward	SIO	B. Tucholke	LDGO
G. R. Heath*	URI	R. VanBoxtel	SIO
R. R. Hessler	SIO	F. S. Wishner	SIO
J. R. Hetherman	URI	A. A. Yayanos*	SIO

*Current member of the Seabed Disposal Program Executive Planning Group

SECTION 3

PROGRAM RESEARCH AND SCIENTIFIC EFFORT

Program attention remains focused on the unconsolidated, fine-grained, deep-sea sediments as a potential medium for containment of solidified, encapsulated, radioactive HLW. During 1976 and 1977, emphasis was divided between data collection to define and characterize generic MPG sediments, initial laboratory investigations into the ion exchange capabilities of clay sediments, and analytical and modeling efforts to define the near-waste thermal environment. While the major research effort of the program centered on generic MPG-type red clay sediments, other activities relative to the overall technical feasibility study, such as environmental impact considerations, international cooperation, and sociopolitical considerations, continued in 1977.

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, environmental predictability and characterization, nuclide migration (containment mode), nuclide migration (accident/release mode), emplacement, and sampling and instrumentation development. Throughout the text the reader is referred to the appropriate appendix or other reference for more detail.

SYSTEM DEVELOPMENT AND ANALYSIS

The SDP is currently structured as a three-phase program concluding in 1995. Program objectives are

1. To assess the environmental and technical feasibility of isolating HLW or spent fuel in geologic formations beneath the ocean floor, in remote, predictable, climatologically and geologically stable, biologically inactive regions where impact on resources is minimal, and
2. To develop and maintain a capability to assess ocean disposal programs developed by other nations.

During Phase I (concluding in 1983), major short-term objectives are to acquire data to establish whether the deep sediments in isolated regions of the ocean floor are an effective barrier to dispersal of radionuclides from suitably emplaced waste. If nothing is found during Phase I that would eliminate the concept from further consideration, Phase II (1984-1990) will assess the engineering aspects of handling and emplacement of HLW or spent fuel into the chosen geologic units beneath the ocean floor. Provided Phase II is successfully completed and nothing is identified which would eliminate the concept, Phase III (1991-1995) will be implemented and will demonstrate the capabilities of the concept through semi-routine emplacement of waste containers.

Individual components of the program are coordinated into a total-system engineering effort designed to deal with the waste from the time it leaves the reprocessing or repackaging facility until safely emplaced at the repository. Major elements of the total program are system development, conceptual design of the handling and emplacement facilities, environmental impact analysis, and construction of facilities. Included in system development are site selection (characterization and criteria development), waste confinement, emplacement, transportation, risk and safety analyses, and economic and sociopolitical analyses. No program funding was applied to the areas of transportation, risk and safety analyses, or economic analyses during 1977. Initiation of activities on some tasks in these areas is planned for 1978.

Program philosophy was spelled out in early documentation and has remained unchanged.[1] This philosophy is to treat the disposal question as a multiple-barrier assessment problem. A formalism based on a set of sequential barriers to the release of radioactive waste has been adopted to compare rates of decay of waste constituents against the rates of migration of the nuclides toward man. This multiple-barrier concept[3] encompasses the waste form, the waste canister, the subseafloor emplacement medium, any controlled modification of the medium, the benthic boundary layer, and the water column.

The major task of the program at this time is to determine whether or not any submarine geologic formation can contain radioactive waste long enough for it to decay to innocuous levels. Attention is focused on the waste form and canister for short-term containment and on the sediments for long-term containment.

The basis from which to view the critical scientific decision points of the containment problem is the Barrier System Logic and Decision Diagram. This diagram, discussed in Reference 2, prescribes the program needed to address the containment problem from generic site-type selection, through all necessary scientific and engineering investigations, to a disposal pilot project. The diagram is centered around a number of models which are in various stages of development.

Since the required time of waste isolation is much longer than is attainable in any manmade experiment, the attributes of each component of the barrier system must be adequately known so that a credible prediction of barrier-system effectiveness can be made. This effectiveness will be evaluated by the use of suitably substantial models which will be used to characterize subsystems and to enable parametric studies and sensitivity analyses to be conducted. Details of the subsystem models are given in the appendices indicated:

- Ion transport through porous media (Appendix C),
- Thermal interaction (conduction and convection) between waste canister and sediment (Appendix K),
- Long-term sediment deformation and buoyance resulting from heating (Appendix M),
- Sediment column response to dynamic loading associated with canister emplacement (Appendix M),

- Sediment column response to quasi-static emplacement (Appendix M),
- Paths and rates of biological mobilization and transfer of radioactive ions from sediment to water column and within the water column (Appendix D), and
- Predictive environmental model of the sediments for the next one million years (Appendix F).

While program research activities through 1976 continued to be focused on study areas in the central North Pacific, during 1977 studies were initiated to find a generic study area in the Atlantic in a region of pelagic sedimentation. This activity furthers development of the international aspects of the program and is necessary to allow a sound system analysis of the disposal concept. The goals of this extension of the program are

- To identify generic site-type study areas in the Atlantic,
- To ascertain that existing methodologies for assessing the feasibility of the disposal concept are applicable in the Atlantic,
- To compare the lateral and vertical coherence of Atlantic pelagic sediments with those being studied in the Pacific,
- To determine small-scale depositional patterns and predictability of sedimentation in Atlantic areas, and
- To compare the sorptive and geotechnical properties of Atlantic pelagic sediments with those of the Pacific.

ENVIRONMENTAL PREDICTABILITY AND CHARACTERIZATION

The development of an adequate understanding of the natural system and its response to such perturbations as pertain to the feasibility of nuclear waste disposal continued to be a major area of program effort in 1977. An immediate objective is an understanding of the complex interactions between wastes and sediments. To accomplish this objective, descriptions of the sediments, their physical and chemical properties, and responses of the sediment column to mechanical, chemical, thermal, and radiation perturbations are needed. One aspect of this effort is an investigation of ambient background conditions to establish initial conditions and to furnish the basis for an understanding of natural processes caused by perturbations other than waste disposal. The result of this work will be the development of a predictive environmental model of the sediments for the next one million years.

This model will then be coupled with the results of other investigations into the interactions which develop when the environment is perturbed by the presence of waste canisters, mobile waste ions, heat, and radiation to enable a technical assessment of the disposal concept to be made. To establish that a region has undergone no perturbations for millions to tens of millions of years before the present (mybp) requires the careful analysis of a continuous sedimentary record, commencing with the present.

A major accomplishment during 1976 was the successful acquisition of a long (24.38 m), large-diameter (11.4 cm) core sediment sample from the central North Pacific study site MPG-I, as reported in Reference 1. The core is designated GPC-3. Many of the results reported in this section are derived from samples obtained from this core. Detailed characterization of the sediment cover from MPG-I in particular and the red clays of the central North Pacific in general continues to evolve as laboratory work with samples from this significant core progresses.

Another core obtained from the same cruise and designated GPC-2, consisted of approximately 500 liters of flow-in. This "core" was essentially a bulk sample of smectite clay from 10 m below the sediment surface. This quantity of bulk sample, unobtainable under usual circumstances, has proven most useful as a source of "standard" samples for metallurgical and chemical investigations, emplacement studies, thermal properties research, and numerous other laboratory studies requiring smectite samples.

Data from a continuous undisturbed sediment sample represents the only ground-truth information available for determining past depositional environments. Each change in sediment character represents one or a combination of changes in environment of deposition, in sediment provenance, and rate of accumulation of material or post-depositional alteration. It is necessary to determine which if any of these types of changes could affect a site's suitability as a future repository and how they would affect a site after emplacement. The credibility of forecasting of future environmental conditions is one key element in the total question of "predictability" and the development of a repository.

Characterization of Sediment Cover -- Data from GPC-3 sediment samples have been extensively analyzed and integrated with other short (< 13 m) core data obtained by the program and other available data from the central North Pacific to yield a number of observations and conclusions which are summarized here and detailed in the appendices and references:

- Studies of the magnetic properties of sediments from GPC-3 and from VEMA Cruise 32 cores in the MPG-I study area show consistent core-to-core variations, even though the integrated accumulation rates vary by a factor of two within the area (see Figure 1). The long-term stability of the patterns suggests that inertial or tidal currents, rather than advective bottom flow, which likely has varied over geologic time, exert the greatest influence on the deposition of fine sediments (Appendix E).
- The MPG-I and MPG-II study areas, which are 700 km apart, show a great similarity in depositional features; this suggests that sedimentation beneath the central North Pacific gyre has been continuous and predictable for millions of years (Appendix E).
- Most of the mineralogic variations in GPC-3 can be accounted for by a combination of NNW plate motion (from a position at about 5° N to its present location at 30° N) through regions having differing sediment provenance, by

temporal and spatial variations in wind and current directions, and by variations in aeolian transport of terrigenous and volcanic debris (Appendices E and F).

- Throughout the last 70 million years MPG-I has been below the calcium carbonate compensation depth, i.e., below at least 4000 m of water, with the assumption that present temperature-salinity characteristics have obtained over that period (Appendix F).
- All available data suggest that the rate of sediment accumulation for 70 million years has been continuous and generally very slow, i.e., 0.2 to 0.[illegible] m per million years; however, rates increased considerably, from 1.1 to over 2 m per million years, between the early Pleistocene and the present (Appendix F).
- Stratigraphy based on zonation of fish teeth has error bars of the order of 4 to 5 million years, thus limiting the time resolution for any observed oceanographic event by this amount (Appendix G).
- A zone in the GPC-3 core, 10 to 12 m, shows marked changes in most of the data profiles; this zone correlates with a basin-wide sub-bottom acoustic reflector at about 11.5 m (~25 mybp). This abrupt change may be related to a hiatus of nondeposition, although fish-teeth stratigraphy shows no indication of this. Concentrated resampling at close intervals in this zone will be done in 1978 (Appendix H).

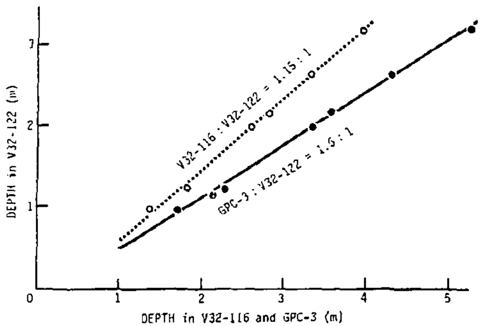

Figure 1. Uniform depositional patterns in the MPG-I area revealed by correlation plots of magnetic reversal boundaries in GPC-3 and V-32 cores. Even though core-to-core accumulation rates vary by factors of up to 2, the cores respond virtually identically to the marked increase in sedimentation rate from less than ½ m per million years during the Tertiary to several m per million years for the youngest sediments.

- Stratigraphic data from GPC-3 also suggest the presence of shortened sections or hiatuses at about 35 mybp and 45 mybp; however, the data are not conclusive and other profiles, e.g., geotechnical (see Appendix H), suggest continuous deposition (Appendix F).
- Glacial stages have had no deleterious effect on the MPG-I environment (Appendix F).
- Detrital remanent magnetization results from GPC-3 provide a detailed chronology that is consistent with ichthyolithic stratigraphy. Taken together, the magnetic and biostratigraphic data indicate that sedimentation has been continuous at the site of GPC-3 for the past 70 million years (see Figure 2). The sedimentation rate has increased from less than 0.3 m per million years at the base of the core to 2.5 m per million years at the seafloor (Appendix E).

Once it has been demonstrated within reasonable doubt from the limited number of cores and preliminary acoustic data available that an area appears suitable as a possible repository site, it is then necessary to determine whether a sufficiently large area has continuous properties and uniform sediment characteristics. A method is needed to reasonably verify the validity of interpolating "continuity" from one core site to the next.

Extensive progress has been made in the last decade in perfecting the technique of continuous sea-bottom acoustic profiling, capitalizing on the excellent propagation characteristics of compressional waves in water and the underlying water-saturated sediments. This technique allows definition of the acoustic character of the sediments in any water depth, from the surface of the seabed to the top of the basement rock, which may be as much as 5 to 10 km below the ocean floor.

Acoustic profiles from mid-plate regions characteristically show one or more sub-bottom reflecting horizons; some lie within the penetration range of piston cores. To demonstrate that any study site has been affected by the same process in space and time, cores are taken through the reflectors to identify the reflecting horizons, and then the reflectors are traced acoustically across the basin using spot cores to validate the correlations and to establish similarity in the sedimentary sequence. Development of this method of basin-wide extrapolation using long cores which contain undisturbed environmental records for 1 million to 10 million years is critical to verification of an extensive area as a repository site.

The first attempt at determining the lateral continuity of an MPG study area was initiated several years ago and was completed in 1977. Progress is reported in Reference 3. Further analysis of data from MPG-I during the past year reveals the following:

- No data show large-scale faulting (tens of metres in vertical throw) in any areas covered with acoustically penetrable sediments (Appendix F).

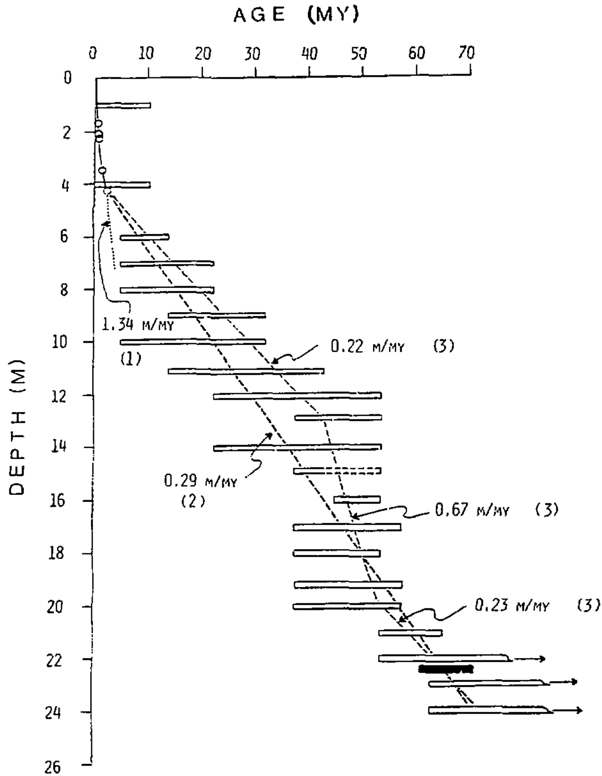

Figure 2. Age versus depth plot for GPC-3. Open bars are age estimates based on ichthyolith assemblages (Appendix G). Solid bar is the age estimate derived from a plate-motion model and a paleolatitude calculated from paleoinclination data (Appendix F). Solid line and open circles are from magnetic stratigraphy; dashed lines are three models for the sedimentation rate history of GPC-3 (Appendix F).

- The region between 158° W and 159° W and between 30° N and 31° 30' N (~6000 square miles) is relatively uniform acoustically, with the profiles showing an even blanket of 30 to 50 metres of sediment containing one continuous sub-bottom reflector at about a 10- to 12-metre depth. This appears to be the most homogeneous portion of the MPG-I region (Appendix F).
- Acoustic profiles taken east of 158° are much more variable, with more discontinuous reflectors, rougher topography, and possible basement outcrops present (Appendix F).
- Further conclusions concerning lateral coherence will have to await closer-spaced track coverage from surface ships and detailed near-bottom acoustic surveys augmented by a number of long piston cores for final demonstration of site homogeneity (Appendix F).

Characterization of Sediment Properties -- Characterization of sediment properties of the MPG study areas continued in 1977. Extensive initial analyses of the GPC-3 core recovered from MPG-I are reported in Reference 3. A summary of the results obtained during the past year from continuing analyses of these and other core data from the study areas follows:

- Studies have begun to evaluate the geochemical and sedimentological parameters which control the sorptive capacity of the sediment. The goal of these studies is to predict sorptive properties from simpler geochemical parameters. This information, combined with knowledge of the accumulation rates of sediment components and elements, will allow comparison of MPG-I sediments, as reflected in GPC-3, with other study areas (Appendix E).
- Long-term trends of geochemical variations in GPC-3 have been established. Samples were analyzed for Mg, Al, Ca, Mn, Fe, Ni, Cu, and Zn. The pattern of transition-metal enrichment corresponds roughly to the increase in sorptive capacity of the GPC-3 sediments for Eu (Appendix E).
- The first scanning electron microscope (SEM) photographs of GPC-3 were made during the past year (Figures 3 through 9). The fineness of the deeper clays can be visualized by noting that the particles in 6 grams of smectite (two pennies weigh 6 grams) have a combined surface area equal to that of a football field.
- SEM photographs of samples from GPC-3 reveal the characteristic clay-floc fabric (honeycomb structure) of ultra-fine-grained abyssal clays (Figures 3 through 6). This material has very high porosity and very low permeability (Appendix H).
- SEM photographs of lighter-colored clays of GPC-3 show a variety of sediment characteristics (Figures 7 through 9). This variety can generally be attributed to the post-depositional alteration (diagenesis) of volcanic ash layer or to authigenic precipitation of zeolite crystals or amorphous silica in the form of cristobalite (Appendix F).

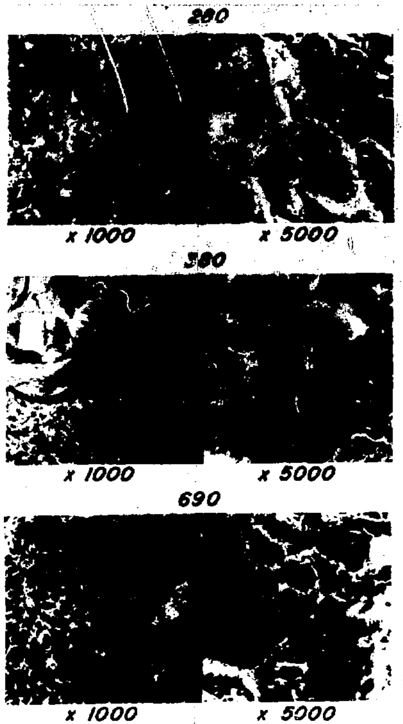

Figure 3. 280 cm (Upper); quartz-illite-rich clay containing wind-blown continental debris (left) probably derived from glacial deposits of Asia and North America. Age ≈1.2 mybp.

380 cm (Middle); quartz-illite-rich clay containing wind-blown continental debris (left). Age ≈1.8 mybp.

690 cm (Lower); clays of the "Transition Zone," a region where the illite mineralogy changes to primarily authigenic smectite-ferromanganese oxyhydroxide-rich sediment. Note typical honeycomb structure of clay fabric; this structure is the primary cause for the high porosity and low permeability. Age ≈4 mybp.

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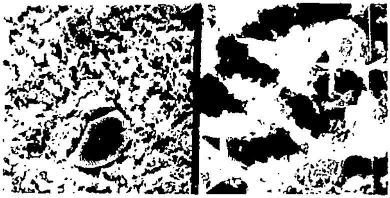

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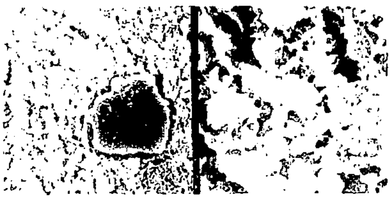

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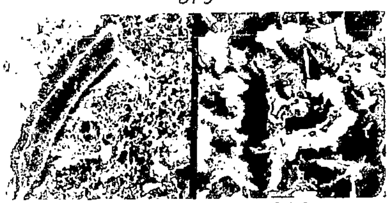

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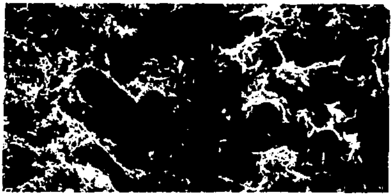

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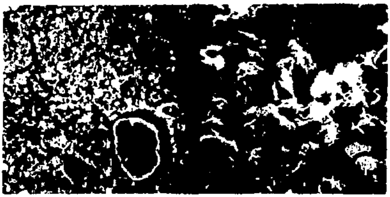

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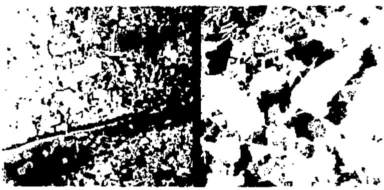

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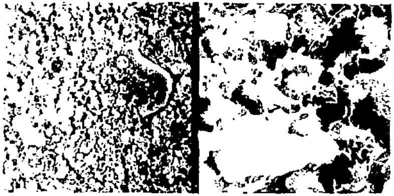

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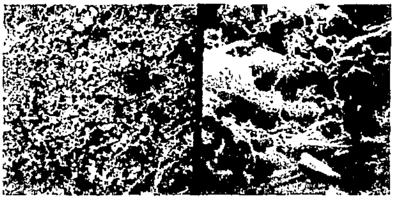

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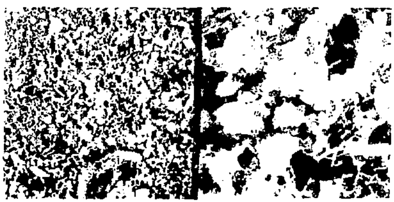

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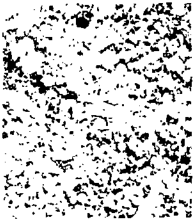

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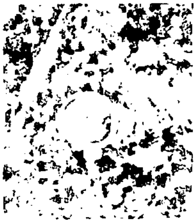

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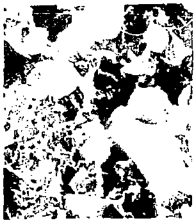

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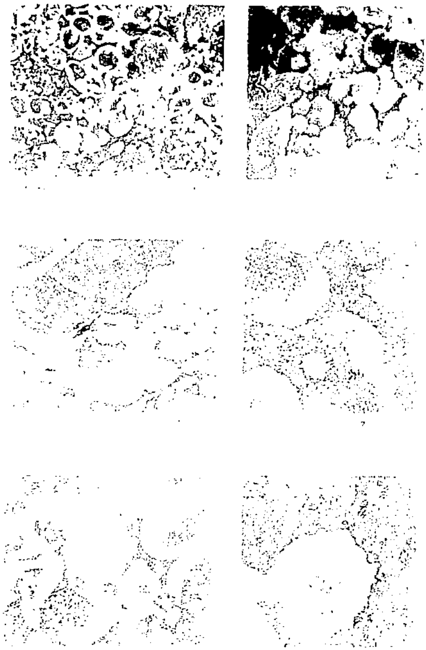

Information on the physical properties of sediments provides part of the data base necessary for long-term prediction of the behavior of potential repository sites. A combination of spot sampling by coring (or drilling) and sub-bottom acoustic profiling techniques is used in these studies. To date, investigations have been directed at deep-sea clays generically rather than in a site-specific manner. The two study areas of the central North Pacific (MPG-I and MPG-II) were selected for initial studies, but the development of a way to characterize the areas is of first importance, on the theory that the information will be applicable to any potential site once feasibility of the disposal concept has been established.

Geotechnical property studies on samples recovered from the study areas have been concerned with (1) permeability characteristics, (2) compressibility characteristics, (3) shear strength, and (4) index properties (void ratio, water content, grain-size distribution, plasticity, and specific gravity). Typical profiles of geotechnical properties at the study areas have been extensively reported.[1,2,3,4] A summary of lithology, water content, shear strength, and acoustic properties of GPC-3 is shown in Figure 10 and discussed in Appendix H. A summary of significant results from geotechnical investigations conducted during the past year follows.

- Data from consolidation tests on MPG-I samples show the present in-situ overburden stress to be the maximum preconsolidation stress. This indicates that the area has not undergone any dramatic changes in topography due to removal of overburden and that there is essentially no water migration due to compaction (Appendix H).
- This stress information, coupled with sedimentation rates established by other studies, yields a picture of a stable stress environment over the past tens of millions of years (Appendix H).
- The phenomenon of apparent overconsolidation in the upper few metres has been observed in a wide variety of deep-sea sediments and is attributed to high interparticle bonding stresses which overshadow overburden stresses (Appendix H).
- The water content/density profile shows a dramatic increase in porosity (decrease in density) beginning at about 6 metres in MPG-I (from an average water content of 110 percent in the upper 6 metres to 230 percent at 11 metres). This is due to a mineralogy change from illite in surficial sediments to smectite in deeper layers, which is finer grained and more active with respect to cation exchange capacity (Appendix H).
- Permeability of smectites at in-situ porosities is estimated to be of the order of 3×10^{-7} cm/s. Illites are estimated to have a permeability of the order of 3×10^{-6} cm/s (Appendix H).

NUCLIDE MIGRATION -- CONTAINMENT MODE

An essential element in evaluating the feasibility of a disposal system is an understanding of the interactions between the waste and the environment. If there were no effects or modifications of the environment, there would be no threat to the biological system or to man. There is no way to separate the effects of the environment on the waste from those of the waste on the environment in this highly complex system, interlaced as it is with many feedback pathways.

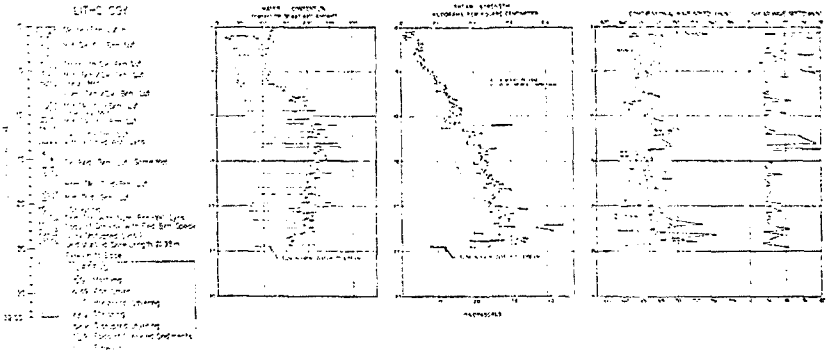

Figure 10. Cruise No. LL-44; Core No. GPC-3; Lat. 30° 19.9' N, Long. 157° 49.4' W

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 ions 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.

As discussed in "System Development and Analyses" earlier in this section, primary concern is with the three barriers that lie between wastes buried in the seabed and the biosphere: (1) the waste form, (2) the canister, and (3) the sediments surrounding the canister. Results of studies summarized here deal with corrosion studies of possible canister materials; geochemical characterization as it relates to ion migration, diffusion, and advection within the sediments; evaluation of nuclide sorption distribution coefficients; and thermal studies.

The useful life of an emplaced canister will depend on several factors: (1) the nature of the waste form and its compatibility with the canister; (2) the compatibility of the canister with the natural or modified external environment; and (3) the mechanical integrity of the canister under the stresses of emplacement, heat load, and the deep ocean environment. The expected lifetime will determine whether a canister will be useful only as a shipping container or also as a barrier against dispersal of buried waste.

Because marine corrosion has always been a problem, a large data base is available on low-temperature marine corrosion, though very little is available on high-temperature investigations. Corrosion studies of a number of materials at temperatures up to 90°C have been conducted and summarized as part of this program.[3] The expected temperatures of actual buried waste[4] make a high-temperature corrosion program mandatory.

- A study has been initiated to provide a strong basis for the selection of materials to be used in the construction of waste canisters and in-situ instrumentation. The goal of this study is to identify materials which (1) are compatible with an environment heated by radioactivity for necessary lengths of time, (2) have the desirable mechanical strength and thermal conductivity properties, and (3) have low cost and minimal consumption of critically limited materials (Appendix I).

- Literature surveys have been conducted and data compiled on corrosion information for most alloy systems in hot brine and seawater: aluminum, copper, titanium, and nickel-based alloys; mild, low-strength steels; and stainless steels (Appendix I).

- Corrosion response of a wide range of alloy systems is being studied to determine the influence of (1) temperature, (2) brine composition (solution chemistry), (3) dissolved oxygen concentration, (4) external pressure, (5) coatings, (6) welding and sensitization of the base metal, (7) heat treatment, (8) stress, and (9) radiation damage and radiolysis products (Appendix I).

- Temperature effects on quenched seawater pH have been determined for a range from 25° C to 270° C. Seawater pH varied from 8.1 to 3.3 over this range (Appendix I).
- Short-term corrosion rates at 200° C have been determined for five alloys. Rates ranged from 0.146 mm/year for 1018 steel to 0.012 mm/year for 3046 stainless steel and 0.004 mm/year for Inconel 600 (Appendix I).

Chemical characterization of the central North Pacific clays has progressed. As discussed in "Environmental Predictability and Characterization," under "Characterization of Sediment Properties," studies are underway to investigate the correlation between geochemical data and sorption results. Samples from GPC-3 were analyzed using atomic absorption spectrometry, and downcore profiles of the variations of Mn, Al, Ca, Mg, Fe, Ni, Cu, and Zn were established. These profiles were then compared to the vertical profiles established for the sorptive properties of Sr (Appendix E).

Similarly, standard samples obtained from core GPC-2 have been subjected to elemental analysis by emission spectroscopy. Elements identified in this analysis include Ba, Cr, Sr, Al, Ca, Zr, Ni, Ti, Cu, Be, V, Fe, Mo, Mn, Si, Na, Li, K, and Rb (Appendix J).

The purpose of this work is to establish a standard set of material characterizations which is applicable to similar sediments and to which the sorption and migration properties of each sediment can be related. By establishing correlations between material characterization data and sorption data, it is anticipated that sorption behavior of other sediments can be predicted from the more easily determined geochemical properties and that only a minimum amount of verifying sorptive data will need to be collected (Appendices E and J).

The migration of radionuclides from a point of emplacement in sub-seafloor sediments will result from both diffusion and advection. In examining the barrier properties of deep-sea clays, it is desirable to decouple the effects of diffusion from those of advection for initial analyses, though it must be kept in mind that the two will ultimately have to be considered as interacting. The advection problem is discussed in conjunction with thermal studies.

As discussed in "System Development and Analysis," models are required with which reliable predictions can be made of the migration rates of nuclides from a point of emplacement toward the biosphere. To develop the necessary models with which to address the ion transport problem, the dominant mechanisms for nuclide sorption and migration must be adequately understood and their mathematical description formulated, solved, and verified experimentally.

Extensive studies to investigate the total nuclide sorption and migration problem are being pursued with the highest priority in the program. The major emphasis of these studies is the evaluation of equilibrium sorption distribution coefficients as functions of temperature, pressure, pH, nuclide concentration, competition concentration, and sediment type.

The initial sorption experiments of the program, begun in 1976, have been completed. These investigations were to assess Th and UO_2 reactions as functions of temperature and concentration with illitic and smectitic North Pacific clays. Results are discussed and data tabulated in Appendix E.

One effort addressed in 1977 was development of a program to evaluate the vertical variability of the sorption characteristics of GPC-3 sediments. Such information is a necessary input to numerical models of the migration of dissolved nuclides. The first phase of the study involved determination of the sorption and desorption equilibria of Eu (using an Eu-154 spike) dissolved in 0.7N NaCl relative to GPC-3 sediments as a function of Eu concentration and temperature. Eu is being used as a representative of the rare earths and because its column exchange behavior is similar to the heavier actinides, particularly americium. Concentration experiments at 15° C were completed during 1977, and experiments at 85° C will be completed during 1978. A number of observations and conclusions can be made at this time:

- The partition coefficient (K_p) for Eu varies by an order of magnitude down the core (Appendix E).
- Downcore variations in K_p are not random (Figure 11) but increase systematically for a 1 micromolar solution from around 3000 ml/g in illitic surface sediments to 30,000 ml/g and more in the smectite-ferromanganese oxyhydroxide sediments from 11 to 19 m in the core. The deepest sediments (below 20 m) show slightly lower K_p values of around 10,000, which are consistent with the greater detrital content of these deposits inferred from magnetic and geochemical studies (Appendix E).
- Sorption and desorption experiments yield essentially identical K_p values at 1 millimolar (Figure 11), suggesting that 1-day equilibration times are adequate for the reactions to approach equilibrium (Appendix E).
- The concentration dependence of K_p for sorption reactions also varies systematically downcore, with values of d log K_p/d log C ranging from about -0.7 near the surface to less than -0.8 in the 11- to 19-m interval (Figure 11). Preliminary high-temperature data suggest that this difference is less at 85° C than 15° C.[3] Such a difference implies at least two sorption reactions: a fast, highly reversible ion exchange, and a slower Eu uptake, whether into structural or inaccessible interlayer sites, that is less reversible. It is noteworthy that for an ideal system where the activities of dissolved and sorbed ions are independent of concentration, d log K_p/d log C is 0, whereas for a system where sorption is irreversible, d log K_p/d log C is -1. The values measured are closer to -1 than to 0. In a number of desorption experiments, where solution concentrations are in the micromolar range, the d log K_p/d log C values are analytically indistinguishable from -1 (Appendix E).

In parallel with the above investigation, determination of the sorption and desorption of Eu in 0.7N NaCl solutions with respect to a suite of siliceous and calcareous oozes has been underway:

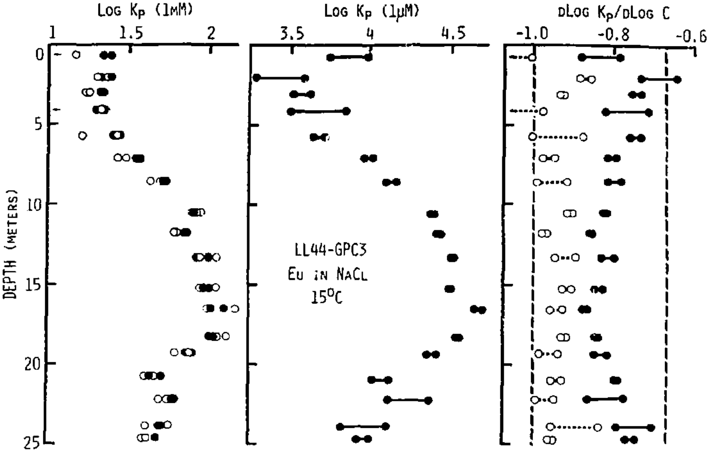

Figure 11. Downcore variations in Eu sorption from 0.7N NaCl solutions at 15° C by MPG-I sediments from core GPC-3. Filled circles are based on sorption experiments, open circles from desorption experiments. A value of −1.0 for d log K_p/d log C implies irreversible sorption. Each data point is the mean of three determinations for a sediment sample. Differences between pairs of points are a measure of the variability in sorption properties of closely spaced samples.

- At 15° C, calcareous oozes have K_p values of 40,000 to 70,000 for 1 micromolar Eu, and sorption d log K_p/d log C values in the −0.9 to −1 range (Appendix E).
- At 15° C, siliceous ooze and red clay samples have 1 micromolar Eu K_p values of 12,000 to 16,000 and sorption d log K_p/d log C values of −0.8 to −1 (Appendix E).

If these initial results are indicative of what is to follow and are applicable to a range of elements and environmental conditions, the selection of a sediment type for disposal may depend more on thermal properties, permeability, and other geotechnical properties than on its sorptive characteristics.

Investigations were started during 1977 to evaluate the full matrix of equilibrium sorption distribution coefficients for the suite of waste radionuclides. These data are needed so that critical engineering parameters in the models can be evaluated for anticipated conditions. This work is being pursued using a sample of "typical" smectite clay from GPC-2. Initial experiments have been conducted at 4° C and 11° C as well as ambient laboratory pressure. Some of the preliminary results are as follow:

- Distribution coefficients were evaluated for Cs, Rb, Sr, Ba, Ag, and Cd at concentrations from 10^{-3} to 3×10^{-6} molar and were generally found to be of the order of 100 ml/g. Coefficients for Cs and Ba were also evaluated at nuclide concentrations from 3×10^{-7} to 10^{-10} molar and found to be of the order of 10^{4} ml/g (Appendix J).

- Coefficients for Cs appear to be little affected by pH in the range of 2.7 to 8 for all concentrations studied. However, coefficients for Ba at pH 2.6 and concentrations of 10^{-5} molar and less were of the order of 3×10^{2} ml/g (Appendix J).

- Work with solutions containing both Cs and Ba indicates that the sorption of either species may not be affected by the presence of the other when the concentration of each is between 10^{-3} and 3×10^{-6} molar or when the concentration of each is less than 3×10^{-7} molar (Appendix J).

- Coefficients evaluated for Ce, Pm, Gd, and Eu ranged from 10 to 10^{5} ml/g as concentrations varied from 10^{-2} to 10^{-11} molar (Appendix J).

- Coefficients for Eu, Ce, and Gd appear to be little affected by pH in the range of 6 to 8 for concentrations of 10^{-2} to 10^{-9} molar. However, coefficients for Eu were only of the order of 20 ml/g at pH of 2.7 for a concentration of 2×10^{-6} molar (Appendix J).

Extensive work is planned for 1978 to [illegible]. As equipment is made available, experiments will be done with many other waste constituents at low temperatures and ambient pressure, and studies will be extended up to 300° C and 9000 psi. Details of planned activities are given in Appendix J.

Figure 12 summarizes some results obtained through 1977 from experiments carried out with single-element additions to a 0.68N or 0.7N NaCl solution at low temperatures.

Understanding the response of sediments to heat generated by a waste container is another complex problem. However, waste heat appears to be a problem that can have more than one solution and, in the end, may be ameliorated by "tuning" the disposal system through alteration of waste concentrations, aging prior to disposal, nuclide partitioning, developing a container that will outlast several half-lives of the waste heat, or some combination of these.

Thermal studies during the past year included analytical modeling activities, laboratory experiments, and first steps in the development of a field experiment. The analytical work was divided into three major efforts: (1) thermal conduction models, (2) thermally induced convection (closed-form models), and (3) thermal convection (numerical models).

- It has been shown[3] that it is possible to decouple the momentum and energy conservation relationships and obtain the resulting temperature field for the generic clay sediments being investigated. Because of extremely low interstitial water velocity, thermal conduction models should be valid as long as instability mechanisms do not short-circuit the sediment barrier (Appendix K).

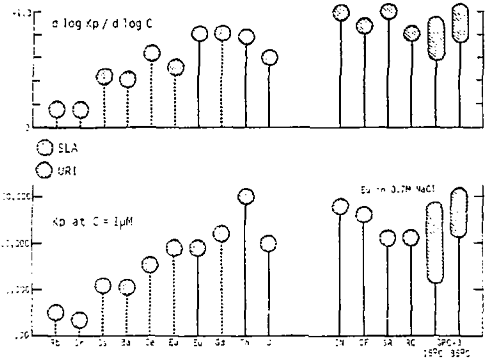

Figure 12. Summary of sorption data (partition coefficients at 1 micromolar cation concentration in solution and concentration dependence of partition coefficients) obtained at Sandia Laboratories (SLA) and University of Rhode Island (URI). The individual element work used a pelagic clay from the MPG-I area (core LL44-GPC2, 30° 20.9'N, 157° 50.85'W) and a matrix solution of 0.7M NaCl. For the lithologic variability experiments, the sediments used were: CN = North Pacific nanofossil ooze from 7° 36.7'N, 134° 1.2'E; CF = equatorial Pacific foraminiferal ooze from 0° 52.5'N, 160° 56.6'E; SR = North Pacific radiolarian ooze from 14° 13'N, 146° 24'W; and RC = South Pacific pelagic ("red") clay from 7° 20.6'S, 168° 20.8'W.

- To date, constant properties -- both thermal and transport -- have been assumed in analytical work on conduction modeling. Temperature-dependent properties can be accounted for in the numerical models once the thermal behavior of the sediments is known. Details of the conduction models are given in Reference 5 and Appendix K.
- Closed-form models for saturated porous media now exist for (1) the convective field surrounding a point or a spherical heat source in an unbounded medium, (2) a boundary point source below a semi-infinite medium, and (3) a point source below a constant-temperature interface (Appendix K).
- Using the closed-form model for a 1.0-kW point source and a 1/t relationship for radioactive decay, it is estimated that the maximum vertical displacement of a water molecule will be no more than 35 cm in 1000 years (Appendix K).
- By means of numerical models, some work has been done in evaluating the pressure increase that would result from a localized heat source in the sediments. Calculations for a 2-kW heater with a length-to-diameter ratio of 4 and buried at a depth of 6 m resulted in a maximum pressure increase

near the heater of 0.1 atm at 5 days. At 95 days, the pressure dropped to 0.05 atm, and at 300 days, to 0.02 atm. For comparison, the hydrostatic head over the 6-m burial depth is 0.6 atm (Appendix F).

Laboratory thermal work during 1977 was largely limited to a few small scoping activities and preparation for future experiments. These activities are discussed in Appendixes H and F.

Planning for a major thermal-properties field experiment was initiated during 1977. This would be an in-situ heat transfer experiment (ISHTE). ISHTE is a test which may require more than one [illegible] of thermal processes and material properties, and is not intended to be a simulation of an emplaced waste container. Details of the experiment were [illegible] at the end of 1977. [illegible] experiment [illegible] requirements, [illegible] are given in Appendix [illegible].

Movement of emplaced waste canisters as a result of long-term sediment creep deformation has been postulated as a possible mechanism for breaching the sediment barrier. Density differences that result from heating the sediment produce buoyant forces within the sediment, and convective cells capable of upward transportation of canisters could be formed. Thermomechanical analyses that include both creep deformation of the sediment and heat transfer within the canister-sediment system have been performed to evaluate possible [illegible] produced by the buoyant forces.

While the need for creep data in sediment characterization is clearly [illegible] recognized, a demonstration of the capability of the analytical models and some scoping calculations based on assumed parameters have been performed as an initial investigation of the potential buoyancy problem. A description of the model, the need for creep data, and a discussion of the scoping calculation results are given in Appendix M.

NUCLIDE MIGRATION -- ACCIDENTAL RELEASE MODE

While the conclusion has been reached that the placement of wastes, even in canisters, within the water column is ill-advised[1] and that the water column should not be considered as a containment medium or as a primary barrier to the migration of waste ions,[2] there is ample justification for further study of the water column and the benthic boundary layer. The processes of the water column and the benthic region must be understood before the problems of transportation, safety, and environmental impact can be addressed.

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

Extensive discussions of the deep ocean currents of the central North Pacific, the potential mobilization of wastes by benthic fauna, and the developing interest in deep-sea amphipods have been presented in previous annual reports.[2,3,4]

The critical problem being addressed concerns the potential pathways and rates of transfer back to man of radionuclides accidentally introduced into the benthic region. The magnitude of potential pathways is a function of the standing crop of benthic organisms, their rate of activity, their mobility, the nature of their interactions with other organisms, and their interaction with specific radionuclides likely to be released. By looking at the suite of organisms making up the benthic community, i.e., microbiota, meiofauna, macrofauna, and mobile, [illegible] organisms, with special attention devoted to mobile, [illegible] [illegible], information needed to evaluate the potential role of organisms in the transport of radioactive wastes is beginning to be obtained. The complexity of this problem can be appreciated when one considers that the introduction of radionuclides into the benthic region via 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.

While this portion of the program was only minimally funded during 1977, a variety of research activities were conducted which addressed the biological characterization of the benthic region, chemical response of the benthic region to radionuclide input, and potential transfer pathways in the biological system. The results and conclusions of these studies will aid in the development of a model for nuclide transport in marine ecosystems (see "System Development and Analysis"). A summary of results from some of the research activities follows:

- Large numbers of amphipods have been captured from the MPG-I area by free-vehicle trapping. Initial work of determining species composition and separating the amphipods into species groups has been accomplished (Appendix N).
- Amphipods have been trapped from near the sediment/water interface to as high as 30 m in the water column. Preliminary indications are that the mean size of trapped individuals increases directly with height above the sediment (Appendix N).
- This evidence for a semi-pelagic mode of life for amphipods lends importance to two potential ways of transporting radionuclides off the bottom: (1) excretion by amphipods of metabolic waste products into the water column and (2) the possibility that highly mobile amphipods could combine bottom foraging with swimming up into the water column to feed and be eaten themselves by wider-ranging organisms (Appendix N).

- One of the primary reasons for studying MPG-I is the assumption that it is representative of mid-plate/mid-gyre regions. While amphipods have not been trapped for these studies in other mid-gyre regions, the ubiquity of amphipods is shown by successful trapping efforts on abyssal plains and trenches of the Pacific and in the North Atlantic (Appendix N).

- Amphipods from the MPG-I study area have been successfully recovered from 5700-m depths and returned to the laboratory in a live condition for visual observation and analyses (Appendix O.)

- A successful mark-and-capture experiment has been conducted in the central North Pacific. A labeled bait drop resulted in the capture of an amphipod containing the labeled bait 7 nautical miles away less than 21 hours later (Appendix N).

- Extensive studies are underway to establish suitable tagging techniques (both stains and radionuclide tracers) to press forward investigations of possible biological mobility and transport of radionuclides (Appendix N).

- It has been suggested that lipid-containing particles rising to the surface from the deep benthos could rapidly transport matter through the water column. Benthic amphipods contain large amounts of lipid. The ascent rates of buoyant lipid particles ranging in size from 0.005 to 0.02 cm in radius and with densities ranging from 0.9 to 1.0 g/cm are calculated to range from a week to several hundred days (Appendix O).

- Respiration rates of deep-sea amphipods have been successfully measured in situ. An active rate comparable to that of shallow-water amphipods and a resting rate two to three orders of magnitude lower were observed. These rates seem to be associated with periods of food searching and dormancy. Such rapid respiration rates by a ubiquitous abyssal species suggest that transfer rates of food or radionuclides may be more rapid than previously suggested (Appendix P).

- Catches of two significant species of abyssopelagic animals were made in the central and eastern North Pacific using a newly developed free-vehicle gill net, baited trap, and hook system. The cosmopolitan abyssobenthic rat-tail was caught at depths ranging from 50 to 750 m above the bottom (3800 to 5700 m) and represents the first capture of this species in midwater. Scavenging amphipods were trapped 400 m above the abyssal floor in the MPG-I study area. The presence of either of these animals in midwater, along with gut-content analyses, suggests an active two-way exchange of food energy between abyssopelagic and benthic communities (Appendix P).

- Studies of the species and spatial structures of zooplankton in the upper 500 m of the central North Pacific gyre show strong trends in both structures. The observed constancy in the proportions of the species and their vertical patterns over long periods of time (seasons, years, and decades) suggests a strongly regulated system. Some of the species should be good candidates for studies of pollutant concentration factors and transfer rates (Appendix Q).

Cruise reports covering two field operations undertaken during 1977 in support of some of the above research activities are given in Appendix R.

Initial steps to develop a plan for a major field experiment to address mobilization and transfer of radionuclides in the benthic region and in the water column were taken in 1977. This is an in-situ biological experiment (ISBE) and details have not been developed. A preliminary meeting, held to discuss the possible scope and objectives of the ISBE, is reported in Appendix S.

The chemistry of fallout nuclides and their dispersion and redistribution on earth has been the object of ongoing studies reported previously.[2,4] 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 be able 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 disposal of low-level solid wastes, both in the Atlantic and the Pacific, are given in Appendix T.

Studies of the oceanic distributions of radionuclides from nuclear weapon testing are discussed in References 2 and 4 and in Appendix T. A summary of the relevance of water column fallout data to the problem of marine radioactive waste disposal follows:

- Regional patterns of delivery of soluble radionuclides must be assumed to persist for at least decades, despite the homogenizing action of ocean current systems (Appendix T).
- Although there are delays governed by density discontinuities in the water column, particle-associated radionuclides are generally delivered directly to the sediment surface (Appendix T).
- The chemistry of particle association appears increasingly complex, in relation both to element selectivity among kinds of particles and the stability of the associations once formed (Appendix T).
- Regional conditions may lead to retention of Pu, and possibly other nuclides, in discrete layers or throughout the water column, despite its general tendency to associate with particles (Appendix T).

EMPLACEMENT

Knowledge of the deformations of seabed sediments not only during emplacement of waste canisters 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 emplaced waste container. Analytical and laboratory efforts to obtain the necessary knowledge are being conducted.

Development of analytical capabilities required to predict rates of hole closure following emplacement continued during 1977. Both one-material and two-material models of sediment behavior are being studied to determine their ranges of applicability. The one-material models, which consider the sediment and pore water as a single homogeneous substance, are being evaluated for making sediment deformation predictions after relatively rapid waste emplacement. The two-material models provide for description of both sediment skeleton deformations and pore-water movement. The need to use models with both fluid and sediment descriptions arises for processes in which significant dissipation of pore-water pressures can occur in the time frame of the deformations (Appendix M).

- One-dimensional hole closure analyses were performed to investigate the effect of using different material models on the predicted rebound of cavities formed during canister penetration. Elastoplastic models have been used to represent sediment behavior. Using these models, variations in elastic moduli, yield surface, and strain hardening characteristics were considered. The analyses indicated that it will be important to determine both the yield surface shape and the degree to which saturated sediments appear to strain harden (Appendix M).
- Two-dimensional calculations were initiated which can include the effects of shear deformations that occur as a canister passes through the sediment. Although the computations are incomplete preliminary results indicate that the shear layer that develops near the canister may strongly influence the magnitude of rebound seen immediately following emplacement. Also, as in the one-dimensional model, the effects of varying material model parameters are being studied to determine which are most influential (Appendix M).
- The degree to which the generation of excess pore pressure and dissipation of this pressure through pore-water flow affects deformations of the sediment skeleton is being studied. Articles have been reviewed that address methods of analyzing the coupled movement of the sediment skeleton and the dissipation of excess pore pressure. None of the articles reviewed to date, however, includes inertia and compressibility of system constituents. Possible implementation of a model that includes these features is under study (Appendix M).

Further development of laboratory capabilities to obtain necessary hole closure data is reported in Appendix H.

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, a part of the effort and of the available funds of the program has been directed toward the development of needed instrumentation and sampling techniques and equipment. Numerous development efforts are listed below and the reader is referred to appropriate appendices for details.

- A new version of a large-diameter gravity corer has been successfully field tested and will be used during 1978 cruise operations (Appendix H).
- An engineering workshop on deep sea coring was held to assess existing technologies for the recovery of long undisturbed sediment cores, to determine the most effective means of sample recovery, and to recommend a course of action for future development (Appendix H).
- A high-temperature (350° C) high-pressure (6000 psi) autoclave laboratory suitable for handling marine sediments and to be used in evaluating corrosion properties of canister materials has been constructed (Appendix I).
- Autoclaves have been designed and are being constructed for operation in gloveboxes to allow sorption experiments with actinide elements to be conducted at temperatures up to 300° C and pressures to 9000 psi (Appendix J).
- A significant effort is underway to develop a suitable technique to mark and recapture selected components of the deep-water biological system to evaluate rates and pathways of radionuclide transfer (Appendix K).
- A quick and simple method for the preparation of sterile silica-gel-based media for the cultivation of bacteria under hydrostatic pressure and low temperature has been developed (Appendix O).
- A free-vehicle grab respirometer for in-situ measurements of benthic community metabolism has been developed and successfully tested in the deep ocean (Appendix P).
- A free-vehicle midwater net and trap system for catching deep midwater animals not taken by towed nets has been developed and successfully tested in deep water (Appendix P).
- A specialized chamber for culturing and sampling anaerobic or aerobic bacteria has been designed. The versatile all-glass chamber incorporates a wide spectrum of features: selected atmospheric conditions, homogeneous cell suspension, continuous gassing, rapid sampling with minimal atmospheric exposure, and turbidimetric measurements (Appendix T).
- A deep-ocean conductivity, temperature, depth (CTD) measuring instrument has been detailed in previous annual reports.[2,3,4] A status update on the instrument is given in Appendix U.
- Numerous investigations into the wide array of instrumentation and equipment developments required for the planned in-situ heat transfer experiment are discussed in Appendix U.

SECTION 4

INTERNATIONAL AND LEGAL/POLITICAL ASPECTS

The radioactive waste disposal programs of most countries are focused on investigation of land-based geologic formations as possible waste containment media. However, over the past few years, several countries have initiated programs to investigate the possibilities of using the geologic formations in the sub-seafloor for the disposal of HLW. Aside from the various technical advantages and disadvantages involved, use of the international seabed for radioactive waste disposal raises a multitude of social, economic, political, legal, institutional, and ethical issues.

The technical aspects of seabed HLW disposal are being addressed on an international level via a series of international workshops. The results of the first of these workshops are discussed in References 3 and 6.

An international Seabed Working Group was created at the meeting of the Second International Workshop on Seabed Disposal of Radioactive Waste held March 1 to 3, 1977, in Washington DC. At the end of 1977, membership included representatives from France, Japan, the United Kingdom, and the U.S. The goals of the SWG are

1. To provide a forum for discussion, exchange of information, assessment of progress, and planning of future efforts,
2. To encourage and coordinate cooperative research vessel cruises and experiments,
3. To share important facilities and test equipment, and
4. To maintain cognizance of international policy issues.

To facilitate accomplishment of these goals, the SWG is divided into seven Task Groups and an Executive Committee. The Task Groups are made up of individuals from participating countries and are organized to address the specific areas of system analysis, physical oceanography, waste form development, canister development, biology, sediment and rock, and site selection.

A report to the NEA Radioactive Waste Management Committee on the second international workshop is given in Appendix A. Late in 1977, arrangements were being made for a third international workshop to be held in February 1978.

Early reactions to seabed disposal range from assertions that any country should be permitted to use the deep seabed for waste disposal to the conviction that under no circumstances should use of the international seabed for radioactive waste disposal be permitted. Detailed preliminary study of the concept reveals a complex and evolving picture. Since almost everyone reacts negatively at first to use of the sub-seafloor for HLW disposal and almost everyone confuses the distinct concepts of disposal in the oceans, on the seabed, and in the seabed, it is not yet clear what the legal and political future of the concept is to be. Implementation of HLW disposal in the deep seabed 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 Seabed Disposal Program, research continued in 1977 in looking at (1) national and international legal issues, and (2) national and international political issues. Results of these activities are discussed in Appendix V. Some results and conclusions follow:

- At this time, national and international policies are clearly inadequate to implement a rational sub-seabed disposal program for radioactive waste. Research on nuclear waste disposal possibilities is far enough advanced to justify at least a serious attempt at the delineation of policy priorities and decision criteria. Even in the U.S., however, few policymakers comprehend the waste disposal problem in general, let alone possess a balanced understanding of each disposal possibility (Appendix V).
- Governments must politically evaluate sub-seabed disposal in the context of all available possibilities for managing nuclear wastes. Countries will offer real support only if sub-seabed disposal is considered necessary for national wastes, industries, or other clear interests (Appendix V).
- Assuming technical feasibility, it is still too early to determine the political feasibility of burying HLW within the deep seabed. Although early foreign and international political responses will influence U.S. policy, the most important initial decisions must come from the U.S. Whether or not American support of sub-seabed disposal will influence other nations will depend upon future law-of-the-sea, general nuclear policy, and nuclear nonproliferation efforts. Pending the development of national and international policy on whether, where, and how long spent nuclear fuel will be stored and/or reprocessed, it is possible to state only that sub-seabed disposal does not seem to be ruled out--for now--on political grounds (Appendix V).
- Undoubtedly, this is an area of scientific and technological development where the final decision, as well as many of the interim ones, must be based upon policy considerations. At a minimum, careful and comprehensive political management is required; prevention, through policy and law, could also prove necessary. If decisions are made, by default or otherwise, to keep the sub-seabed option open, early consultations with a large number of governments and agencies will be essential. If such consultation is neglected, the result may be a sub-seabed disposal option that is technically acceptable but politically unworkable. The political response itself will be largely determined by the extent to which appropriate institutional arrangements are available as development progresses (Appendix V).

- As long as countries continue serious research and development on the sub-seabed disposal concept, a significant component of their efforts must be devoted to research on the associated social, economic, political, legal, institutional, and ethical considerations (Appendix V).

SECTION 5

STATUS

During the first year of this program, 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 HLW.

Program emphasis during the second year shifted from the water column to the characterization of mid-plate, mid-gyre 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 mid-plate/mid-gyre 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 MPG-I 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 first-hand 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 part of these data indicates long-term stability of the region and has 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 has shown a high affinity of the clays for the ions, suggesting very favorable ion-exchange properties for the deep-sea sediments.

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 inter-*national Seabed Working Group.

The attention of the program has been focused on the waste form and canister for short-term containment and on the sediments for long-term containment. Data thus far suggest that the normally slow diffusion of waste elements through the highly impermeable deep-sea clay is further reduced many times by the sorptive properties of the clay. Similarly, the low permeability of the clay strongly inhibits thermally driven convection of pore water. These preliminary results from the sorption and thermal studies encourage optimism, but further extensive validation is required.

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

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