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Nuclear Waste Disposal in Subseabed Geologic Formations: the Seabed Disposal Program

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NUCLEAR WASTE DISPOSAL IN SUBSEABED GEOLOGIC FORMATIONS: THE SEABED DISPOSAL PROGRAM

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ABSTRACT

The goal of the Seabed Disposal Program is to assess the technical and environmental feasibility of using geologic formations under the sea floor for the disposal of processed high-level radioactive wastes or repackaged spent reactor fuel. Studies are focused on the abyssal hill regions of the sea floors in the middle of tectonic plates and under massive surface current gyres. The red-clay sediments here are from 50 to 100 meters thick, are continuously depositional (without periods of erosion), and have been geologically and climatologically stable for millions of years. Mineral deposits and biological activity are minimal, and bottom currents are weak and variable. Five years of research have revealed no technological reason why nuclear waste disposal in these areas would be impractical. However, scientific assessment is not complete. Also, legal, political, and sociological factors may well become the governing elements in such use of international waters. These factors are being examined as part of the work of the Seabed Working Group, an international adjunct of the Seabed Program, with members from France, England, Japan, Canada, and the United States.

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NUCLEAR WASTE DISPOSAL IN SUBSEABED GEOLOGIC FORMATIONS: THE SEABED DISPOSAL PROGRAM

Introduction

The Seabed Disposal Program has been under way since 1973 with the primary goal of assessing the technical and environmental feasibility of disposing of high-level nuclear wastes in the geologic formations under the world's oceans.[1] The total area considered represents about 70% of the surface of the planet (of which less than 0.0001% would be used) and contains a wide variety of geologic formations. Theoretically, all wastes from the once-through, uranium-only, and uranium-plutonium recycle options could be emplaced in subsea formations but, because of implantation costs due to large volumes, other methods may be more practicable for low-level and TRU wastes. The program's secondary goal is to develop and maintain a capability to assess the nuclear waste disposal options of other nations.

The seabed program is divided into four phases:

1. Investigation of technical and environmental feasibility on the basis of historical data
2. Determination of technical and environmental feasibility on the basis of historical and newly acquired oceanographic and effects data
3. Determination of engineering feasibility
4. Demonstration of capability.

Although the program is just in the second phase, a reference system is needed for study purposes and to simplify explanation, even though that system may have to be altered as additional information is acquired later.

The reference system is the emplacement of appropriately treated waste or spent reactor fuel in a specially designed container into the red clay sediments in the middle of a North Pacific tectonic plate, under the hub of a surface circular water mass called a gyre (midplate/gyre:MPG). (However, selection of the North Pacific as a study area in no way implies its selection as a candidate seabed disposal site.)

Use of a penetrometer* is the reference method for emplacing wastes in the sediments in a controlled and monitorable manner. A specially designed surface ship will transport waste

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*A penetrometer is a projectile which, when dropped from a height, penetrates a target material. It can carry a payload of nuclear waste and instruments designed to measure and transmit its final position and orientation relative to the sediment surface. Penetration depth is controlled by the shape and weight of the penetrometer, its momentum at contact with the sediment, and the mechanical properties of the sediment.

from a port facility to the disposal site and emplace the waste containers in the sediment. A monitor ship, which will have completely surveyed the disposal site before operations begin, will determine the locations and monitor the behavior of individual disposal containers for appropriate lengths of time, and will maintain an ongoing survey of the surrounding environment.

Since the areas under consideration are in international waters, one goal (to start only after demonstration of technical and environmental feasibility) will be to aid in solving national and international legal and political problems so that an area could be used for disposal if such use were feasible from an engineering standpoint.

An international seabed study group, now made up of representatives from England, France, Japan, Canada, and the United States, has been meeting annually since 1975 to discuss technical problems concerned with ocean biology, the sediments, subsediment basaltic rocks, the waste form, the canister, physical oceanography, site selection, and system analysis.

Advantages and Disadvantages of the Subseabed Geologic Disposal Concept

Major potential advantages of nuclear waste disposal in a carefully selected area of the subseabed are:

- Ability to make long-term predictions of stability and uniformity on the basis of samples of sediments that have been accumulating continuously for 70 million years
- Lack of resources in the areas of interest, reducing likelihood of human intrusion or future resource conflicts in the disposal area.
- Plastic nature of the sediments, which will allow closure of any openings, man-made or natural
- Low-permeability and high-sorption qualities of the sediments
- Continuously depositional nature of the sediments, eliminating the risk of erosion down to or including buried wastes
- Large size of the areas of interest, of which approximately 0.006% would be used for waste disposal
- Remoteness of the areas of interest from normal human activities
- Lack of need for mining activities or waste-handling facilities at the site
- Lack of need to resolve questions about federal-state relations and authority over disposal sites.

Major potential disadvantages are:

- Requirement for at least acquiescence by foreign governments and international agencies before the program can proceed beyond the demonstration phase
- Requirement for dock and ocean transportation facilities not now available
- Need for a special canister and waste form or overpack for spent fuel

Criteria for Selection of Study Areas and Specific Disposal Sites

Deep ocean floor areas that would be acceptable for waste disposal should have certain characteristics:

- *Tectonic Stability. They should be areas of* low earthquake or volcanic activity, with minimum evidence of faulting, and characterized by slow, continuous depositional processes.
- Climatic Stability. Combined movements of the two mobile media (air and water), including changes in climate (e. g., ice ages), should have minimal effect on the underlying geological formation.
- Absence of Resources. There should be low biological activity*, both present and past, and few or no mineral resources of use to man.
- Remoteness from Man's Activities. The areas should be remote from and as inaccessible as possible to man. The ocean floors are among the most remote regions on earth. To enter these areas requires technical sophistication and a large, planned effort. The risks of intrusion upon a subseabed disposal site by less sophisticated cultures would be quite low.
- Predictability. To be suitable for emplacement of long-lived toxic materials, a geologic medium must be predictable, both in respect to anticipated changes in its properties with time, and in respect to the broad horizontal and vertical applicability of local measurements of these properties. The more predictable *and uniform the geologic environment, the less detailed the specific site studies* must be to determine the properties of the geologic formation. Oceanic areas where processes are slow and continuously depositional, and where tectonic processes have been and are predicted to be minimal for millions of years, are the most uniform and predictable on the globe.

Description of Ocean Regimes

The ocean floor comprises three principal regions, each occupying about a third of the total ocean:

- Continental margins
- Midoceanic ridges
- Ocean basin floors.

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*There are large areas under the seas which are the marine equivalent of deserts. These areas have been stable for millions of years; their biological processes are governed, not by lack of water *as on continental deserts, but by the absence of critical nutrients* (nitrates and phosphates) and light, which is essential for photosynthesis.

The continental margin is one of the most dynamic ocean environments, with wide seasonal changes in water temperature, variable chemical and biological processes, and complex and unpredictable geological structures. Here lie most of the remaining unexploited pools of hydrocarbons as well as most of the world's great fishing grounds. Sediment accumulation is rapid, and this, combined with the relatively steep margin slopes, provides conditions for frequent catastrophic sediment failure (slumping, turbidity currents, etc). This region is therefore unsuitable for consideration as a possible waste disposal site.

The midocean ridge region surrounds the hot, seismically active rift (fault-bounded) valley where new crust is continually extruded. The outer flanks of the ridge slope imperceptibly to the ocean basin floor, which includes the flat abyssal plains, the gently rolling abyssal hills, and the deepest parts of the oceans, the deep-sea trenches.

Fracture zones in the midocean ridge have been suggested as possible waste disposal sites. Such proposals do not take into account the high seismic activity of this region, the rapid chemical changes, the lack of sorptive media, the channeling effects of current flow, the limited area of these zones, and the lack of horizontal and vertical uniformity and predictability. On the basis of present knowledge, therefore, the fracture zones are not probable candidates as study sites.

The abyssal plains contain widespread deposits of coarse continental debris swept there by sporadic rapid (several metres per second) underwater avalanches or turbidity currents, and are therefore unacceptable for further consideration.

The abyssal hills, which occasionally form broad low swells (midocean rises), lie seaward of the abyssal plains and are old ocean crust originally formed by extrusions and faulting of the basalt from the midocean ridge spreading centers. These vast abyssal-hill provinces (areas of gently sloping hills make up most of the deep sea floor of the North Pacific) are generally covered with 50 to 100 m of red clay. The abyssal hills and rises that occur in the middle of the subocean tectonic plates are seismically passive. Where they also occur below the centers of wind-driven, surface-current gyres (large, circular water-flow systems), they are stable and relatively unproductive biologically. Bottom currents in the mid-plate gyre (MPG) areas of the North Pacific are generally weak and variable. For all these reasons, the abyssal hills appear the most promising for seabed disposal and are identified for purposes of this study as the reference seabed area.

The dynamic deep-sea trenches often form the landward boundaries of abyssal hills at the collision zones between crustal plates, especially in the Pacific. In such trenches the ocean crust is being over-ridden by lighter crustal rock at rates of 2 to 6 cm/yr, with attendant crustal destruction. This process, called subduction, is accompanied by massive volcanism. In some cases, portions of a crustal plate being bent downward into the mantle have been uplifted, sometimes high above sea level.[2] Many high-intensity earthquakes occur in or near these subduction zones, triggering massive submarine slides. Trenches on portions of the Pacific Ocean's periphery are some of the most geologically dynamic regions on the plant. It has been proposed that nuclear wastes be placed in the trenches, at the edges of plates being subducted, so that wastes would be carried under the earth during the subduction process. However, even though the time needed to contain the wastes is long by man's standards (250 to 500 thousand years), a plate being subducted would have moved only tens of kilometers during that time and would not be subducted fast enough for waste disposal purposes. These seismically active trenches are the least desirable of the four regimes for nuclear waste disposal.

Waste-disposal-related factors for the oceanic regions are summarized in Table I.

TABLE I

Comparison of Major Oceanic Regimes

	Control	Geologic Stability	Environmental Stability	Resources	Biological Productivity	Accessibility	[illegible]	[illegible]
Continental Margin								
Shelf	1	Very low	Very low	Very high	High	Very high	[illegible]	< 20
Slope	1	Very low	Low	Medium	Medium	Medium	[illegible]	< 20
Rise	4	Medium	Low	Medium	Low	Low	20	< 10
Deltas and fans	4	Very low	Low	High	High	Medium	5-10	< 10
Midocean Ridge								
Fracture zone	2	Low-high	Low-high	Low	High	Low-very low	Small	[illegible]
Crest	1	Low		Low		Medium-high	Small	0-0.1
Rift valley	2	Very low		Low		Medium	Small	0
Flanks	3	High	High	Very low	Low	Low-very low	[illegible]	[illegible]
Ocean Basin Floors								
Abyssal hills (midplate)	[illegible]	High	High	Very low	Very low	Very low	[illegible]	[illegible]
Abyssal plains	4	Low	[illegible]	Medium	Very low	Very low	[illegible]	[illegible]
Seamounts	2	[illegible]	[illegible]	Low		Very high	[illegible]	[illegible]
Trenches	4	Very low	Low	Very low	[illegible]	Very low	[illegible]	[illegible]

Controls: 1 = None; 2, 3 = Intermediate; 4 = Best

[illegible]

The Multibarrier* Concept of Radionuclide Containment

Seabed nuclear-waste disposal is treated as a multiple-barrier assessment problem. A formalism based on a set of sequential barriers to the release of radioactive nuclides has been adopted to balance the rates of decay of waste constituents against the rates of migration of the nuclides toward man. These barriers are 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 benthic boundary layer and the water column are the dilutional barriers, and any environmental impact evaluation should include these two regimes.

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*A barrier is defined as a quantifiable passive-delay mechanism to the movement of radionuclides, allowing time for decay to make the waste less harmful or ultimately harmless.

The major task is to determine whether any submarine geologic formation can contain radioactive waste long enough for it to decay to innocuous levels. Attention is now focused on the waste form and the canister for containment during the period of high heat release (30 to 100 years) (near-field interactions), and on the sediments for long-term (10^2-10^5 years) containment (far-field transport).

Since the required waste isolation time is much longer than can be simulated in manmade experiments, the attributes of each component of the system must be adequately known so that a credible prediction of barrier system effectiveness can be made. This effectiveness can best be judged by the use of suitably substantiated models. These will be used to characterize subsystems and to permit parametric studies and sensitivity analyses to be conducted.

Near-Field Interactions -- Nuclide movement through the sediment is controlled by natural or induced pore-water movement, by diffusion due to concentration and/or temperature gradients, and by the natural or modified chemical properties of the sediment. During the first 100 yr after waste emplacement, the fission-product-dominated thermal output may induce much larger pore-water velocities than those naturally present. Performance of the canister and waste form will also be important during that period. In addition, any chemical, mechanical, or thermal changes caused by heating of the sediments will be of critical importance to the integrity of the primary sediment barrier and to the predictability of containment. The entire influence of heat on the sediment barrier must be identified, described, and experimentally verified. A specific problem is the "buoyancy" effect, wherein heat from the wastes may cause a volume change in the sediment-water mixture, with a risk that the canister may sink through the clays toward the basaltic basement rocks, or that the heated sediment may rise toward the water column.

After the main thermal problems are identified and quantified, the initial thermal output of the canister can be controlled by dilution and/or aging of the wastes and by modifications of canister size.

Far-Field Ion Transport -- The plastic seabed sediments are considered the primary long-term geologic barrier to the migration of radionuclides back to man. These sediments typically consist of fine-grained (2μ), water-saturated clays with low permeabilities ($\sim 10^{-7}$ cm/s) as measured in the laboratory. The only known natural driving force for pore-water movement within the sediments in the abyssal hill region is sediment compaction, which occurs at rates of 1-3 mm/10^3 yr. Existing permeability data suggest that this natural pore-water velocity is in the same range as the rate of sediment accumulation ($\sim$1 m/10^6 yr).

Migration of radionuclides from a point of emplacement in the subseafloor sediments could occur through a combination of diffusion and advection. Models are required by which the rates of nuclide migration from the point of emplacement toward the biosphere can be reliably predicted. To develop the necessary models to address the ion-transport problem, the dominant mechanisms for nuclide sorption and migration must be adequately identified, quantitatively described, and experimentally verified.

The effect of sorption properties on long-term radionuclide transport is shown in Table II. These calculations, using a transport model developed by Burkholder,[3] are based on a pore-water velocity of 10^{-1} m/yr (a factor of 10^5 over the estimated natural pore-water velocity), a 30-m sediment column, and estimated sorption coefficients. The results indicate containment for about a million years for radionuclides with a sorption coefficient of 50,000.

TABLE II

Initial Calculations of Long-Term Radionuclide Transport Produced by Possible Pore-Water Movement[a]

Ion	Estimated Sorption Coefficient	Assumed Water Velocity (m/yr)[b]	Exit Time of Peak (yr)	Exit Time of 1% of Peak (yr)	Half-Life (yr)
^{242}Pu	50,000	0.1	15×10^6	14×10^6	3.9×10^5
^{230}Th	50,000	0.1	1.1×10^6	7×10^5	7.4×10^4
^{137}Cs	20	0.1	Not released	Not released	30

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[a] Assume: Homogeneous sediment column = 30 m
Total solubilities of waste forms = 333 yr
No effects from heat, chemical gradients, competitive ions, or dispersion.

[b] Sedimentation rate = 1 m/10^6 yr

For another set of assumptions, where there is no natural pore-water movement, no interactions between dissolved nuclides and the sediment, a diffusion constant of 3×10^{-6} cm^2/yr, and a burial depth of 100 m, breakthrough time is about a million years. For the same assumption with sorption by the seabed sediment, as indicated in Reference 4 (K_d of between 10^2 and 10^5), breakthrough times are 10^8 and 10^{11} years. The dependence of sorptive coefficients on temperature, concentration, and the presence of competing ions is poorly known, but preliminary data indicate that, at least for thorium, elevated temperatures and the low nuclide concentrations likely around a waste canister lead to higher sorption coefficients, and hence to longer breakthrough times. Preliminary assessment of the barrier properties of the seabed sediments indicates that the sediments may be an adequate barrier.

Water Column -- Another potential barrier to the migration of radionuclides from subsea geologic formations to man is the water column. Some of the water at the bottom of the ocean basins is believed to have been at those great depths for thousands of years, and is thought to move in a very slow, uniform, plate-like manner. The age of these deep water masses, and their horizontal and vertical advection and dispersion characteristics, need to be known (1) to allow estimates of the barrier properties of the water column and (2) to allow evaluation of benefits and consequences of dilution and dispersion of any radionuclides inadvertently released. Models must be developed to predict transport rates and concentrations for different repository locations and accident scenarios.

Also, the possible role of the biological community in transporting accidentally released radionuclides back to man must be determined. These studies must be for both deep and shallow-water organisms, in order that all release scenarios may be addressed (port facilities, transport to site, and emplacement). Somatic and genetic effects on biota must also be quantified.

Benthic Boundary Layer -- The benthic boundary layer (BBL), defined as the mixed layer ≈ 50 m above the sediment to the bottom of the bioturbated area ≈ 1 metre below the sediment/water interface, was found not to be a barrier to the migration of nuclides.

Basement Rocks -- Basaltic rock underlying the plastic sediments could be an additional barrier to migration of radionuclides back to man. The seabed program to date is only monitoring research supported by the National Science Foundation through the International Program of Ocean Drilling, and relevant work by oil companies on the structure and barrier properties of these rocks. If the sediments are found inadequate as barriers, the barrier qualities of the basement rocks will be assessed. This evaluation will include thermal, mechanical, and chemical responses of the rock to heat, radiation, and intrusion by man; the behavior of interstitial fluids, both natural and induced; the sorption and ion migration properties of the rock formations, and the selection of sites at which these parameters are optimized.

Waste Form -- Both repackaged spent fuel and processed HLW are considered. However, studies of packaging techniques and waste forms for both wastes must remain dormant until detailed information on the environment in which they must survive is acquired. Baseline characteristics for other sections of the program are the thermal, mechanical, and radiative properties of 10-year-old glassified (≈30% by weight radionuclide oxide) HLW in a geometry of 0.3 m dia. and 3 m long. Fuel elements could be repackaged in this "reference" canister, but will probably be packaged in different geometries. Since repackaged spent fuel rods contain fewer fission products than does a similar volume of processed HLW, the energy released in the first 300 years will be smaller, thus making the critical early-time containment problem easier. Sediments which are hot (over 200°C) and moist are known to be a very hostile environment for glass materials; therefore the main thrust is to protect the waste form in early years by use of a canister and by control of the surface temperature of the waste by either aging or decreasing the amount of radionuclides in the canister. Several options are available for reducing the thermal problem. Similar disposal technology could be used for low-level and TRU wastes; however, economics may make such a course impractical.

When the near-field environment has been characterized, a program will be initiated to design a waste form (if reprocessing is acceptable) or an overpack (for spent fuel) compatible with the sedimentary geologic environment. Possible criticality problems arising after disposal of spent fuel, and migration of fissionable material after canister and waste-form breachment, will be addressed when the necessary data are available.

Canister -- 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) compatibility of the canister with the external environment (either natural or modified); and (3) the mechanical integrity of the canister under the stresses of radiation, heat load, and the deep ocean environment. The expected lifetime will determine whether a canister will be useful only as part of a shipping container and emplacement package, or in addition will act as a barrier to the migration of radionuclides to man's immediate environment for some finite period.

For calculational purposes it is assumed that the canister and waste form will act only as temporary barriers and will cease to be effective shortly after emplacement. However it is hoped that a canister will be developed that would remain intact through the initial heat period (~300 years). The canister could be used either for spent fuel or for reprocessed HLW from the uranium and plutonium recycle option.

Emplacement

Sediment emplacement alternatives are shown in Figure 1. Data are not available that are needed to specify sediment types and emplacement depths for radionuclide containment over the periods required. Therefore only concepts for possible emplacement methods have been developed.

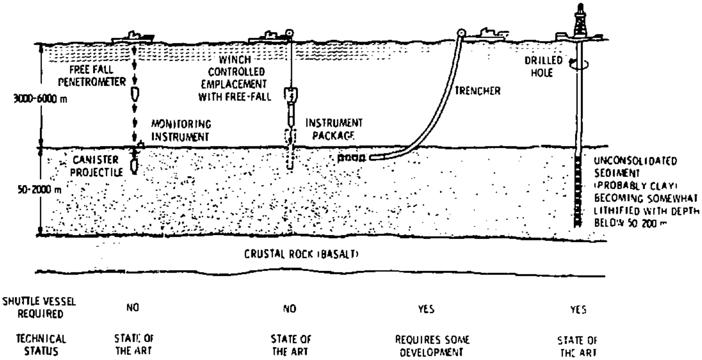

Figure 1. Sediment Emplacement Concepts for Seabed Isolation

The first two concepts illustrated in Figure 1 use penetrometers for waste emplacement in the sediments. In the first case, the penetrometer is released from the ship and guided to an emplacement location. In the second case the penetrometer is lowered by a cable to a predetermined depth and then released. These ship-launched penetrometer concepts place the fewest technical demands on the transport/emplacement vessel.

Present navigational techniques would allow guidance of the ship and the penetrometer to within metres of a desired spot. The winch-controlled penetrometer concept employs techniques in current use by marine geologists. Either penetrometer method could emplace waste to the same depth in the sediment since the winch-controlled penetrometer would be released at a height above the sediment sufficient to allow near-terminal-velocity free-fall impact. If additional sediment depth is needed, either concept could be modified to obtain higher velocity and deeper penetration.

Laboratory and field testing will be required to confirm the penetrometer emplacement concept.

The trenching concept, which may be feasible if a few meters of burial are adequate for containment, would require some engineering development. The basic techniques are similar to those used in deep-sea drilling and near-bottom survey systems, or the burial of oil and gas lines or cables. However, the ability to feed waste canisters to a slowly moving sub-bottom "plough" does not exist. Because of the time required to deploy or recover a trencher or "plough," it appears that this concept would require one vessel to carry the waste from land to the disposal area and another for actual emplacement.

Drilled-hole emplacement would use existing technology (D/V *Glomar Challenger*). Positioning capability is again within a few metres (as with the penetrometer). Because of the time required to drill each hole, this concept would probably require that many canisters be emplaced at each location. For efficiency a separate vessel would be required to carry waste to the disposal area.

The reference sediment emplacement method for this document is the penetrometer. This choice is based on preliminary data indicating self-induced hole closure following dynamic emplacement, the lack of need for a separate shuttle vessel, and the technical state-of-the-art of this emplacement alternative.

Assuming continued concept feasibility, engineering development of specific emplacement techniques will be required.

Transportation

It is assumed that solidified HLW or spent fuel will be transported by land to an embarkation port which is on an existing government facility. The need for waste storage at the port would depend on the scheduling of overland waste shipments and of the transport ship. Interim storage at the port could be in a water pool or in shipping casks, and is expected to last a maximum of a few months, during which time the canister will be fitted with penetrometer equipment.

After having been loaded on the combination transport/emplacement ship, the waste, packaged in a specially designed penetrometer container or overpack, would be transported to the disposal area by a route planned to minimize risks to the general population and environment and to avoid interference with ongoing marine activities (fishing, traffic in shipping lanes, etc). The waste would be cooled and shielded aboard ship using known methods.

Each canister's position in the sediments would be documented (for example, each canister might contain a simple passive interrogatable transponder). Monitoring techniques for the disposal area would be developed to insure that system performance is as predicted.

Retrievability

Retrievability has not been designed into the system (though obviously during the experimental period all emplaced radioactive material will be either retrieved or designed for retrievability). Waste canister recovery from any of the four emplacement schemes is possible with existing ocean engineering technology but is estimated to be costly. Relative ease and costs of retrieval for the four seabed emplacement options scale directly as the engineering costs and difficulty of emplacement.

Legal Issues and Political Problems

It is against U.S. law to dump HLW or spent fuel in the ocean. Internationally, the legality of dumping of HLW is much less clear. Since the seabed concept does not involve dumping, but guided emplacement of the waste into subseabed geologic formations, the legal status of the concept is in doubt. Preliminary studies indicate a very complex and still-evolving picture in both the national and international arenas. When legal issues can be supported by positive research and development data from ongoing technical and environmental feasibility programs, they may be brought more completely into focus, and will have to be resolved at that time through national and international political processes.

Existing Data Bases

Site Selection

Application of the previously discussed selection criteria to the ocean regimes resulted in identification of generic study areas: mid-plate/gyre (MPG) regions. The data base consists of the following elements.

Tectonic Stability -- Current understanding of seafloor evolution is based on a model of "plate tectonics," in which a number of crustal plates slowly move over the planet's surface. Figure 2 shows the earth in cross section and identifies the different regimes. Both the direction and speed of plate motion are predictable (Figure 3). Plate boundaries can be areas of crustal destruction where the edges of plates are thrust over or under other plates, or they can be areas of construction where, if the earth's diameter is to remain constant, new crust must be made at a rate equal to the destruction rate, or they can be areas where plates slide against each other without destruction or creation of crustal boundaries. These areas are all characterized by their high tectonic activity (Figure 4).[1]

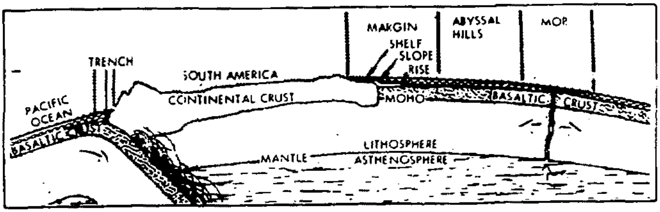

Figure 2. Cross Section of Earth's Crust Showing Tectonic and Geologic Behavior (MOR: midoceanic ridge)

Since the "conveyor belt" of the formation and destruction of continental topographic features begins with erosion from high elevations above sea level and deposition on lower elevations (including the sea floors), with solidified sediment deposits later uplifted so that erosion can begin again, areas with the greatest uniformity and predictability will be those where uplifting will not occur again for millions of years and where deposition is continuous and uniform.

Environmental Stability -- In addition to the slow movement of the brittle crustal layer across the planet, there are two fluid layers covering the earth which have a profound effect on the stability of any location on or near the surface of the crustal layer. These layers are the air and water masses over and in the ocean; on land the equivalent layers are the air and surface water. These two layers help to sculpt the face of the earth as we know it, mainly through erosional processes on land and depositional processes in the ocean.

Since all geologic and environmental processes are dynamic, the areas where these processes are least active will have the most predictable stability. In the ocean regime, the areas least affected by movement of the water and air (modified by changing seasons, changing climate, ice ages, etc.) are in certain central basins. This assertion is supported by samples from the sediment column beneath the gyre hubs, which show minimal changes in the depositional patterns or in the temperatures of overlying surface waters, even during the climatic extremes of an ice age. Areas (indicated by 0) showing minimal or no changes in temperature during the last glacial cycle are shown in Figure 5.

On the basis of these and other criteria, two study areas for the seabed program have been chosen in the central North Pacific.[1] Both are in the same mid-plate/mid-gyre area, but are about 700 km apart to allow assessment of lateral continuity of seabed properties.

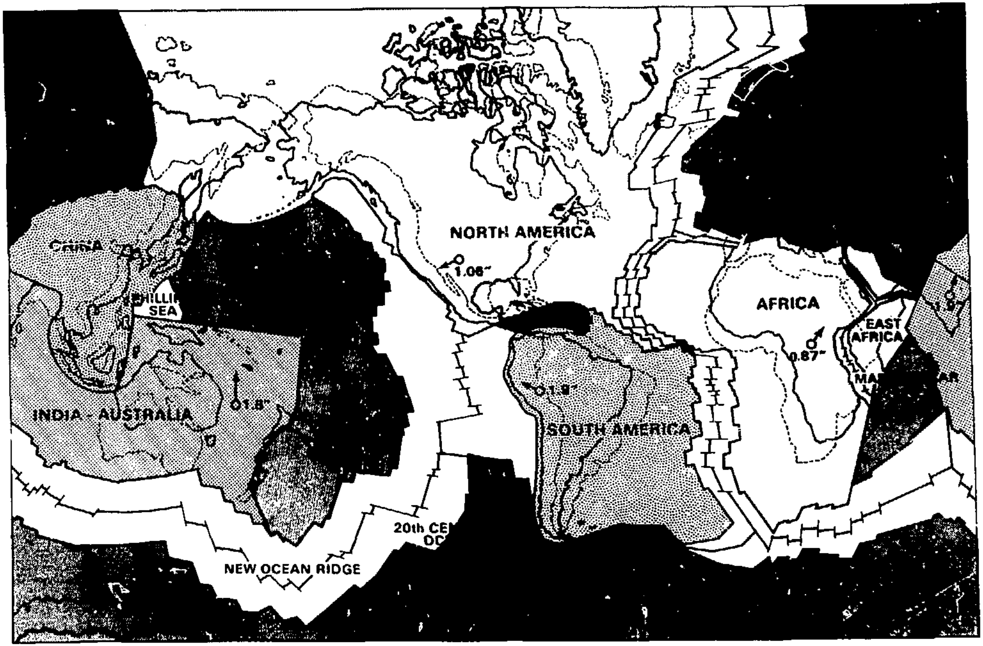

Figure 3. Crustal Plate Motion. Dashed lines show where continents were millions of years ago. Arrows indicate current direction of plate motion. Numbers indicate current rate of movement, in inches per year.

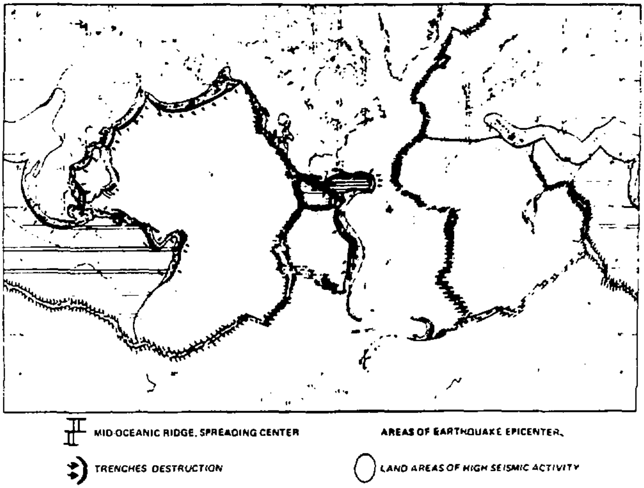

Figure 4. Identification of Crustal Plates, Indicating Spreading Centers (≋), Trenches (heavy solid lines), and Earthquakes (dotted areas)

Resources -- *Important resources available from the ocean include hydrocarbons, food,* fertilizer, sand, gravel, and heavy minerals and metals. Around the shores of almost all land masses, and associated with diverging and converging surface currents, are zones where nutrients are especially abundant. At these locations the ocean supports an enormous amount of plant and animal life (Figure 6). However, as these waters move in age-old patterns away from the nutrient supply areas into the open ocean, the nutrient-laden organisms die and sink, leaving the surface waters barren. The benthic regions below such areas are marine deserts more devoid of life than the Sahara.

Hydrocarbon resources are found on the continental shelves and in other areas having great sediment accumulations. On the abyssal hills of the ocean floor in the mid-plate regions, however, the only known mineral resources are manganese nodules, found over much of the very deep (>5 km) ocean floor. In general, nodules having immediate commercial interest because of their high cobalt, nickel, and copper content (Figure 7) are limited to areas of the deep ocean floor that underlie surface waters of intermediate biological productivity, and that are characterized by sediments containing appreciable siliceous ooze. Because of the large reserves of

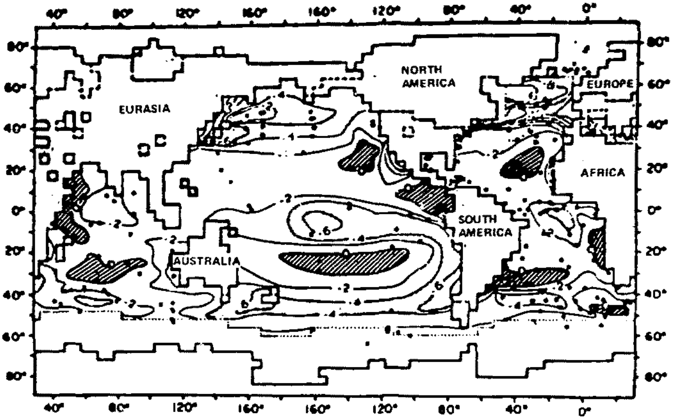

Figure 5. Areas of No Temperature Change During Last Glacial Cycle (▨ = zero gradient)

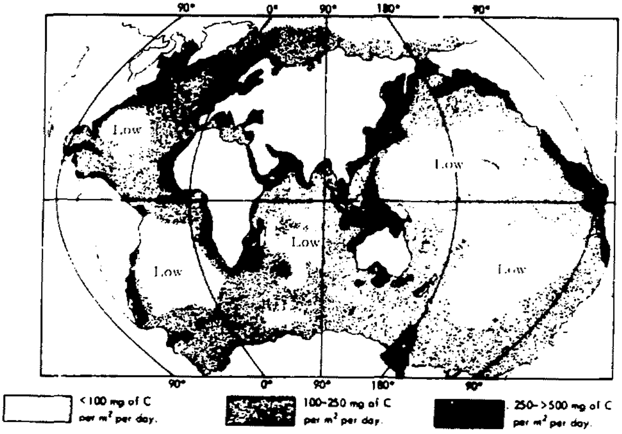

Figure 6. Areas of Low Surface Biological Productivity

low-grade ores on land, the likelihood is exremely remote for future mining of nodules low in copper, *nickel, and cobalt, such as those from mid-gyre areas.*[1] Because of the slowness with which the sea floor changes in relation to the resource-controlling processes of the ocean surface, the present distribution of resources can be predicted to continue for millions of years.

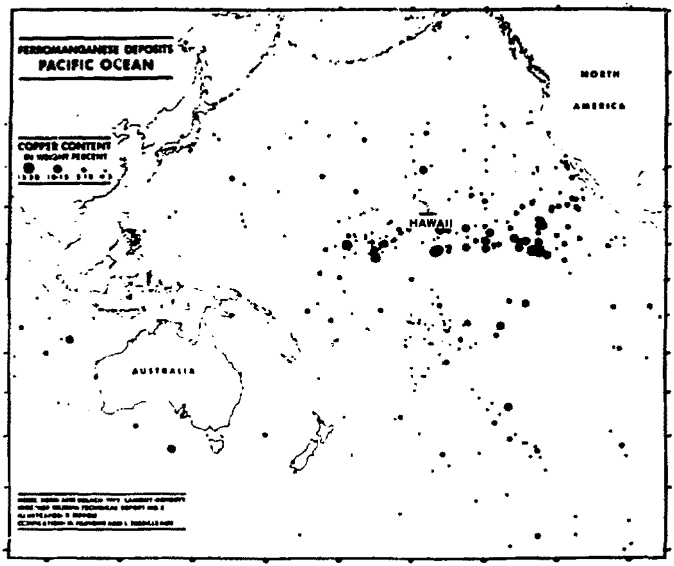

Figure 7. Copper Content of Ferromanganese Deposits of the Pacific Ocean. Chemical analyses reveal a broad band of nodules rich in copper south of the Hawaiian Islands.

Predictability -- In considering the suitability of subseabed sediments as a repository for long-lived wastes, predictability is a most essential criterion. This criterion applies not only to the ability to predict the future, but also to the ability, by extrapolation from local measurements of the physical, chemical, and mechanical properties of the medium, to extend these properties over wide areas horizontally and vertically.

Regarding prediction, there is concern about the possibility of distortion of the environment by earthquakes, faulting, or volcanism, or by gross changes in sediment deposition, either through massive new depositions that may result from turbidity currents, or through erosion caused by an increase in bottom current activity.

Mid-plate abyssal hill areas are not characterized by large earthquakes or the catastrophic turbidity currents which carry coarse sediments to the abyssal plains. Mid-plate/mid-gyre (MPG) sediments deposited over the past 30 to 40 million years (represented by available 10 to 13-m cores) show uniform deposition. The sedimentary layers do not appear to be folded or faulted on the scale of tens of metres, which is the limit of resolution of present surface-deployed reconnaissance profiling instruments.[1] Near-bottom profiling techniques have much better resolution. These tools, coupled with the acquisition and analysis of sediment cores, allow a detailed, three-dimensional profile to be developed of study areas of interest.

Data from numerous short (10-m-long) sediment cores taken in valleys and on tops of the very low rolling hills indicate extreme lateral coherency of accumulation. This extends over 6000 square nautical miles, with the hilltops accumulating at a lesser rate than the valleys. The continuity of chemical gradients and stratigraphic data in cores indicates an uninterrupted accumulation of sediment for at least 30 million years. Major world climatic changes (ice ages) have not caused major changes in these conditions; the postulated coherence and predictability still stand. The only event that appears to have altered this geologically tranquil environment over the millenia is a periodic dusting of small (micron-sized) wind-blown ash particles from volcanoes far upwind of the study area.[1]

The increase of silicon and aluminum toward the sediment-water interface and an increase in manganese and iron with depth reflect a change from a regime dominated by locally produced precipitation and influx of oceanic volcanic material to a wind-blown continental material characteristic of present non-ice-age conditions.

To establish that a region has undergone no damaging perturbations for tens of millions of years requires the most careful analysis of a continuous sedimentary record of longer cores, commencing with the present. For the MPG-1 region, this became possible when the giant piston core GPC-3 was obtained in 1976. GPC-3 is a sediment sample 11.4 cm in diameter and 24.5 m long, brought up from the central North Pacific. Another core from the same site, called GPC-2, is a bulk sample of deep smectite clay from about 30 m below the sediment surface.[1]

Data obtained from GPC-3 have been analyzed and integrated with earlier short (10 to 13 m) core information plus historical data, to yield several observations and conclusions:[1]

- Studies of the magnetic properties of sediments from GPC-3 and other cores in the MPG-1 study area show consistent core-to-core variations even though the integrated accumulation rates vary by a factor of two within this area of 6000 square nautical miles.[2] The long-term stability of the patterns suggests that inertial or tidal currents, rather than advective bottom flow (which probably has varied over geologic time) exert the greatest influence on the deposition of fine sediments.

- There is a great similarity in depositional features between the MPG-1 and MPG-2 study areas, suggesting that sedimentation on the plate beneath the central North Pacific gyre has been continuous and predictable for tens to hundreds of millions of years.
- Most of the mineralogic variations seen in GPC-3 can be accounted for by a combination of north-northwest plate motion (from a position at about 5 degrees north to its present location at 30 degrees north) through regions having differing sediment origins, temporal and spatial variations in wind and current directions, and variations in wind-blown transport of continental and volcanic debris.
- For 70 million years MPG-1 has been below the calcium carbonate compensation depth; i.e., below at least 4000 m of water.
- Judged on the basis of ichthyolithic stratigraphy (fish teeth zonation), the age of the oldest (bottom) section of the GPC-3 core is about 75 million years. *(This type of stratigraphy has error bars of the order of 4 to 5 million years.)*
- Detrital remanent magnetization results from GPC-3 provide a detailed chronology consistent with ichthyolithic stratigraphy. Taken together, magnetic and biostratigraphic data indicate that for the past 70 million years at MPG-1, sedimentation has been continuous and slow (0.2 m to 0.3 m per million years). Rates increased considerably, however (to over 2 m per million years) as the supply of wind-blown continental material generated by ice-age glaciations increased 2 or 3 million years ago.
- Glacial stages have had no deleterious effect on the MPG-1 environment.

Once it has been demonstrated within reasonable doubt, from cores and preliminary acoustic data, that an area meets criteria with respect to its suitability as a possible repository site, it will then become necessary to determine whether a sufficiently large area has continuous properties and a uniformly characterized sediment cover. A method is needed to reasonably verify "continuity" from one core site to the next.

Extensive progress has been made in the last decade in perfecting the technique of continuous subsea-bottom acoustic profiling, using the excellent propagation characteristics of compressional waves in water and in 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 processes in space and time, cores must be taken through the reflectors to identify the reflecting horizons, and to ensure that when the reflectors are traced acoustically across the basin, they correspond to the same sediment horizons. Development of this method of basin-wide extrapolation, combining acoustic profiles with long cores containing undisturbed environmental records for 10^6 to 10^7 years, is critical to final verification of an extensive area as a suitable repository site.

Initial assessment of the sediments in the Pacific (MPG 1 and 2) and the Atlantic (MPG-3) study areas was begun several years ago and was completed in 1977. However, many additional data are needed before satisfactory demonstration can be completed. Further analysis of data from MPG-1 and 2 during the past year reveals the following:

- No large-scale faulting (tens of metres in vertical displacement) has been discovered in any area covered by acoustically penetrable sediments.
- The region between 158 and 159 degrees west and between 20 and 31.5 degrees north (≈6000 square nautical miles) is relatively uniform acoustically, with profiles showing an even blanket of 30 to 50 m of sediment containing one continuous sub-bottom reflector at about 10 to 12 m in depth. This appears to be the most homogeneous sub-portion of the MPG-1 region.
- Acoustic profiles taken east of 158 degrees are much more variable, with reflectors more discontinuous, rougher topography, and possible basement out-crops.
- Further assessment of 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.

Data from MPG-3 indicate no large (1° square) areas that meet the above-stated criteria, but one site 1/2-degree square has been identified for additional study.

Radionuclide Containment

Near-Field Sediment/Canister/Waste-Form Interactions -- Assuming for calculation purposes that the sediment matrix is rigid (although in fact the sediments are plastic), initial calculations and laboratory experiments indicate that the thermal field around a container can be calculated by assuming only conduction. This assumption allows for a set of parametric calculations which provides guidance for both canister and waste-form studies as to size, amount, and concentration of waste. Again assuming a rigid matrix, the induced movement of pore water within the sediments driven by a nondecaying point heat source of 5 kW over 1000 years is 350 cm. For a decaying point heat source over the same time the pore water moves only 32 cm.[1] From these calculations it is obvious that in these very impermeable red clay sediments, if they do not deform, thermally induced radionuclide movement is small.

Studies have been initiated to quantify changes induced in the sediments by heat and radiation. Both laboratory and in-situ experiments are required to assess changes in the chemistry of pore waters and in sorption properties of the fine-grained sediments. In any case, the area heated to a relatively high temperature will be small and is considered part of the near-field system. The important data needed are those that directly influence the effect of the canister and waste form on the sediment barrier.

Far-field Ion Transport Through Sediments -- From literature and supplemental laboratory data, the four sediment types (hemipelagic, red clay, calcareous ooze, and siliceous ooze) have been ranked using measured batch sorption coefficients.[1] The sorption coefficients for several ions in the four sediments have been found to vary by less than a factor of 10. These are listed in Figure 8 and are identified by their respective amounts of contained $CaCO_3$. Of the two critical parameters for ion migration (sorption and permeability), the data in Figure 8 indicate that sediment sorption is quite invariant and thus the less important when used to rank sediments. Data on relative permeabilities are not yet available.

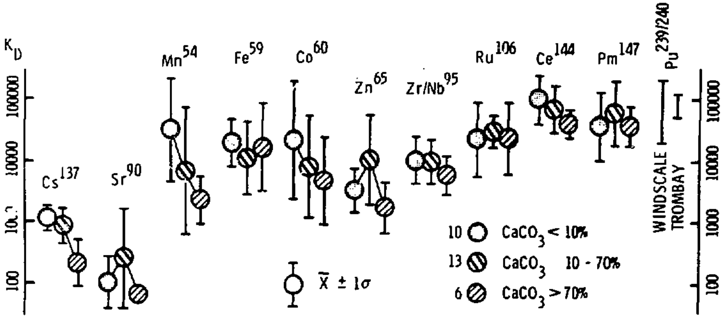

Figure 8. Sorption (Distribution) Coefficients for Silts and Clays. Data obtained for $Pu^{239/240}$ in sediments from the Windscale (UK) and the Trombeg (India) reprocessing plants.

The oxygen content of these red clays in the mid-plate/mid-gyre areas is in all cases greater than zero, and the organic carbon content less than 0.2%. In deep smectite clay layers, the organic carbon content approximates 0.017%. From this information, it is assumed that *organic chelating (complexing) will be minimal, and therefore the effective sorption coefficient* (K_d) of the sediments will remain high. This, however, must be experimentally verified.

Canister -- Because marine corrosion is such a significant problem, many detailed studies of corrosion have been conducted and documented. A large data base is available on low-temperature (up to 25°C) marine corrosion, but very little is available on high-temperature (over 25°C) investigations. The expected high temperatures of actual buried wastes make a high-temperature corrosion program mandatory.

Literature surveys have been conducted and data compiled on corrosion information for most alloy systems in hot (up to 200°C) brine and seawater; aluminum alloys, copper alloys, low-strength steels, stainless steels, nickel-based alloys, and titanium alloys. Very little pertinent information was gained.

Short-term corrosion rates at 200°C in seawater and wet sediment have been determined for five alloys. Rates ranged from 0.146 mm/yr for 1018 steel to 0.012 mm/yr for 3046 stainless steel and 0.004 mm/yr for Inconel 600. Initial estimates are that metal canisters can be built which, when the water/canister interface temperature is kept below 200°C, will last for the several hundreds of years of isolation needed for the high heat period.[1]

Waste Form -- No research and development studies are under way at this time as part of the seabed investigations. However, studies are being made under DOE's Waste Management program, and their results may be applicable to seabed purposes. As the seabed effort advances, studies will be initiated which will allow development of a waste form especially suited to the sediment environment.

Water Column -- The balance between rising and sinking water masses plus the age of bottom water in the great basins indicate that 100 to 1000 years are needed for the movement of dense water from the regions of its formation in high latitudes to areas where this water is returned to the surface layers. Deep-current measurements (100 m off the bottom) for a 19-month period at MPG-1 indicate a mean current velocity of 3 cm/sec. These figures suggest geologically rapid dispersal of dissolved nuclides throughout the oceans. In addition, the biological community may provide mechanisms for transporting radionuclides either laterally or vertically. Therefore studies must be undertaken to evaluate these mechanisms, including the development of models and the acquisition of data regarding the standing crop, turnover rates, and radionuclide concentration factors, to make possible the prediction of radionuclide transport back to man. The genetic and somatic effects of radionuclides on the ocean biological environment must also be assessed.

For the reasons given, the water column is likely to be a poor barrier for large quantities of nuclides but would provide a mechanism for delay and dilution of nuclides inadvertently released in smaller amounts, such as might occur in transportation accidents.

A diagnostic model for nuclide transport through the water column does not exist and may be unattainable. Stochastic models, however, may permit integration of effects resulting from simple bulk diffusion and advection, as well as from more complex internal motions in the water column.

Rock -- The basaltic rock underlying the deep ocean sediments is the least understood of the potential disposal settings because of the paucity of observations on its bulk properties. However, recent developments both in the field (by the International Program of Ocean Drilling and by several foreign agencies) and in the laboratory provide information on the basaltic crust and relevant processes there.

Initial results from the Deep Sea Drilling Project and from observations of segments of oceanic crust that have been thrust above sea level (in Oman, for example) indicate that the basalt is overlain by limestone or shale, grading to compacted sediments. The upper several hundred meters of basalt consist largely of lava pillows with some sills and layered sediments. The highly fractured nature of the pillows (resulting from thermal contraction as they cooled) and the existence of channels and cracks between them produce a bulk permeability that is orders of magnitude greater than would be inferred from examination of fist-sized basalt specimens. Hydrothermal systems of recirculating seawater identified in areas of newly formed basalt indicate that the upper rock layers are unlikely to constitute an effective barrier to waste migration. Deeper portions of the basalt layer are more monolithic but still fractured. At present, no data exist on the bulk permeability or rate of migration of seawater through such rocks. The oxygen isotopic composition of deeper basalt specimens indicates that they have exchanged oxygen with seawater, but the rate at which this occurred and the duration of the reactions are unknown.

Emplacement

Since the task of emplacing a waste canister in the sediments has only begun to be addressed, a few preliminary calculations and laboratory experiments regarding one phase of the penetrometer emplacement concept are all that have been made. These early studies suggest that when an object has penetrated the sediments to a sufficient depth, restraining forces in the sediments will cause the hole to close at some intermediate point. From that closure point to the surface, however, the hole will remain open for longer periods until filled by other natural actions. Initial laboratory experiments support this observation, but much additional work, including more laboratory experiments and the determination of dynamic and static sediment material properties, will be necessary before the closure mechanism can be completely understood.

International Seabed Program

The radioactive disposal programs of most countries are focused on investigation of geologic formations on land as possible containment media for nuclear wastes. However, in recent years, several countries have initiated programs to investigate use of geologic formations in the subseafloor.* Beyond the technical advantages and disadvantages involved, use of the international seabed for radioactive waste disposal raises social, economic, political, legal, institutional, and ethical issues.

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*In addition, several nations have formerly dumped or are still dumping low-level solid and liquid wastes into the oceans.

The technical aspects of seabed disposal are being addressed on an international level via a series of international workshops. Results of the first three of these workshops are contained in reports by the workshop managers.[6]

An international Seabed Working Group (SWG) has been created, with a membership including France, Japan, the United Kingdom, the United States, and Canada. The goals of the SWG are to (1) provide a forum for discussion, information exchange, assessment of progress, and planning of future efforts, (2) encourage and coordinate cooperative research vessel cruises and experiments, (3) share important facilities and test equipment, and (4) maintain cognizance of international policy issues.

Legal and Political Issues

Implementation of HLW disposal in the deep seabed is far enough in the future that many current legal and political trends could change. However, it is not too early to identify important problems, so that developments can to some degree be foreseen and guided.

The use of subseabed disposal will be governed by a complex network of legal jurisdictions and activities on both national and international levels. The U.S. Marine Protection, Research, and Sanctuaries Act of 1972 (the Ocean Dumping Act) bans subseabed disposal of HLW and strictly regulates other radioactive substances, although implementation of a subseabed disposal program for non-HLW is now possible under EPA's ocean disposal permit program. Subseabed disposal of HLW would, however, require a complete review through NEPA, major public participation, and compliance with EPA general radiation standards and NRC licensing criteria, as well as with all NRC, DOE, DOT, NOAA, and Coast Guard transportation rules.

Since 1970, the laws and policies of many countries have reflected growing environmental awareness; laws on water and marine pollution control, general environmental protection, waste management, and radioactive substances are increasing. Countries with nuclear power programs are formulating legal structures to deal with these problems, but at present the structures are inadequate for effective regulation and enforcement.

The London Convention of 1972, a multinational treaty on ocean disposal, addresses the problem of dumping of low-level and TRU wastes at sea.[7] This treaty is currently being revised to deal more specifically and completely with the problem of dumping low-level and TRU wastes. This treaty, however, does not address the controlled disposal of high-level wastes or spent fuel into geologic formations beneath the ocean floor.

Subseabed disposal offers the important political advantage of not directly impacting any nation, state, or locality. The importance of this advantage will be determined by the outcome of burgeoning opposition to local siting of disposal facilities.

The primary political disadvantage of subseabed disposal is its possible perception as an ecological threat to the oceans. If national publics, governments, and international agencies view such disposal as merely an extension of past ocean dumping practices, final use will be difficult if not impossible. However, if this option is understood as involving disposal in submarine geologic formations that have protective capacities comparable to or greater than similar formations on land, opposition may be less.

Waste Handling and Treatment

Spent Fuel Reprocessing

It is assumed that during seabed studies, a criterion for optimization of the waste form will be developed from properties and parameters of the sedimentary barrier acquired in other sections of the program. If reprocessing is the accepted option, the waste form will be designed specifically for the geologic disposal medium; size, waste concentrations, waste matrix, etc., may be specified after appropriate study. It is assumed that the resulting optimized waste form will be placed in an appropriately designed container at the reprocessing plant.

Repackaging of Spent Fuel

If disposal of spent fuel is the accepted option, criteria developed from optimization of the properties and parameters of the sediment barrier will be used as a basis for optimizing the overpacking of the spent fuel rods. A material which is incompressible, has good thermal conductivity, and is compatible with the sediments will be chosen. It is assumed that overpacking will be done at the central plant.

No conceptual designs are under way at this time.

Storage at Plant or Dock

Storage of solidified HLW or overpacked spent fuel at either the waste processing plant or the dock will be in a cooled and shielded facility, using existing spent-fuel storage technology. The maximum expected storage time at the port facility would be a few months.

No conceptual studies are under way at this time.

Land Transportation

It is assumed that the concepts and data developed in land-based repository studies for the transport of spent fuel or waste will be applicable to transport of high-level waste to the port facility (see Appendix N of Ref. 8).

Ocean Transportation

For the reference penetrometer system it is anticipated that the waste, packaged in a specially designed penetrometer container or overpack, would be placed in storage aboard the combination transport/emplacement ship, and would be transported to the disposal area by a route designed to minimize risks to the general population and environment, with minimal interference to other ocean activities (fishing, shipping, recreation, etc). It is expected that acceptable sites can be identified in both the North Pacific and North Atlantic.

Load weights of 7500 tons (300 25-ton transportation casks or 750 10-ton penetrometers) are well within the capabilities of present-day ships, some of which are built in the 400,000 ton dead-weight class. The transport ship could travel a 6000 nautical mile (11,100 km) round trip in about 25 days. With allowance for loading, unloading, fueling, bad weather, maintenance, etc., a net average trip requirement of 90 days is believed reasonable. A total of 3000 penetrometers per year per ship could be emplaced. The dock facility could handle three ships, for a total of 9000 canisters per year.

While being loaded onto the ship, waste canisters would be fitted with locating devices and recovery mechanisms. The location devices would be designed for a 5-year operational life and would, upon activation, continuously identify the position of the waste container. Once emplaced in the subseabed sediments, each canister's position would be documented by instrumentation on a second ship.

No conceptual designs have been completed. However, rudimentary assessments have resulted in the conclusion that waste canisters would be loaded onto the ship under water through an opening in the ship's side and emplaced through a port in the ship's bottom to minimize risks of worker exposure.

Risks and Environmental Impacts

The knowledge does not yet exist that would allow a quantitative assessment of the risks and impacts for man and for the near and far ocean environments. However, an attempt is made below to identify the larger problem areas and to qualitatively estimate their impacts and risks for the reference repository system.

Land and Sea Transportation

During the operational period (through emplacement), probable accidents are primarily transportation-related. Potential risks during ocean transport chiefly concern the release of waste to the water column and hence to the biology of the ocean. The maximum risk would be posed by the sinking of the transporting ship or by loss of waste canisters overboard. Natural events which could cause similar accidents are tsunamis (great sea waves caused by submarine earthquakes or volcanic activity -- usually much more dangerous in shallow waters than in the deeps), typhoons, or hurricanes. Other potential initiating events include explosions, collisions, or running aground.

Techniques that could be used to reduce the likelihood of accidents include double-hull ship construction, minimum use of standard shipping lanes, and the use of redundant advanced navigational aids. Early warning systems for tsunamis are currently operational, and with present weather prediction capabilities and satellite monitoring systems, typhoons and hurricanes can be avoided by moving the ship out of their paths. It is worth noting, however, that even an accident such as those described would not result in immediate release of radionuclides to the ocean because the canister and waste form will be designed to survive such accidents intact.

The consequences of a release into the surrounding media depend on its location. If a release should occur over a continental margin, the consequences could be larger than if it happened on the deeper ocean. Consequences of a release on or near a continental margin would be reduced by a leach-resistant waste form, long container lifetime, minimizing travel routes over continental margin areas, and recovery of waste canisters sunk or dropped as a result of an accident. Procedures and system design alternatives that could be used to increase the probability of waste receovery after an accident include operational and system design options. The primary operational procedures that could be used to increase retrieval probability after a canister loss are appropriate route selection and continuous monitoring and transmission to a fixed base station of the transport ship's position. System design options include the use of remotely actuated locating devices and flotation mechanisms, and a canister design specifying both a high probability of waste containment for a period of a few years and ease of retrievability from either the sea surface or the bottom. Cask-locating devices and retrievability will be designed into all phases of the transportation system in the seabed disposal program.

Environmental impacts during transport, if any, will mainly result from the fossil fuel consumed by the transport ship. The consequences of transportation accidents have not been assessed in detail but are assumed to depend upon the kind of accident and the quantities of waste being transported. Waste canisters could be cooled during sea transport by a closed fresh-water circulating system with heat transfer to the sea. Such heat dissipation is expected not to adversely affect the ocean except for a nearly undetectable local temperature rise comparable to that produced by operation of the ship itself. Fossil fuel usage for land and sea transport is estimated to be 660 ℓ/MT (fuel).*

Dock Facilities

It is estimated that the risks and environmental impacts of dock facilities (1 km^2 in area) would be no greater than those associated with surface storage and transfer facilities to be used with a reprocessing plant or spent fuel overpacking facility. (See Section 3.1.5.3 of Ref. 8.)

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*Calculated from the first two lines of Table 6.1 of Reference 5 and normalized by the 45,625 MT/reprocessing plant indicated in Reference 5, Vol. I, p. 3.66.

If the docks were located near a major population center, only a small social and economic impact would result, but a small increase in occupational exposure would be expected. Appropriate trade-offs of these risks versus the risks posed by longer land and/or ocean transport routes would have to be made before a dock location was selected.

The use of existing government facilities would further decrease environmental impacts.

Repository

The direct short-term risks to man from either an operating or completed repository in the subseabed sediments should be very small. Post-emplacement releases of radionuclides which might migrate either by direct mixing with seawater or by some unknown biological-pathway to man would be primarily related to inadequate containment by the sediments. This containment potential might be subject to modification by either natural or waste-induced processes. Earthquakes, volcanic action, major climatological and circulational changes, and meteorite impacts are examples of natural processes that might affect containment stability. Selection criteria used to identify the reference ocean area would minimize the probability of the first three processes; no method is known of minimizing the probability of meteorite impact other than more concentrated emplacement, which, while reducing the random target area, would correspondingly increase the source term for potential consequences of a meteorite strike. However, any meteorite impact that could penetrate 5 km of water would cause such other disasters as would make the release of emplaced radioactive waste insignificant.

Potential migration driving forces resulting from waste-induced heat or radiation effects on the sediments are temperature and chemical gradients, or stress distribution around the emplaced waste. All are being studied.

The potential consequences of far-field long-term releases from seabed geologic disposal have not been estimated. In a study based upon an unverified theoretical model, an estimate was made of the consequences of placing on a North Atlantic sediment surface the solidified HLW resulting from 12,000 GWe-yr of electrical generation by a light-water reactor. The study concludes that "even for the actinides which do not occur to a significant extent in nature, the concentrations predicted by the models are less than the natural concentrations of comparable radionuclides. The predicted maximum future levels of the fission products, most of which do not occur naturally, and of ^{239}Pu are comparable with current levels due to (weapons testing) fallout."[9]

Detailed design calculations showing the amount of seabed area needed for disposal do not exist, but preliminary estimates have been made. The assumptions are 0.5 MT of 10-year-old HLW or spent fuel per canister, with 100-m spacing between canisters, in a square array. The resulting emplacement density would be 50 MT fuel/km^2. At this density, the area required for the disposal of all HLW or spent fuel created by the operation of all light-water reactors in the

U.S. through the year 2040 (380,000 MT fuel) is 7600 km^2, which is 0.006% (6×10^{-5}) of the available abyssal hill area in the North Pacific mid-gyre study area.

The maximum thermal flux at the sediment/water interface imposed by this amount of waste or spent fuel at the stated density is estimated to be between one and four times the normal flux for the MPG area (the normal flux is 1-2 microcalories/cm^2). Other ocean regimes such as the midocean ridge system have normal thermal fluxes of 10 to 15 microcalories/cm^2.

Even though aquatic ecology is not yet well understood, experience with thousands of sediment cores suggests that the effect of a penetrometer passing through the water and the benthic boundary layer will be very small. Disturbance of the surficial sediment layers will also be small (about three diameters of the penetrometer; or for a canister 30 cm in diameter, about 0.8 m^2). When cans or penetrometers are emplaced on 100-m centers in a square array, about 0.003% of the repository surface area will be affected.

Research and Development Programs

Needed research and development programs are categorized in five areas. The objectives are to provide concepts, data, models, etc., to quantify the risks and environmental impacts of nuclear waste disposal in submarine geologic formations, and to allow assessment of the feasibility of the seabed disposal concept. These major research and development categories are:

- Site selection, surveying, and preparation
- Multibarrier identification, quantification, and breachment
- Emplacement
- Transportation
- Legal and political issues.

In the first three of these areas, the overall plan is first to acquire, in the laboratory, the necessary knowledge about sediment properties, and second to develop mathematical models. The third step is to validate the models and properties by either laboratory or field (in-situ) experiments. Since the geologic sites which are optimal for radionuclide containment are ones whose processes are very slow, experiments and measurements made in these sites, and continuing for a year or two, are inadequate to demonstrate feasibility of containment. It is therefore necessary to develop predictive models backed by laboratory and in-situ material property evaluations. Both the predictive models and the property evaluations would have to be validated either by tests in similar but more rapidly responding media or by comparing initial response predictions with in-situ tests and extrapolating to longer times. From this kind of information, risks and environmental impacts can be assessed.

After initial validation tests, the process of obtaining properties, models, and validation will be repeated until adequate predictions are possible.

Site Selection and Preparation

For the reference system (sediment emplacement), the following generic activities will be undertaken for each ocean basin.

Geographic and geologic exclusionary criteria will be developed which will eliminate from consideration areas that are tectonically or environmentally unstable, contain resources of current or future interest, are small in area (from 1/2 x 1/2 to 1 x 1 degree), or respond unpredictably to changes in currents and climate.

Criteria will be developed which will allow ranking of the remaining areas in the ocean. It is expected that 6 to 12 potential sites will be identified in each ocean basin.

Surveys will be fielded to acquire additional data on these sites, and the ranking criteria will be updated, after which two or three sites will be identified for further study. Detailed analyses of the chosen sites will then be initiated, and some in-situ thermal and mechanical experiments begun. After data from the detailed site analyses have been evaluated, a site will be prepared for use.

The Multibarrier Research and Development Program

The multibarrier concept, developed in 1974, assumes a continuously wet environment in which the packaged (canister and waste form) radionuclides are placed. The geologic sediments are considered the primary barrier to radionuclide migration, with the canister, the waste form, and the water column acting as supplemental barriers. Studies of the primary sediment barrier are broken down into near-field interactions and far-field ion transport, each of which is discussed below.

Near-Field Interactions -- An appreciable part of the research and development effort is devoted to identifying and quantifying interactions among the sediments, the canister, and heat and radiation from the waste.

The first phase of the study has been to develop the necessary thermal models and acquire the laboratory thermal properties to allow predictions of thermal profiles with time in the sediments, and of variations of sediment/canister interface temperatures with time for any waste form or canister geometry.

The second phase was to develop models and laboratory physical properties that will allow prediction of thermally induced pore-water movement through a fixed sediment matrix.

The third phase is to acquire the laboratory physical and mechanical properties and develop models necessary to assess the risk of thermally induced movement of the canister and the surrounding sediments. The sediments are plastic and may seal any hole or fracture made in them.

From this standpoint the plastic nature of the primary sedimentary barrier is beneficial; however, buoyancy forces generated by heating of the sediments and pore water may cause the sediments to expand and either develop a breachment path to the sediment/water interface or allow the canister to sink.

The fourth phase is to develop an understanding of the chemical responses of the sediments, pore water, and seawater to heat and radiation. This study will examine such things as pH and Eh changes, released organics, changes in mineral composition, released trace ions, changes of K_d with heat, ions and complexes formed by radiation, etc.

The fifth phase will be to quantify the response of the sediments and pore water to the introduction of foreign materials (the canister and radionuclides) both at ambient and elevated temperatures.

Laboratory simulation tests will allow the acquisition of much-needed data and insight in each of the phases, but in-situ field tests will be needed to verify the models and the conclusions drawn. An In-Situ Heat Transfer Experiment (ISHTE) is planned for the early 1980's. This experiment is intended to verify information obtained from laboratory experiments and analytical studies of the response of red clay sediments to long-term deployment of a heat source. Specific properties of interest are those related to heat transfer such as thermal conductivity and thermal diffusivity. Attempts are being made to measure these properties in the laboratory under seabed-like temperatures and pressure. Models of sediment behavior are also being developed which require the above thermal properties.

Far-Field Ion Transport -- Another important area is quantification of the size of the primary undisturbed sediment barrier. The first part of the study is comparative evaluation of the four generic sediment types (hemipelagic, calcareous ooze, siliceous ooze, and red clay) using batch K_d's for single ions and permeabilities. The second part is to begin to acquire laboratory data and models which will allow assessment of the sediment barrier. Since large areas of the MPG's in both the Atlantic and Pacific are covered with red clay, and also because the clay has very large K_d's and low permeabilities for waste ions, preliminary work has been initiated on the red clay sediments. Single-ion and multiple-ion batch K_d's are being measured, after which thick-layer and column K_d's will be acquired for the natural, thermal, and radiation environments. Third, a transport model will be developed with which to calculate the movement of radionuclides in the sediment columns and in the natural and modified environments. Fourth, in-situ field validation experiments are planned.

Waste Form -- No work is under way on the waste form; however, when the near-field environment has been quantified, a program will be initiated to design a waste form specifically for the subseabed environment. This waste-form matrix could either surround the spent fuel rods or could dissolve and retain the radionuclide oxides.

Canister -- Limited material studies are under way and will continue through approximately 1983. At that time reference materials will be chosen and a preliminary canister design completed. The canister design must include: a mechanism for equalizing the pressure that will develop when the canister descends to the sea floor; a penetration guidance and early-time monitoring system; a combination flotation acoustic and visual locating device to aid in canister recovery in case of an accident, and a capability for underwater recovery.

Basement Rock -- This barrier has yet to be assessed, and may never be assessed if the easier-to-reach sediments are found to be an adequate barrier. No work is being done in this regime. However, other research programs are being monitored, such as those associated with the International Program for Ocean Drilling (IPOD) in which basaltic and overlying lithified sedimentary formations are being studied. Data from these programs are available for future consideration.

Water Column -- As stated previously, the water column was assessed during early seabed studies and was judged inadequate as a containment barrier.* However, an understanding of deep physical circulation and biological processes is necessary to address the long-term risks of repository failure or accidents during transport of waste to the disposal site. Physical oceanographic and biological transport models must be developed and the necessary data acquired to allow estimates of the concentrations of escaping radionuclides and their rates of movement throughout an ocean basin. Some field studies will be necessary to acquire such data as vertical and horizontal advection in certain sections of the oceans, as well as detailed information on the movement of deep water masses from the selected sites and the mixing of these waters with others as they move from the site. For the biological studies, standing crop, turnover rates, rates of accumulation, and the transport of specific radionuclides through the food web of the ocean basin must be assessed. Models of these processes must be constructed for use in assessing the risks and environmental impacts of seabed disposal.

The genetic and somatic effects of radionuclides on both shallow-water and deep-water biota must be assessed. Field verification experiments are planned for both the biological and physical oceanographic models.

Emplacement Research and Development

In addition to the research necessary for the canister, physical and mechanical (static and dynamic) properties are needed to support the model for developing an understanding of the sediments' response to the passage of the penetrometer. It is possible that the hole may close by itself immediately or shortly after placement, due to both dynamic rebound and plastic creep

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*While the water column could be beneficial in that it will allow very large dilution and dispersion of radionuclides (an old technique of waste disposal) in worst-case accidents or long term unexpected events, it has not been found to be an acceptable long-term confinement barrier to prevent the migration of radionuclides to man.

of the sediments. Laboratory and in-situ field experiments must be designed and completed to validate the models. The short-term monitoring equipment designed into the canister must be periodically interrogated and the data analyzed. In addition, if data generated in ion-transport studies (see pp. 26-27) indicate that deeper burial is needed than can be achieved in the free-fall mode, studies must be started which will allow for additional penetration (e.g., rocket-assisted penetration or the use of a long, heavy reusable weight). These emplacement studies should also include design and testing of handling and other facilities on board ship (e.g., winches, cables, and exit and entry ports through the ship's hull).

Transportation Research and Development

Studies addressing the development and construction of the port facility and the transport and emplacement ship have not been initiated. They will be started when technical and environmental feasibility of the basic concept has been assured. It is estimated that the dock facilities and ship can be designed and built in 5-7 yrs. Waste storage could be provided by a water-filled pool at dock-side and on the ship, which would supply shielding and cooling for the canisters. A closed circulation system would dissipate the heat to the ocean through heat exchangers. The coolant would be continuously monitored for leakage and temperature change. The ship would be equipped with handling devices for moving casks, for examining the condition of canisters, and for some amount of canister repair or waste repackaging. A special area would be available for storage of canisters requiring return to the repackaging plant.

Social-Scientific (Interface with Nontechnical Issues)

Social-scientific research and development encompasses both national and international aspects. On the national level it is currently illegal to "dump" HLW or spent fuel in the ocean. The U.S. seabed concept involves neither "dumping" nor placement of wastes in the ocean or on the seabed. It is obvious that not only must technical and economic feasibility be established, but national and international legal and political definitions must be clarified. This study area is broken down into six sections.

First, current national and international legal and institutional positions must be assessed. Then, if technical and environmental feasibility is established, attention will be given to the development of new positions.

Second, the current U.S. political position must be identified. Then, if technical and environmental feasibility is established, assistance will be given in modifying the national position to allow use of the option.

Third, important factors from the standpoint of the public must be identified, after which the public must be made aware of goals and progress and be involved to the greatest possible extent in all aspects of the program.

Fourth, a preliminary cost estimate must be developed for the selected emplacement option (penetrometer/MPG/red-clay). After technical and environmental feasibility has been established, a detailed cost estimate will be made. In addition, the socioeconomic effects of seabed disposal will be assessed.

Fifth, if this option is found acceptable, an international subseabed disposal program will be developed, involving as many nations as possible.

Sixth, the capability must be developed within the U.S. to assess the technical and environmental feasibility of ocean disposal options undertaken by other nations.

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