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Subseabed Disposal Program Plan

Volume I: Overview

Seabed Programs Division

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Volume I

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Volume I: Overview

I. Introduction

The Subseabed Disposal Program (SDP) was conceived in 1973 as part of the United States federal Waste Management Program. In 1975 it was placed under what is now the Office of Environmental Compliance and Overview for the initial technical and environmental feasibility assessment phase. The program remained under this office until the fall of 1979, when it was transferred to the Department of Energy's Office of Nuclear Waste Management to facilitate interactions with other programs under the National Waste Terminal Storage (NWTS) program. The SDP is at present under the administration of the DOE Albuquerque Operations Office.

The NWTS project is managed for DOE by the Office of NWTS Integration (ONI). The overall goal of the NWTS program is to identify and/or develop technologies that will provide a high degree of assurance that existing and future high-level nuclear waste produced by government and commercial activities can be isolated from the biosphere in a safe, environmentally acceptable manner. Present evidence indicates that these demands can best be met by disposal in stable geologic formations. The major thrust of the NWTS project is toward isolation of the wastes in conventional mined repositories within the continental U.S. Three of the project's four Project Elements are devoted to research in this area.

A supplement and longer-term option is disposal in stable geologic formations under the world's oceans, and the Subseabed Disposal Program constitutes the NWTS' fourth major Project Element. The program for assessing subseabed disposal has been managed from its inception by Sandia National Laboratories (SNL). More than 100 scientific and technical investigators, both from SNL and from universities and research centers all over the nation, are involved in studies related to the SDP. These studies are closely interfaced with the land investigations and with other programs that ONI does not manage.

* * * *

Why is the deep sea sediment being considered as a possible disposal area?

First, some of the most stable geologic formations on earth are found underlying the deep oceans, and some are laterally uniform and predictable over many hundreds of miles, especially in the mid-plate, mid-gyre (MPG) regions. These vast sedimentary areas (many thousands of square miles) are distant from the active edges of the tectonic plates, and are in the construction phase of the tectonic process. The sediments are formed by a slow but continuous accumulation of fine particles that may in the distant future become sedimentary rock. Some of these sedimentary regions that have been sampled by coring show uninterrupted records covering tens of millions of years, allowing the future stability of these areas to be predicted with high confidence.

Second, these sedimentary geologic formations are plastic (self-healing). These plastic sediments are made up of very small, uniformly sized grains that are highly nuclide-absorbing. The grains pack together in such a way that water in the pores surrounding the grains has a very high resistance to movement. The primary nuclide transport mechanism through these essentially static pore waters is diffusion, and even this very slow process is further slowed by the high nuclide-absorptive qualities of the sediment grains. Thus the high plasticity of these sediments means not only that the emplacement hole for the waste package, but also any crack or fissure, would close.

Third, the deep ocean environment, in addition to being uniform and predictable, is stable not only geologically but in many other ways. Temperatures are low (<2.0°C) and vary less than a degree Centigrade from day to day, season to season, or millenium to millenium. At such temperatures, chemical processes are slow and predictable. These high pressures (0.5 kbar) are beneficial in that they assure that the sediments will remain uniformly saturated (without voids), and that pore water, if heated, cannot boil. Ice ages and other large climatic changes have little or no effect on the stability and uniformity of the deep ocean environment, and the vast oceans comprise an essentially infinite sink for the heat that would be generated by decaying radionuclides in nuclear waste.

Fourth, the deep ocean mid-plate geologic formations are practically devoid of useful resources. Benthic and pelagic organisms are sparse at the depths under discussion (>6,000 m), and the only discernible minerals are manganese nodules, which in the areas of interest to the Subseabed Disposal Program (SDP) are low in the commercially important elements copper, nickel, and cobalt.

Fifth, even though emplacement and containment have yet to be demonstrated for specific geologic formations, the engineering tools needed for work in the deep ocean and the seafloor sediments already exist, and can be adapted for full-scale use. Some examples of these tools are the drill platform used in the Deep Sea Drilling Program *(Glomar Challenger)*, the *Glomar Explorer*, submersibles (such as *Alvin*), *Trieste*, the Deep-Tow remote vehicle, and penetrators developed for ice, earth, and Mars penetration.*

The current activities of the SDP are governed by the awareness that, even though our understanding of subseabed sedimentary geologic formations indicates that they are candidates for disposal of nuclear waste, much additional specific research and engineering is needed before the feasibility of the Subseabed Disposal Concept can be assessed.

This document outlines the current plan for a continuously developing program that is aimed at assessing (1) the technical and environmental feasibility of the concept, (2) its engineering development, and (3) the operation of a nuclear waste repository in a geologic formation beneath the ocean floor.

This overview volume is intended to be useful for several years, or until the program has developed to the point where presently unforeseen modifications or expansions become necessary. Each year a supplemental volume will be issued containing Subtask Work Plans and the budget and milestones projected for that year.

*Penetrator technology has consisted of developing shapes and cases that can survive high-speed impact into hard natural materials. Instrumentation has been developed or modified to fit into these long, narrow cases for the purpose of reporting subsurface density variations. This surveying concept has proven successful in rock, desert soils, and ice, and has been proposed for use in remote planetary investigation.

II. Program Summary

The primary objective of the Subseabed Disposal Program (SDP) is to assess the scientific, environmental, and engineering feasibility of disposing of processed and packaged high-level nuclear waste in geologic formations beneath the world's oceans. High-level waste (HLW) is considered the most difficult of radioactive wastes to dispose of in oceanic geologic formations because of its heat and radiation output. From a scientific standpoint, the understanding developed for the disposal of such HLW can be used for other nuclear wastes (e.g., transuranic—TRU—or low-level) and materials from decommissioned facilities, since any set of barriers competent to contain the heat and radiation outputs of high-level waste will also contain such outputs from low-level waste. If subseabed disposal is found to be feasible for HLW, then other factors such as cost will become more important in considering subseabed emplacement for other nuclear wastes.

A secondary objective of the SDP is to develop and maintain a capability to assess and cooperate with the seabed nuclear waste disposal programs of other nations. There are, of course, a number of nations with nuclear programs, and not all of these nations have convenient access to land-based repositories for nuclear waste. Many are attempting to develop legislative and scientific programs that will avoid potential hazards to man, threats to other ocean uses, and marine pollution, and they work together to such purpose in meetings of the international NEA/Seabed Working Group. The US SDP, as the first and most highly developed R&D program in the area, strongly influences the development of subseabed-disposal-related policy in such nations.

Research Approach

The research approach for the SDP, shown in Figure 1, is first to develop the best predictive mathematical models for each scientific unit, using first principles of physics, chemistry, mechanics, etc.; second, to extract from the existing literature and through laboratory measurements estimates of maximum and minimum values for needed input parameters (henceforth called properties); third, to make response predictions using the best combinations of properties available at that time; fourth, to compare these predictions with laboratory and field verification experiments, and fifth, if the predictions and verification experiments agree, to use that model unit for sensitivity studies and for coupling with other units to prepare a predictive system model. If predictions and verification experiments do not agree, the model and the properties will be improved and again verified with appropriate laboratory and field tests. From the results of this process, risks and environmental impacts can be assessed. The major components of the program are represented by boxes in Figure 2. The total systems model represents both the flow of the effort and funding (from the most important to the less important areas) and the flow of the thermal energy and radionuclides toward the environment and man. The final result will be the assessment of the technical, environmental, and engineering feasibility of the subseabed disposal concept.

The Subseabed Disposal Program (SDP) is divided into four phases:

Phase 1—Estimation of technical and environmental feasibility on the basis of historical data. Completed: 1976.

Phase 2—Determination of scientific and environmental feasibility from newly acquired oceanographic and effects data. Estimated completion date: 1988.

Phase 3—Determination of engineering feasibility and legal and political acceptability. Estimated completion date: 1998.

Phase 4—Demonstration of disposal facilities. Estimated completion date: 2010.

At the end of each phase of the program, a review is made and concept feasibility is assessed. This assessment requires both internal (i.e., peer) and external (e.g., NAS) reviews. At each of these go/no-go gates, beginning with Phase II, a major program document will be prepared summarizing the results of that phase. If an item is identified that makes the concept unacceptable, the program will be terminated and emphasis thereafter will be placed on demonstrating this unacceptability to other nations that are considering or are using the seabed for HLW disposal.

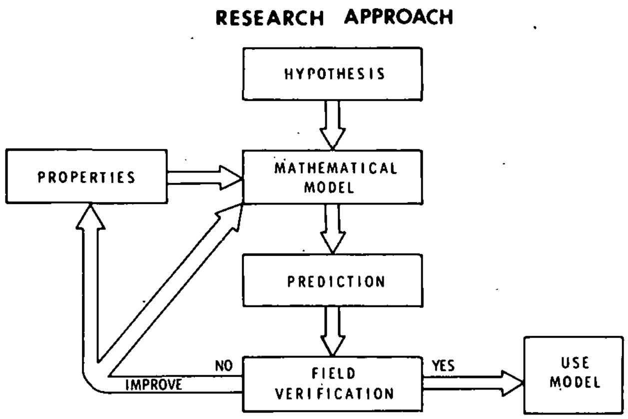


Figure 1. SDP Research Approach. The research approach to the Subseabed Disposal Program is a reiterative one in which the hypothesis and known properties lead to the formulation of a mathematical model. The prediction made based on the model is verified in the field. Such field verification leads either to improvement of the properties and of the mathematical model (which is then again subjected to field verification) or, when proven satisfactory, to a usable model.

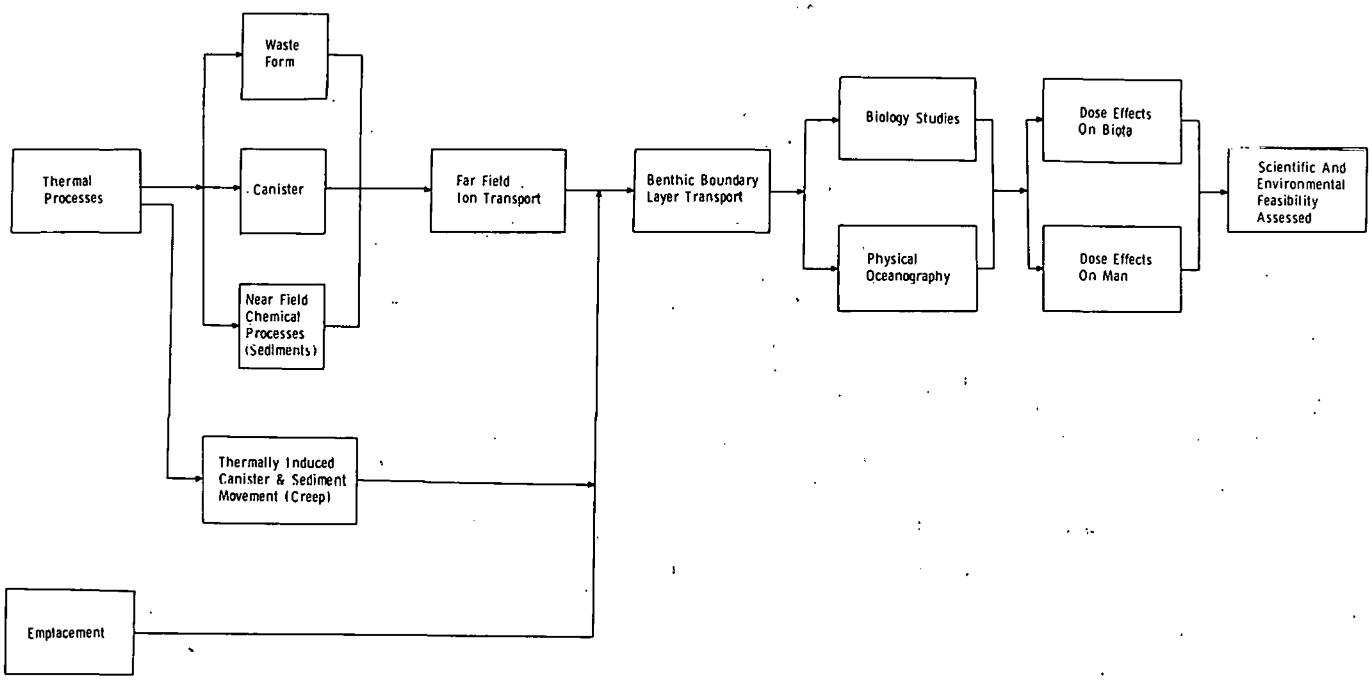


Figure 2. Systems Component Model Diagram. All tasks (shown in boxes) of the SDP are being pursued in parallel with the exception of Emplacement, which is primarily an engineering study. The diagram shows how the tasks are interrelated and how the problem-solving process will eventually lead to the assessment of technical and environmental feasibility.

The historical data examined in Phase I, although incomplete, has revealed no technological or environmental reasons that would preclude the successful disposal of nuclear waste in selected stable sedimentary geologic formations beneath the abyssal floors of the deep oceans.

To date, the plan for the program has been to complete the phases sequentially; this allows optimal use of the limited funds. However, if time of completion becomes more important, several sections of Phases 2, 3, and 4 could be pursued simultaneously. This approach involves certain risks, however, in that an unexpected negative event occurring in Phase 2 could terminate the program, causing a partial loss of the resources expended in Phases 3 and 4.

The main tasks to be accomplished before completion of each phase are listed below. They can also be seen graphically in Figure 3.

Phase 2—Scientific and Environmental Feasibility

- All units of the system mathematical models made operational. A mathematical model containing all part of the system that address scientific and environmental feasibility (biological transport, physical oceanographic transport, ion transport through sediments, thermal effects on sediments, canister responses, etc.) will be made operational but not validated through laboratory or field experiments (Fig. 1 and top row of Fig. 3).
- All properties used in the models bracketed but not verified. Each unit of the model described above requires certain input properties. During this phase, maximum and minimum estimates of all properties used in the models will be made (bracketed) and sensitivity analyses completed to identify properties that are critical (Fig. 3, row 2). Certain of the properties will be acquired through laboratory and field measurements, but these will not be site-specific.
- Verification tests completed on certain critical model units (e.g., thermal and radionuclide transport and sediment and canister mechanical response). Depending on resources available and the completion dates for sections of the system model, certain sections will be validated through both laboratory and field testing. The model unit nearest completion at this writing (1981), and of highest importance in the assessment of feasibility, is the thermal and ion transport through the sediments. It is hoped that the In Situ Heat Transfer Experiment (ISHTE), which is in development and is planned for deployment in 1984, will verify these sections of the model (Fig. 3, row 4).
- At least one study location (1° x 1°, or 60 x 60 nautical miles) in each of the northern Atlantic and Pacific oceans identified and initially characterized. Although the geologic formations of interest are expected to be stable, uniform, and

		Site	Biological Oceanography	Physical Oceanography	Thermal	Near Field Chemical	Waste Package	Far Field Chemical	Mechanical	Emplacement	Transportation	Regulatory & Institutional	Systems Analysis	
Models	(Row 1)	X	A	A	X	A	X	X	A	A	A	A	A	
Properties Estimated	(Row 2)	X	A	A	X	A	X	X	A	A	O	A	A	—End of Phase 2
Properties Acquired	(Row 3)	A	A	A	X	A	A	A	A	O	O	A	A	
Field/Lab. Verification	(Row 4)	O	O	O	A	O	O	A	A	O	O	O	O	—End of Phase 3

A = Active
X = Complete
O = Not Yet Initiated

Figure 3. Subseabed Disposal Program Scientific/Environmental Feasibility Matrix (progress as of Spring 1981). The matrix should be completed through Row 2 by the end of Phase 2; it will be completed through Row 4 by the end of Phase 3.

homogeneous over large expanses, many regions have not yet been completely mapped. To be considered acceptable, study locations should be completely topographically mapped, and a detailed understanding of the three-dimensional sedimentary geologic formation developed. This task will be accomplished through a combination of ocean-surface and near-bottom acoustic profiling and sampling.*

- Scientific and Environmental Feasibility document. An estimation of impacts on both man and the environment will be made using the total system model and the acquired properties. From this and other studies identified in this section, an assessment of scientific and environmental feasibility will be made and the conclusions published in accordance with the requirements of the National Environmental Protection Act, as amended.*
    - An external (e.g., NAS) review of the program completed. A formal external review of the subseabed HLW disposal program will be completed at this time to identify any items which would make the program unacceptable.
- National and international legal and institutional positions established. Since the legal and institutional implications of the disposal of HLW in geologic formations under the oceans are unclear, issues should be identified and research initiated to allow a complete resolution during Phase 3.

Phase 3—Engineering Feasibility

- All properties verified. Each unit of the system requires input properties. During this phase, the maximum-minimum estimates made in Phase 2 will be reviewed, and, when required, the property information refined through additional laboratory and field experiments and measurements as well as developing a statistically accurate data base (Fig. 3, row 3).
- All units of the system mathematical model developed and verified (Fig. 3, row 4). All units of the system model for both scientific and environmental feasibility and engineering feasibility will be developed, coupled together, and verified through appropriate laboratory and/or field testing (Fig. 1).
- In-situ emplacement tests completed. Several in-situ emplacement tests will be completed to demonstrate that the models developed for placement and hole closure are valid and that canisters can be placed at the required depths.
- Long-term (15-year) in-situ experiments initiated. Several long-term thermal experiments using heat-producing radioactive materials and appropriately designed containers will be initiated to help validate the system models and to allow testing in real time through the critical heat and radiation period. These experiments will be retrievable.
- Conceptual design completed. A conceptual design of the total waste disposal system (from the generating source to the repository) will be completed.
- Preliminary engineering designs completed. Preliminary engineering designs (Title I) for the total waste disposal system will be completed.
- Final engineering designs begun. Final engineering designs (Title II) for the total waste disposal system will be begun.
- Engineering feasibility document completed and reviewed. A summary report of the studies in this section which contribute to the assessment of engineering feasibility will be compiled, reviewed, and published.
- An external review of the program completed. A formal external review of the Subseabed HLW disposal program will be completed at this time to identify any items which would make the program unacceptable.
- Several study locations in the Atlantic and Pacific oceans identified and characterized. At the end of this phase it is planned to have several acceptable study locations (1° x 1°) identified in each ocean for possible use. Each site should have been processed through Phase III, step 5 of the site selection program (see Laine, et al, op. cit.)
- National and international legal and institutional positions established. Since the legal and institutional implications of the disposal of HLW in geologic formations under the oceans are unclear, these must be resolved during this phase of the program.
- Draft Environmental Impact Statement (DEIS) written and reviewed, and license application submitted. The DEIS will contain all the information and understanding developed in

*See also E. P. Laine, D. R. Anderson, and C. D. Hollister, *Site Qualification Plan for the Subseabed Disposal Program*, SAND81-0709, Sandia National Laboratories, in press.

Phases 2 and 3, as well as in long-term experiments and site selection studies in accordance with the requirements set forth in the NEPA, as amended.

Phase 4—Demonstration of Disposal Capability

- Title II designs completed. During this phase of the program, Title II designs for the total system will be completed.
- License or permit received. During this phase, the license requested in Phase 3 should be received.
- Dock and ship built, and tested by emplacement demonstration at anticipated handling rates. After the license or permit has been received and the Title I and II designs are complete, the dock and ship systems will be built and tested.
- Land transportation network made operational. After receipt of the license and completion of the Title I and II designs, the land transportation network, which is similar or identical to the land transportation system for the land repository, will be made operational.
- Monitoring network developed. During this phase of the program, a long-term monitoring network will be developed.

The major task of the program is to determine whether any submarine geologic formation can contain radioactive waste long enough for the radionuclides to decay to acceptable levels. Attention is focused on the waste form and the canister for containment during the period of high heat generation, and on the sediments for long-term containment.

Two key questions must be answered in order to demonstrate technical and environmental feasibility of subseabed disposal:

- Is there a barrier* or set of barriers (geological or man-made) that will offer satisfactory containment of radionuclides (emplacement processes excluded)? The barriers under consideration are:

Natural	Man-Made
Sediments	Canister
Water column	Waste form
	Sacrificial layers (overpacks)

*A barrier is defined as "any medium or mechanism by which the movement of emplaced radioactive material is retarded significantly or human access to the material is restricted or prevented, such as: engineered features including a container, waste form, or backfill material; a natural geologic medium; or institutional site access and use restrictions."

- Will these barriers still be adequate after disruption by the emplacement processes?

  This question must address:

  a) Physical disruption of sediments (resulting from emplacement)

  b) Heat effects

  c) Radiation effects

  d) Long term movement of the canister within plastic sediments

The multibarrier concept, conceived in 1974, assumes a continuously wet environment in which packaged radionuclides* are placed. The purpose of the additive barriers is to contain the wastes for sufficient periods that the rate of decay of waste constituents is higher than the rate of nuclide migration through the barriers toward man. The seabed sediments, together with any modifications to them, are considered the primary barriers to radionuclide migration. The canister is considered very important as a barrier until the geologic formation has returned to essentially ambient temperatures (≈300-500 years). The waste form is a supplemental barrier. The water column will disperse and dilute any nuclides released into it, but is not considered a primary barrier. The very remoteness of the disposal locations tends to create an additional barrier to accidental or intentional human intrusion.

A reference system has been established for purposes of discussion and programmatic planning, even though that system may have to be altered as additional information is acquired. The reference system was chosen on the basis of simplicity, availability of emplacement technology, and estimated cost.

The reference subseabed geological disposal system is the placement of appropriately treated waste or spent reactor fuel in a specially designed container which will be placed into clayey sediments away from the edges of oceanic tectonic plates (to avoid volcanic and seismic activity), and away from the edges of major circular surface currents (to avoid subsurface agitation caused by these currents). These are the abyssal hill areas of the ocean bottom, and we use the abbreviation MPG (mid-plate/gyre) to designate them.

Although several emplacement methods appear feasible, none has been developed in detail. For study purposes, our reference method is the use of either

*The purpose of the waste container is to serve as a production, transport, and burial container, and to contain waste within the immediate vicinity of its initial emplacement location through the use of engineered barriers. The waste package is defined as everything put into the emplacement hole, including waste, canister, and overpacks.

free-fall or boosted penetrators to emplace waste canisters at a substantial depth beneath the sediment surface. (Other concepts include winch-controlled injectors and drilling.) Selection of sites suitable for such emplacement is conceived as an iterative process involving interaction between historical data collection, increasingly detailed local observation, and laboratory studies of the sediments. By the use of near-bottom geophysical techniques, a detailed survey will be made of the disposal area in all relevant aspects; the survey vessel will be charged with identifying specific emplacement sites and marking them for sediment sampling, as well as for the later convenience of the disposal ship. The latter will be a specially designed vessel that will carry the wastes from a special port facility to the disposal site, and will emplace the waste canisters (also especially designed and fabricated) in the sediments. After emplacement, a monitor ship will confirm the location, attitude, and condition of individual disposal containers. By a combination of bottom-emplaced telemetering equipment and periodic resurveys by the monitor ship or its equivalent, surveillance of each disposal locale will be maintained as long as necessary.

The subseabed disposal concept differs appreciably from other disposal concepts by virtue of the relatively straightforward way in which predictive models can be verified. The reasons for this are as follows:

1. In-situ tests to increase our understanding of near-field responses and to verify predictive models for the most critical period can be run in real time (no accelerations or extrapolations needed) for the following reasons:
   a. Canisters will be spaced in a rectangular grid ~100 meters apart so that there will be minimal thermal or radionuclide interactions between canisters.
   b. The maximum temperature at the canister wall/sediment interface will occur in the first two years of disposal. Long-term tests will then allow real-time studies of near-field responses to be completed, not only for the heat-up period but for the initial cooling phase as well.
2. Long-term (15-year) thermal experiments will allow testing in real time of the main failure mechanism (breachment) of the geologic formation, which is thermal heating and cooling. (The thermal pulse from a canister emplaced 50 meters deep in the sediments will take ~10 years to reach the sediment/water interface, where it will then be dissipated in the infinite heat sink of the <1°C ocean waters.) These experiments will also demonstrate retrievability after long-term burial.
3. Since there are no canister-to-canister interactions and the oceanic geology, compared to land geology, is very simple, studies and experiments using individual canisters and accepted size and temporal scaling laws can yield a detailed understanding of the thermal and mechanical responses of the canister and sediments during the hundreds of years envisioned for the total thermal heating and cooling cycle.

Retrievability

From the preceding paragraphs, it can be seen that, before any non-R&D canisters* are placed into the sedimentary geologic formation, thermal and mechanical response tests equivalent to approximately the first 1000 years of land-based repository life will have been completed. Therefore retrievability of non-R&D canisters is not considered of primary importance, and is not included as a significant technical activity in the program at this time.

If retrievability is later deemed necessary to correct canisters incorrectly placed or other accidental conditions, currently existing technology is available to over-core the canisters and retrieve them together with some of the surrounding sediments. It appears that this procedure would be no more costly or difficult than remotely mining back into a land-based repository after backfilling has taken place.

International Program

An integral part of the SDP is international cooperative research and development, as well as annual peer review of programs and tasks, coordinated through the Seabed Working Group. This group, currently chaired by a U.S. member, has been in operation for 6 years under the charter of the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD). Representatives from the United Kingdom, France, Japan, Canada, the Netherlands, Switzerland, Belgium, Germany, the Commission of the European Communities (CEC), and the U.S. meet annually to exchange information and plan the following year's program. Further expansion in membership is expected. The

*All R&D canisters will be designed to be retrievable at the completion of experiments.

group is divided into subgroups specializing in biological oceanography, physical oceanography, sediments and rocks, waste form and canister, site studies, systems, and engineering studies.

III. Technical Approach

Work Breakdown Structure

The Master Program Work Breakdown Structure (WBS) is the framework for task and subtask descriptions established for the NWTS high-level nuclear waste subseabed disposal assessment program. This structure has been adopted for the purposes of organization, planning, and reporting the work in a logical and consistent manner. The structure includes all elements identified in the Program Outline below, and is also cross-referenced to the duties of the Technical Program Coordinators and Principal Investigators shown in the Management Structure (Section IV), as well as other NWTS programs. The elements of the WBS are shown in Figure 4.

The Subseabed Disposal Program Plan is designed to include all functions necessary to make a complete assessment of the subseabed disposal concept. The tasks identified here are being coordinated by both the SDP and ONI management and are supported by the NWTS program even though particular tasks may not be funded directly through the SDP.

Not all tasks identified in the ONI-NWTS Master Program Work Breakdown Structure (MPWBS) for the total Waste Management Program are needed in the SDP. The numbering of the particular work sections in the SDP—e.g. Systems, Site, Program Management—refers to the NWTS MPWBS.* Because some of the tasks in the MPWBS are not applicable to the SDP at this time, some numbers have been skipped. Thus, there are no 4.0, 6.0, or 7.0 tasks in this enumeration. Specific tasks and funding methods are identified in the programmatic work descriptions in Volume II.

*See the NWTS Program Plan, Fiscal Years 1980-1987, to be published.

Program Outline

1.0 Systems

The Systems Task covers the breadth of the Subseabed Disposal Program. It provides information and assistance for the program's efficient conduct through the identification of baseline needs, the preparation of baseline documents for the program's conduct and performance, identification and analyses of major technical and programmatic decisions, assessment of the program's status, assessment of the system's performance, recommendations on programmatic priorities, and other overview activities.

Systems analysis requires the use of systems computer programs and the best currently available data to identify critical parameters, specify data and modeling accuracy, identify areas of risk and environmental impact, and optimize the designs and operation of the repository. A further breakdown of the task is given below.

1.1 Sensitivity studies
1.2 Safety assessment
1.3 Cost/benefit analyses
1.3.1 Models
1.3.2 Data acquisition
1.4 Optimization
1.4.1 Design
1.4.2 Operation

2.0 Waste Package

The Waste Package Task includes all the activities required to design, fabricate, and test waste packages to meet program and regulatory requirements. Design activities include the establishment of design bases to guide the waste package activities, the development of data bases on waste form and barrier materials performance in repository environments, the development of designs, and the evaluations of the overall performance of the designs. Fabrication activities include the production of test packages and the development of specifications for equipment used in fabricating waste packages at the repository site. Testing of waste package components is also included in waste package subtasks. The final design will be addressed in the Repository section (4.0 in the NWTS MWPBS), which will be developed for the SDP in a future update of the Program Plan. A further breakdown of the task is given below.

2.1 Canister
2.2 Waste form

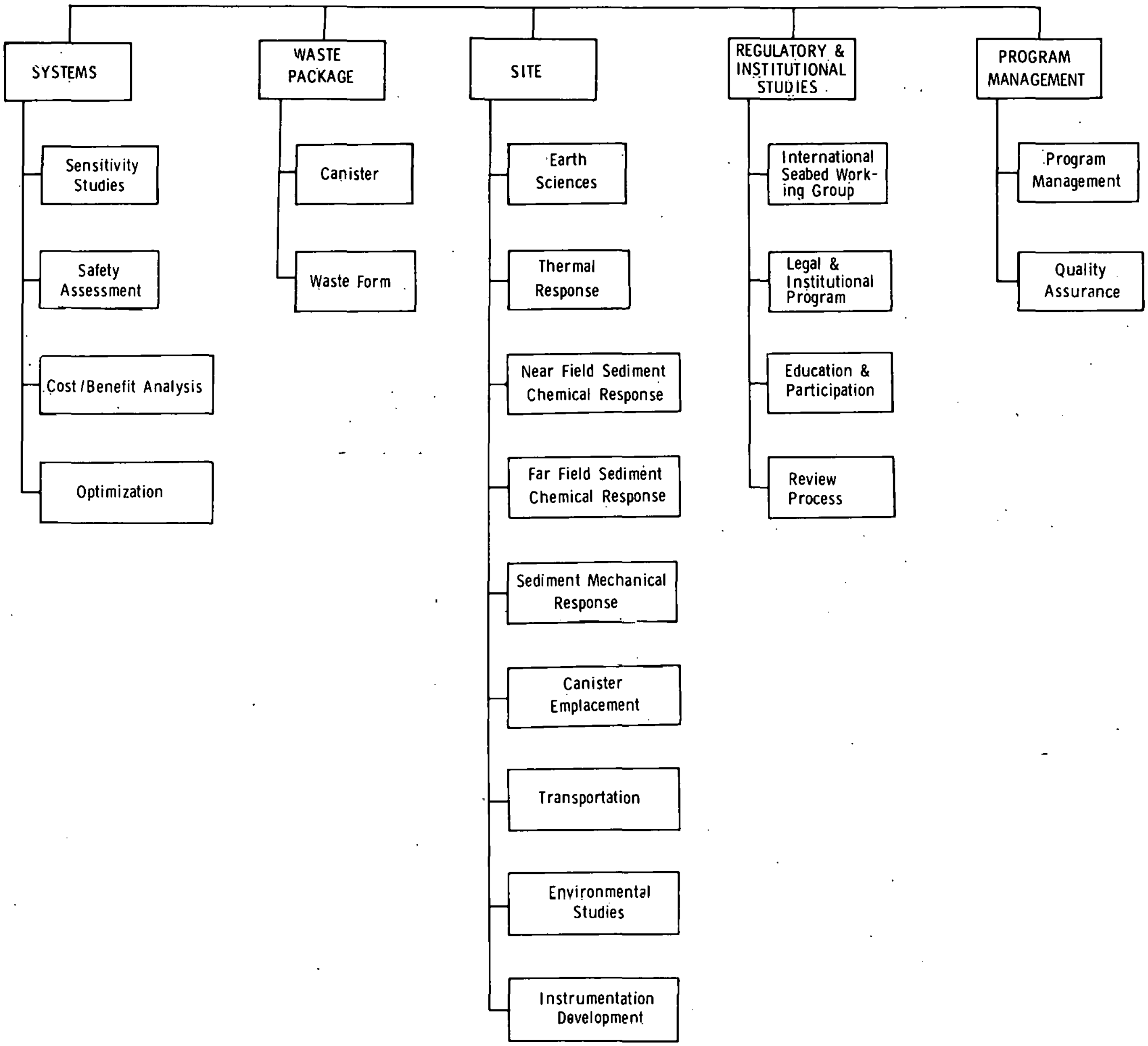


Figure 4. Master Program Work Breakdown Structure, Subseabed Disposal Program. The SDP MPWBS is based as far as possible, for purposes of project comparison and coordination, on the NWTS MPWBS (cf. the NWTS Program Plan, 1980-1987, to be published). The first level (all caps) is derived directly from the applicable NWTS categories (see Section III, Technical Approach, for a discussion of each category). The subheadings name individual task activities in each category.

3.0 Site

The Site Task includes the development of siting criteria and the identification and screening of media and geosystems using these criteria. The criteria address both geologic systems characteristics and environmental characteristics. Basic scientific studies are also conducted to provide a basis for development and verification of the complex models required to predict how a site will perform in isolating the radioactive waste. This task is related to, and benefits from, separately funded site screening activities of other nations, and is coordinated through the International Seabed Working Group described in Section 5.0. A further breakdown of Task 3.0 is given below.

3.1 Earth sciences
3.1.1 Develop assessment criteria
3.1.2 Identify and assess appropriate regimes
3.1.2.1 Pacific
3.1.2.2 Atlantic
3.1.3 Develop and deploy the monitoring system

3.2 Thermal response
3.2.1 Property acquisition and model development
3.2.2 Laboratory and/or field verification

3.3 Near-field sediment chemical responses (within the 100°C isotherm)
3.3.1 Property acquisition and model development
3.3.2 Laboratory and/or field verification

3.4 Far-field sediment chemical responses
3.4.1 Property acquisition and model development
3.4.2 Laboratory and/or field verification

3.5 Sediment mechanical responses
3.5.1 Property acquisition and model development
3.5.2 Laboratory and/or field verification

3.6 Emplacement of the waste canister
3.6.1 Property acquisition and model development
3.6.2 Laboratory and/or field verification

3.7 Transportation
3.7.1 Land transport
3.7.2 Port facilities
3.7.3 Interim storage
3.7.4 Sea transport

3.8 Environmental studies
3.8.1 Physical oceanography
3.8.1.1 Property acquisition and model development for movement of waters and solutes in northern oceans
3.8.1.2 Laboratory and/or field verification
3.8.2 Biological oceanography
3.8.2.1 Property acquisition and model development for biological uptake and movement of radionuclides in the oceans
3.8.2.2 Laboratory and/or field verification
3.8.3 Environmental impacts

3.9 Instrumentation development
3.9.1 Sandia Seafloor Research Platform (SSRP)
3.9.2 Penetrator survey
3.9.3 Long Corer Facility (LCF)

5.0 Regulatory and Institutional Studies

This task consists of development of strategies and plans to meet the requirements of national and international regulatory agencies, the performance of overall safety assessments and environmental impact evaluations, and preparation of required documentation. It includes all liaison with regulatory bodies necessary to carry out these activities. It also includes all cooperative research with other nations, through the NEA/OECD Seabed Working Group, to ensure that data needed to support the legal, social, and institutional discussions are collected and evaluated before the need arises. A further breakdown of this task is given below.

5.1 International Seabed Program
5.2 Legal and institutional program
5.3 Education and participation
5.4 Review process

8.0 Program Management

The purpose of the Program Management Task is to provide the expert and comprehensive management needed to ensure that the SDP program will achieve its objectives. This encompasses program and project planning, organization, and control. It involves QA and peer review of the technical activities, maintenance of interfaces with related DOE programs, and communications and liaison with the public and with federal, state, and local bodies. Special studies which are related to the program objectives but which cannot be foreseen, are not on the mainline of the programmatic thrust, or are strictly management (as opposed to technically) oriented are also included. The further breakdown of this task is given below.

8.1 **Program management**
8.2 **Quality assurance**

Work Description

1.0 Systems

All systems studies will begin with the reference designs and best available data and will be updated as more and better data becomes available and as the designs become more fixed. Inexpensive, easily modified models will be used for most of the parametric studies, but limited use of finite difference and finite element models will also be made. The overall objective of systems studies is to minimize costs and development time while assuring safe disposal of high level nuclear waste.

1.1 Sensitivity studies

These studies are conducted for each scientific and engineering discipline and the results are combined to formulate constraints, requirements, and responses for the system. Sensitivity studies are inputs to all of the other systems studies, data acquisition, design, and operating procedures.

1.2 Safety assessment

The safety assessment provides design specifications, uncovers deficiencies early in the design phase, and provides an input to the PSAR. If the program continues, the safety assessment will evolve into a risk analysis.

1.3 Cost/benefit analyses

Studies will be conducted to minimize as far as possible the total cost of the system, including the data acquisition, modeling design, capital, and operation. Accuracy of data and models will be equated.

1.3.1 Models

Cost/benefit analysis will be used to define the number of runs needed with large, time-consuming computer codes to provide the required confidence.

1.3.2 Data acquisition

The optimum degree of data accuracy will be established to minimize total system cost.

1.4 Optimization

This is an iterative or derivative process, used to find the most efficient designs and operating procedures analytically prior to prototype fabication and construction.

1.4.1 Design

These studies apply to transportation and emplacement equipment and to repository layout.

1.4.2 Operation

These studies apply to scheduling, transportation, emplacement, surveillance, and recovery.

2.0 Waste Package

The near-field environment within the maximum extent of the 100°C isotherm comprises the waste form, the waste canister, and the region immediately adjacent to the canister (see Figure 5). The response of the sediments is discussed in Sections 3.2 - 3.5. This region is one of high temperatures and intense radiation, where large chemical and temperature gradients may be expected to have an effect. The complexities of this region will be examined first by determining the limitations imposed by elevated temperatures alone. The effects of an intense radiation field will then be introduced to see where the tentative temperature limit can realistically be applied to the near-field environment. The methodology involves a coordinated laboratory and modeling program, predictions from which will then be tested in the field using scaled experiments designed to examine specific effects.

2.1 Canister

The waste encapsulating canister will serve as a shipping and emplacement container. In addition, it should be a valuable segment of a multibarrier waste isolation system by surviving the period of high thermal output (first 300-500 years) and thus preventing potentially rapid hydrothermal waste interactions. This 300 to 500-year survival capability should be obtainable with present-day technology at a reasonable cost and would be implemented by overpacking an inner canister with a corrosion-resistant alloy. The inner canister would also provide the mechanical strength necessary for both shipping and emplacing in a high-pressure sealed environment.

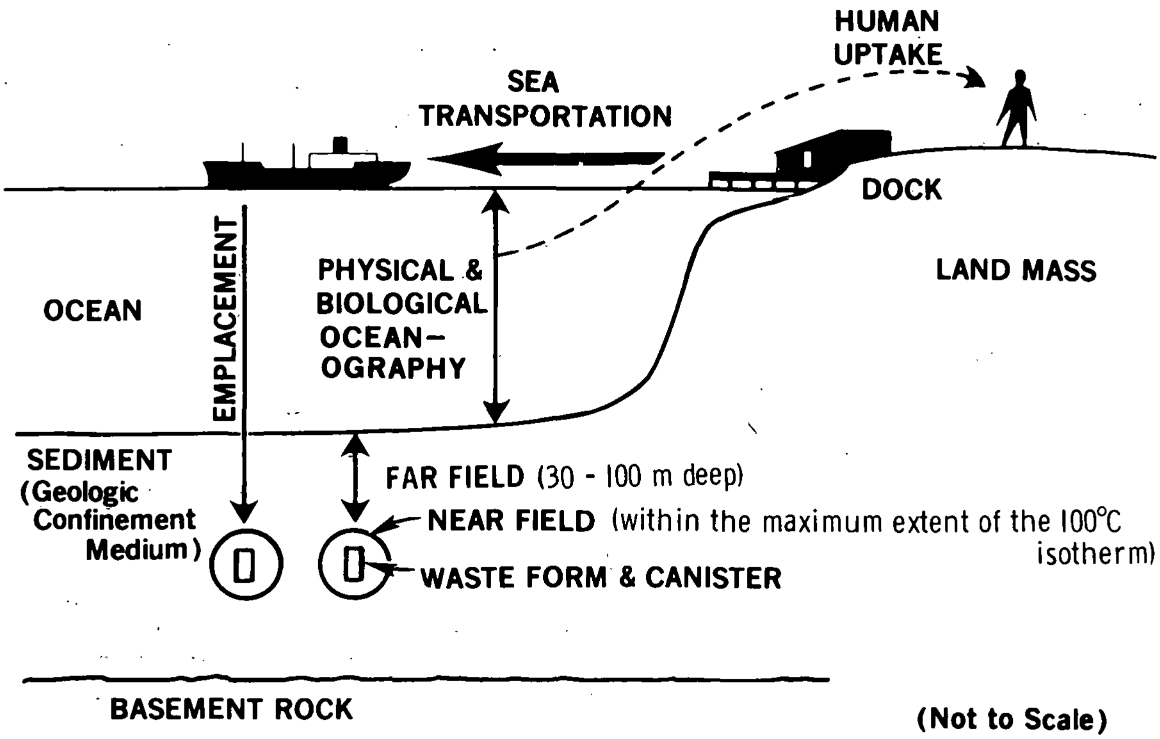


Figure 5. Subseabed Disposal Concept.

Final canister design must include a penetration guidance and early-time monitoring system; a combination floatation, acoustic, and visual locating device to aid in canister recovery in case of an accident, and capability for underwater recovery.

This rather limited effort is being coordinated with larger programs for WIPP* and NWTS.

2.2 Waste form

Aside from a minimal number of scoping experiments, no work has been conducted to date on the waste form by the SDP. (The NWTS Program, however, has been conducting a large generic waste-form effort.) Because preliminary characterization of the near-field environment has been accomplished, a program is being initiated that will determine how well candidate waste form materials perform in the subseabed environment relative to on-land, mined-repository environments, and to verify that the radionuclides leached from the waste form behave as predicted by sorption and diffusion experiments conducted with simple ionic species.

Baseline characteristics assumed at present for the waste form are the thermal, mechanical, and radiative properties of 10-year-old vitrified HLW in a cylinder 0.3 m in diameter and 3 m long. The waste form can be engineered for a wide range of thermal output. Saturated sediments which are hot (over 200°C) are 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 controlling the surface temperature of the waste through either aging prior to disposal, decreasing the amount of radionuclides in the canister, or changing canister diameter. Similar disposal technology could be used for low-level and TRU waste packages; however, economics may make such a course impractical.

3.0 Site

For the reference repository (in the sediments), the following generic activities will be undertaken for each ocean basin. Detailed analyses of the chosen study locations will then be initiated, and some in-situ thermal, chemical, mechanical, and biological experiments begun. After data from the detailed site analyses have been evaluated, a site will be selected.

*WIPP (Waste Isolation Pilot Plant)—a project to determine the feasibility of disposing of military wastes in bedded salt in Southeastern New Mexico.

3.1 Earth sciences

Geographic and geologic exclusionary criteria have been developed which have eliminated from consideration areas that are tectonically or environmentally unstable, that contain certain resources of present or future interest, or that may, with high probability, respond unpredictably to changes in currents and climate.

Criteria will be developed that will allow ranking of the remaining areas in the oceans. It is expected that several locations will be identified in each suitable Atlantic and Pacific ocean basin; the exact number of areas ranked will be governed by available funding.

Surveys will be made to acquire additional data at such locations, and the ranking criteria will be updated, after which two or three sites will be chosen in each basin from the original group for further study.

3.1.1 Develop assessment criteria

The following geographic and geologic exclusionary criteria (see also Laine, op. cit.) for deep ocean floor regions have been developed and used by both the SDP and the Nuclear Energy Agency (NEA) Seabed Working Group to identify oceanic regions for further study:

a. *Tectonic and Sedimentery Stability.* Chosen regions must be of low earthquake or volcanic activity, with minimum evidence of faulting, and characterized by slow, continuous depositional processes.

b. *Climatic Stability.* Combined movements of the two mobile media (air and water), including changes in climate (e.g., ice ages), must have minimal effect on the underlying geologic formation.

c. *Minimal Resources.* There must be low biological activity, both present and past, and few mineral resources of use to man.

d. *Remoteness from Man's Activities.* The regions must be remote from and as inaccessible as possible to man. The deep ocean floors are among the most remote regions on earth. To intrude upon these areas requires technical sophistication and a large, planned effort. The risks of sabotage or other intentional intrusion upon a subseabed disposal site by cultures less sophisticated than our own will be extremely low.

e. *Predictability.* To be suitable for emplacement of long-lived toxic materials, a geologic medium must be predictable, both spatially and temporally. The more uniform and predictable the geologic environment, the less detailed site studies must be to define the properties of the geologic formation. Oceanic areas where sedimentary processes are slow and continuously depositional, and where tectonic processes have been minimal for millions of years, are the most uniform and predictable on the globe.

Other criteria will be generated as the program matures.

3.1.2 Identify and assess appropriate regimes

Criteria will be developed both from field oceanographic studies and data, knowledge, and understanding acquired in the sediment responses (3.2, 3.3, 3.4, and 3.5) and environmental (3.8) sections of the program. These criteria will then be used to further refine the remaining regions in order that a site may eventually be identified. Vast areas in both the North Atlantic and the North Pacific that appear to answer these criteria remain unexamined. Available data have been assessed and areas chosen for further study which (1) have the most information available, and (2) from available surface acoustic records appear to be uniform and predictable (flat, acoustically layered, and without seamounts). The regions identified will be studied as funds and manpower permit, through a process described below, to locate the acceptable areas. From these studies, specific sites will be selected.

Ocean surface seismic surveys. The first and cheapest method of sceening prospective disposal regions is through high frequency 3.5 or 12-kHz and low frequency subbottom acoustic surveys from the ocean surface. These will be carried out using a spacing that will allow major flaws such as seamounts, large faults, historical sediment erosion, sediment folding, etc., to be detected. Regions that successfully pass this screening will then be subjected to another, more detailed screening.

After an area has been assessed acoustically from a surface ship, standard geophysical and geological measurements will be made on selected areas. Near-interface sediment samples will also be taken to allow initial assessment of sediment texture for possible retention of radionuclide ions. If an area successfully passes this test, then it will receive detailed, in-depth, three-dimensional acoustic studies.

Near-bottom saturation acoustic surveys. After reconnaissance by geophysical and geological cruises, prospective study locations will be surveyed in three dimensions, using the latest acoustic techniques, both from the surface and near the bottom.

This will identify any flaws in the study location greater than a few centimeters near the water interface, graduating to meters with depth. If the location successfully passes this acoustic screening, it will be sampled on a grid basis.

Detailed sampling and analysis at selected sites-. During this phase of the assessment process, long, undisturbed samples will be taken on predetermined spacings to verify the lateral and vertical continuity indicated by the earlier acoustic studies, as well as to permit chemical analyses on the full sediment column length to assess in detail the rate of ion migration through the total geologic formation.

3.1.2.1 Pacific

Two ocean basins (defined here as any expanse of >100 square degrees) have been identified for further study (Fig. 6). Others will be identified as additional funds allow assessment of the remaining historical data.

3.1.2.2 Atlantic

Three ocean basins have been identified for further study (Fig. 6). Others will be identified as additional funds become available for assessment of the remaining historical data.

3.1.3 Develop and deploy the monitoring system

After one or more study locations have been assessed using the methods set forth above, a monitoring network will be set up to develop a long-term data base on movements of water masses and the biological, sedimentary, and chemical processes of the natural environment. In the event a given site is used for waste disposal, the location, attitude, and integrity of selected canisters would be monitored. Thermochemical reactions of the near-field sediments and of selected canisters, and the rate of movement of radionuclides through the sediments, would be continuously monitored to perpetuate confidence in the subseabed multiple barrier system.

3.2 Thermal response

The near-field environment within the 100°C isotherm comprises the waste form, the waste canister, and the region immediately adjacent to the canister (see Figure 5). The response of the sediments is discussed in Sections 3.2 - 3.5. This region is one of high temperatures and intense radiation, where large chemical and temperature gradients may be expected to have an effect. The approach used in examining the complexities of this region is first to determine the limitations imposed by elevated temperatures alone. The methodology involves a coordinated laboratory and modeling program, predictions from which will then be tested in the field using scaled experiments designed to examine specific effects.

Nuclide movement through the sediment would be 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 300-500 years after waste emplacement, the fission-product-dominated thermal output may induce larger pore-water velocities than those naturally present. Performance of the canister and waste form will be important during that period. In addition, any chemical, mechanical, or thermal changes caused by heating and irradiation 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.

3.2.1 Property acquisition and model development

This phase of the study focuses on the development of preliminary thermal models and on the acquisition of thermal properties needed to calculate temperature profiles in the sediments as a function of post-burial time, variations in sediment/canister interface temperatures, and temperature distributions in the waste form and canister for geometries of interest. In support of this activity a literature search is under way to obtain available data on changes in physical and chemical properties of sediment/water mixtures that could be expected over the temperature range of interest. Laboratory tests are providing additional data on physical, chemical, and thermal properties.

The second phase of activity extends the thermal model to incorporate thermally induced pore-water motion through a fixed sediment matrix, assuming a Darcian flow in response to a pressure gradient, and develops a model for calculating radionuclide retention assuming a known distribution coefficient. In support of these activities, efforts are under way in the laboratory to determine the extent to which water will actually move through sediments at elevated temperatures.

Figure 6. Regions Identified for Further Study. Two areas in the mid-plate, mid-gyre (MPG) regions in the North Pacific and three in the MPG regions of the North Atlantic have been identified for further study. The MPG regions are among the most stable sedimentary geologic formations on the planet.

3.2.2 Laboratory and/or field verification

A series of laboratory tests in which different sediments are subjected to elevated temperatures and pressures will be completed as a basis for the verification process for the thermal model and input properties.

An In-Situ Heat Transfer Experiment (ISHTE), planned for field deployment in 1984, is being designed to verify laboratory properties and models used to predict the response of red clay sediments to long-term deployment of a heat source. ISHTE will be deployed at MPG-I, northeast of Hawaii, in a water depth of 5000-6000 meters. A heated canister will be implanted in the sediment and the temperature history of the canister/sediment interface will be monitored. A series of thermal probes will be used to measure the history of the temperature field in the surrounding sediments. Anticipated duration of deployment is one year; this is sufficient time for the thermal field around the canister to come to near equilibrium. Data from the experiment will be collected periodically by interrogation of the experiment platform through an acoustic telemetry link.

Specific properties of interest are those related to heat transfer, such as thermal conductivity and diffusivity. Direct measurement of sediment thermal conductivity using line-source techniques will be made in the heat-affected sediment. Given this information, the thermal diffusivity can be determined from the temperature field data.

A simulation of the ISHTE experiment is planned for FY82, prior to the actual deployment, in a large pressure vessel. This will be a small scale heater (approximately 30% full size) in a large tank of reconstituted sediment. In this scaled simulation the one-month experiment will correspond in thermal response to the one-year deployment of ISHTE. The ISHTE simulation does not take the place of the actual ISHTE in that it will not be performed in-situ in undisturbed sediment.

There are several purposes of the ISHTE simulation experiment. It is a test to uncover any surprises prior to the actual ISHTE. It will provide an opportunity to make a bulk laboratory determination of the thermal conductivity of sediment at high pressure. It will provide a test of the correlation between a scaled laboratory simulation and an in-situ experiment. Good correlation will lend credence to other laboratory modeling of thermal response. Finally, it will provide an opportunity to test hardware and electrical instrumentation to be on the actual ISHTE at operating pressure.

3.3 Near-field chemical responses (within the 100°C isotherm)

The near-field environment within the maximum extent of the 100°C isotherm comprises the waste form, the waste canister, and the region immediately adjacent to the canister (see Figure 5). The response of the sediments is discussed in Sections 2.0 and 3.2. This region is one of high temperatures and intense radiation, where large chemical and temperature gradients may be expected to have an effect. The approach used in examining the complexities of this region is first to determine the limitations imposed by elevated temperatures alone. The effects of an intense radiation field will then be introduced. The methodology involves a coordinated laboratory and modeling program, predictions from which will then be tested in the field using scaled experiments designed to examine specific effects.

3.3.1 Property acquisition and model development

This phase of the task focuses on the development of chemical models and acquisition of chemical properties needed to predict the chemical responses within the sediments as a function of temperature, time, and introduced foreign ions. In support of this task, efforts are under way in the laboratory to determine what chemical changes are induced by heat alone; i.e. what changes in corrosion rates, radionuclide release rates, pH, mineralogy, or sorption coefficients (Kd's) are caused by elevated temperature, and whether organic complexing agents are produced, complex species formed, or trace ions released by such elevated temperatures?

Once the limitations imposed by temperature alone have been assessed, laboratory experimental work will be initiated which will incorporate the effects of intense gamma radiation into the hydrothermal chemistry of the system. Particular emphasis will be placed on assessing the amount of strong oxidizing agents or additional complexing agents generated. Modeling at this stage will include revision of various individual models to incorporate synergistic effects. Final objectives of the modeling effort include an assessment of the degree to which radioisotopes may undergo local redistribution in the near-field environment, a source term for far-field migration studies, and finally an assessment as to whether other mechanisms may short-circuit the far-field barrier. Conclusions reached on the basis of this modeling will be tested in scaled field experiments. After the problems associated with heat and radiation have been identified and quantified, allowable design limits can be set and the initial waste loading of the canister can be specified.

3.3.2 Laboratory and/or field verification

ISHTE (Sec. 3.2.2) represents a unique opportunity to perform in-situ experiments. A number of experiments designed to make field verification of a variety of other SDP laboratory measurements of thermal-driven phenomena will be included. These include attempts to measure chemical responses such as changes in pore water chemistry, changes in the sediment minerology, and the diffusion of various ions in the heat-affected sediment. Geotechnical experiments will attempt to measure the effect of temperature on pressure and pore water motion, and the change in in-situ sediment shear strength after exposure to temperature.

3.4 Far-field sediment chemical responses

It is important to quantify the retention capabilities of the primary (i.e., undisturbed) sediment barrier. This study will, first, evaluate comparatively the generic sediment types (hemipelagic and red clays, and calcareous and siliceous oozes) using batch Kd's for single ions and permeabilities. Preliminary work has focused on the red-clay sediments because they have very high Kd's and low permeability for waste cations, and also because large areas of the MPG's in both the Atlantic and Pacific are covered with this type of clay. Single-ion batch Kd's are being measured. Second, column diffusion experiments have been initiated to assess kinetic sorption effects and the possibility that surface diffusion on clay minerals may provide an alternative migration mechanism to that provided by molecular diffusion through the pore water. Third, an ion transport model will be developed to simulate the movement of radionuclides in laboratory conditions and in natural and modified environments. Fourth, the model will be tested and refined through in-situ field validation experiments.

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 ($<1\mu$), water-saturated clays with permeabilities less than 10^{-7} cm/sec at a unit hydraulic gradient.* Migration of radionuclides in the far-field environment is most likely to occur primarily by molecular diffusion. Such diffusion is opposed by a combination of sorption and precipitation of insoluble species.

*This gradient, which allows laboratory measurements to be made in a reasonable time, is orders of magnitude larger than natural gradients in the abyssal hill regions.

3.4.1 Property acquisition and model development

Testable 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.

3.4.2 Laboratory and/or field verification

Field verification of far-field transport processes is planned as soon as sufficient laboratory and modeling data are acquired to allow detailed planning. Some generic criteria must be met, however. The experiment should be completed in the deep ocean at depths greater than 5000 m, with the pre- and post-test cores to demonstrate an understanding of ion migration, including the effects of heat, radiation, and change of pH as they affect the source term, as well as of varying sorption coefficients and disruption of sediment around the source. Deployment should be in an area well understood in a geologic sense.

An ion migration experiment using carefully selected chemical tracers will be included on ISHTE to verify the far-field ion transport model. This experiment will determine the extent of any convective flow of pore waters in the far field, and verify laboratory studies of radionuclide sorption and diffusion.

3.5 Sediment mechanical responses

Once a canister has been emplaced at the proper depth, the surrounding sediment must be shown to retain its effectiveness as a barrier to ion migration back to man. The emplacement path represents a volume of highly disturbed sediment. Sufficient understanding of the sediment's mechanical response subsequent to disturbance must be developed to ensure that the path does not represent a short-circuit of the sediment barrier.

An embedded heat source subjects the sediment to two opposing mechanical response phenomena: The sediment thermal expansion creates buoyant forces, tending to cause a volume of sediment to rise slowly, possibly dragging the canister upward. The sediment may also undergo a reduction in strength due to the increased temperature, which may allow the canister to settle to a greater depth. Detailed studies must be conducted to characterize the sediment in these environments.

3.5.1 Property acquisition and model development

Laboratory physical and mechanical properties must be acquired and models developed to assess the risk of thermally induced movement of the canister and the surrounding sediments, and to determine whether the canister penetration channel remains an adequate barrier. The sediments are low-strengh and plastic, so that any hole or fracture made in them is likely to be self-healed. From this standpoint the plasticity of the sedimentary barrier is beneficial; however, the long term buoyancy forces generated by heating of the sediment and pore water may create creep deformation processes which must be modelled accurately in order to predict the sediment motion over long periods of time. These problems of long term movement of the canister and its surrounding sediment are under investigation.

3.5.2 Laboratory and/or field verification

Laboratory and field experiments will be designed which will allow the models developed in Section 3.5.1 to be tested. These include centrifuge simulation tests as well as in-situ tests in the red clay sediments in one of the study regions identified in Section 3.1. In both cases movement of the canister within the sediment will be monitored. The movement of a volume of heated sediment through colder sediment will also be studied.

3.6 Emplacement of waste canisters

Several potential emplacement concepts, including drilling and the use of penetrators, have been identified for the SDP (Figure 7). Criteria for selecting the optimal method have yet to be defined, but will include (1) depth of emplacement necessary to ensure containment of radionuclides, (2) rate and completeness of hole closure following emplacement, (3) degree of change of sediment properties, (4) engineering feasibility, and (5) economics.

The penetrator concept is the current reference method for the SDP. Penetrator emplacement, discussed in more détail in last year's Program Plan, requires the least engineering development and, because of its simplicity, is economically efficient.

3.6.1 Property acquisition and model development

Sophisticated models are necessary to predict how sediment will react to canister emplacement. Sediment deformation and flow response during emplacement and sediment/canister interaction forces must be assessed before we can know whether a given emplacement concept will satisfy the criteria. Models that properly account for the interaction of the sediment matrix and pore water are needed before we can fully understand how the sediment/water system responds to emplacement disturbances. Such models are now being developed.

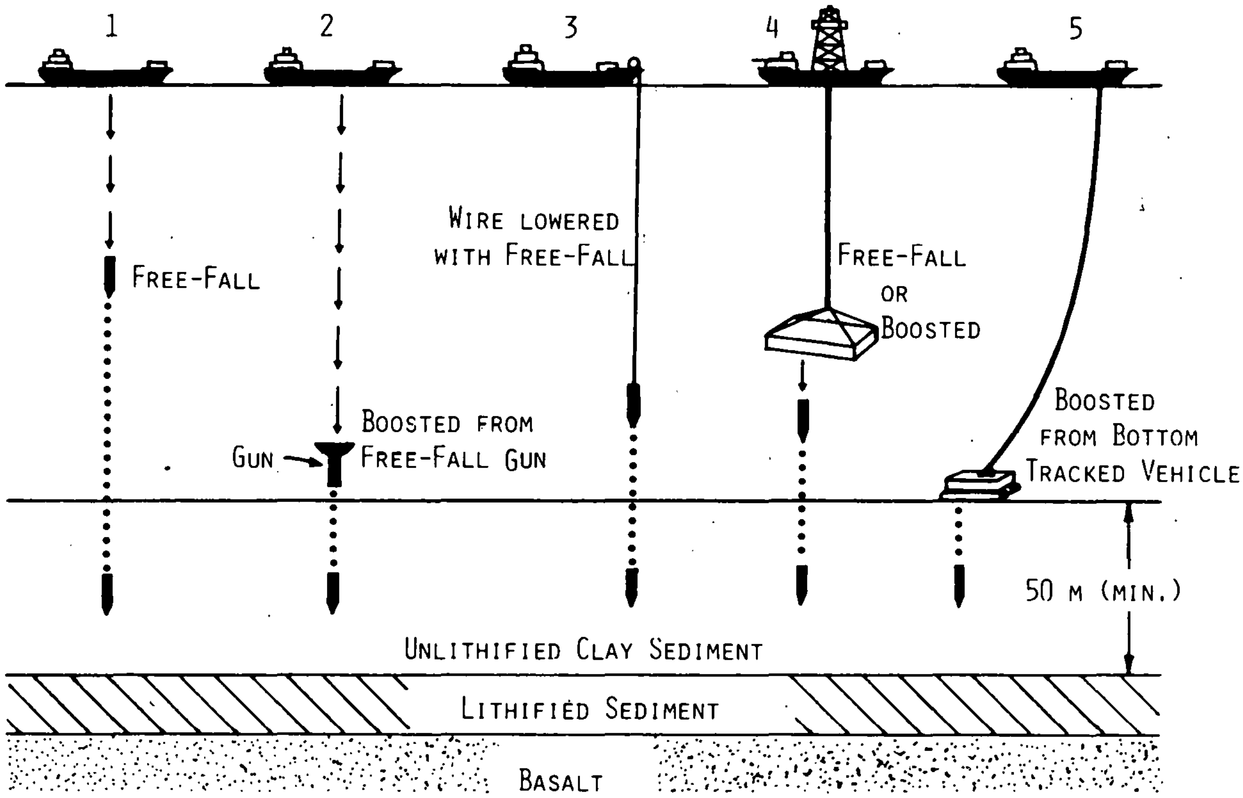
Package. The delivery of wastes to the design position within the sediment column requires that the canister be compatible with the technique selected for emplacing the wastes. A complete system for emplacing the wastes will be designed and integrated with the canister design. The system will be tested and refined through a series of ocean experiments adequate to ensure the safe deployment of waste canisters.

Sediment (hole closure). If it cannot be shown that the emplacement hole closes dynamically as a result of the emplacement process, it may be necessary to provide an engineered system that is capable of inducing closure of the residual penetration hole after waste canisters are emplaced. The system would remove discontinuities in the sediment/water structure and provide the degree of reconsolidation of the sediments necessary to ensure an adequate barrier to the release of radionuclides. The SDP includes provisions for developing and implementing such a technique should it be required.

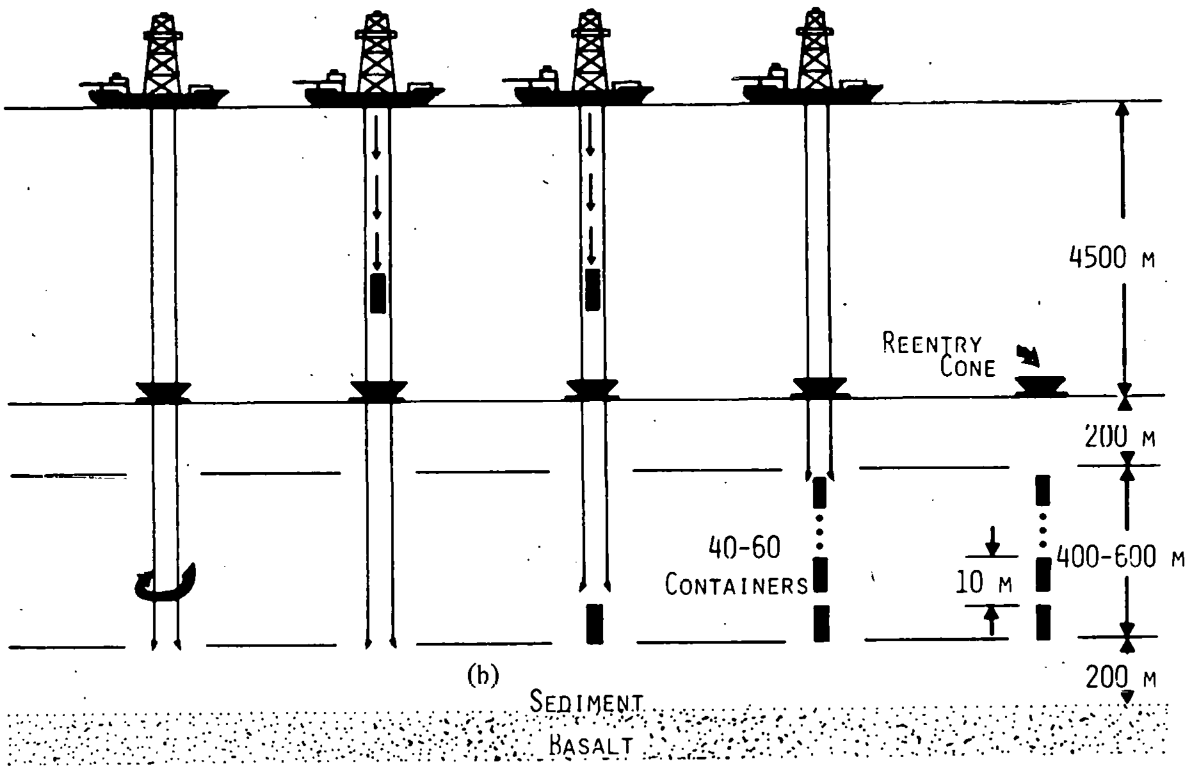
3.6.2 Laboratory and/or field verification

Laboratory testing programs to determine constitutive equations capable of describing the quasistatic and dynamic deformations of sediments are being pursued to fulfill the model requirements. In addition, laboratory simulations are being used to validate the predictive capability of the models developed. Scaling laws governing the phenomena simulated in the laboratory are being developed to determine the relationship between full-scale behavior and laboratory results.

The décision reached using the developed predictive capability regarding the best emplacement technique must be verified through an in-situ validation program. This will consist of instrumented emplacement of prototype canisters. Hole closure rates, degree of sediment disturbance, and proper depth of emplacement will be determined for comparison with established acceptability criteria. In addition, the success of the engineering techniques to emplace wastes, in terms of both reliability and cost, will be evaluated.



(a)



(b)

Figure 7. Potential Emplacement Concepts: (a) Sediment penetrator concept, (b) Drilled-hole concept.

3.7 Transportation

The transportation of nuclear wastes from originating sites such as reactors, reprocessors, or interim storage to final subseabed emplacement will involve six major divisions: (1) land transportation systems, (2) port handling facilities, (3) interim storage, (4) horizontal sea transportation systems, (5) vertical transport through the water column, and (6) vertical transport through the sediments (emplacement). Land transport systems will cover transport from originating sites to receiving stations at the port. Port handling facilities will prepare shipments for transfer to the sea transportation system. Interim storage will accommodate the waste to reduce the effect of delivery and shipping schedules. Sea transport systems will be used to move the waste from the port to the disposal sites. Some of the activities and expected problem areas associated with design, licensing, and fabrication of these systems are identified below. A major portion of this activity will be handled through the DOE Transportation Technology Center.

3.7.1 Land transport

The two nuclear waste forms to be transported for subseabed disposal are high-level waste and spent fuel. The HLW will be canistered and the spent fuel may be shipped either canistered or uncanistered. The fundamental technology for transporting either waste form is generally available, but further development will probably be required as system details become clear. HLW shipping casks have not been designed in detail, licensed, or fabricated, but conceptual designs that have been developed will accommodate about 12 canisters, each 0.3 m in diameter and 4 m long.

Spent fuel casks having NRC Certificates of Compliance are available for shipping uncanistered spent fuel, and a few units have been fabricated and are in use. With modifications, these designs might be used for shipping canistered spent fuel. However, since subseabed disposal may require cooling times longer than those assumed for present spent fuel casks, new cask designs may prove to be more cost-effective.

Major factors associated with land transport will be (1) establishing and maintaining interface requirements at shipping and port facility sites, (2) establishing overall system logistics such as routes to be traveled and desired modes of transport—truck, rail, barge, or combinations thereof—and (3) establishing a cask utilization schedule that will allow timely delivery of an adequate supply of casks. A detailed program plan is being developed by the NWTS/SNL Nuclear Materials Transportation Technology Department.

3.7.2 Port facilities

The port facilities are the interface between the land and sea transportation systems. It is assumed that HLW will be transported to port facilities that already exist on government reservations. It may be necessary to add dockside devices (redundant cranes, shielding, etc.) at these locations. The devices may be as simple as systems for hoisting shipping casks from land transport systems to sea vessels, or as complicated as systems needed to unload rail and truck casks, inspect and overpack waste materials, and load sea vessels. 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 may be fitted with emplacement and accident location equipment.

The port facility must be designed as an integral part of a comprehensive transportation system, in which all aspects of handling and transport, from the land shipping site to the sea disposal site, are considered. Port facility design is strongly dependent upon:

1. Land transportation logistics and interfaces;
2. Sea transportation logistics and interfaces;
3. Overpacking location;
4. Sea transport equipment decisions, and
5. U.S. and international regulatory considerations.

Studies addressing development and construction of the port facility and the transport and emplacement ship have not been started. They will be initiated when technical and environmental feasibility of the basic concept has been assured.

3.7.3 Interim storage

Storage of solidified HLW or overpacked spent fuel at the waste processing plant, the dock, or aboard ship 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.

Studies addressing development and construction of the port facility and the transport and emplacement ship have not been started. They will be initiated when technical and environmental feasibility of the basic concept has been assured.

3.7.4 Sea transport

A sea transportation system must be developed for carrying nuclear waste from the port to the subseabed disposal site, for vertical transport through the water column, and finally for emplacing the waste in the seabed. This system must insure the safe and secure movement of waste during the voyage and emplacment.

At present, no U.S. system for shipping spent fuel or HLW by sea exists other than the use of commercial ships and spent fuel shipping casks. However, the Japanese have developed the *Hinoura Maru* system for transporting spent fuel from one port to another, and the British are transporting Japanese spent fuel from Japan to the UK for reprocessing. Spent fuel is transported in multiple casks in the hold of the ship, which is specially developed for the purpose and has special safety features. However, this system cannot emplace waste canisters in the seabed.

For the reference penetrator system it is anticipated that the waste, packaged in a specially designed penetrator container or overpack, would be placed aboard the transport-emplacement ship, and would be transported to the disposal area by a route designed to minimize risks to the shipping lanes and to the environment, with minimal interference to people participating in ocean activities (fishing, recreation, etc.). It is expected that acceptable sites will be identified in both the Pacific and the Atlantic.

While being loaded onto the ship, waste canisters would be fitted with locating devices and recovery mechanisms. The locating devices would be designed for a 5-year operational life and would upon activation continuously identify the position of the waste container in case of emplacement error or accident, in order to facilitate retrieval.

The ship would be equipped with handling devices for moving casks, for examining the condition of canisters, for cooling 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.

No conceptual designs have been completed. However, preliminary assessments have resulted in the suggestion that waste canisters be loaded onto the ship underwater through an opening in the ship's side and emplaced in the sediment through a port in the ship's bottom to minimize the risk of worker exposure.

Once emplaced in the subseabed sediments, each canister's position would be documented by instrumentation, and the necessary monitoring of the disposal area established or continued.

3.8 Environmental studies

The studies described below will supply data and information for the Systems, Transportation, and Earth sciences activities of the program.

3.8.1 Physical oceanography

After early seabed studies, the water column was judged inadequate as a primary containment barrier* for HLW, even though some of the water at the bottoms of 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, lense-like manner. Nevertheless, the age of these deep water masses, and their advection and dispersion characteristics, need to be studied to allow for (1) understanding of the barrier properties of the water column, and (2) evaluation of the consequences of dilution and dispersion of radionuclides inadvertently released by repository failure or transportation accidents. Models of these processes must be constructed for use in assessing the risks and environmental impacts of subseabed disposal. Field verification experiments are planned.

3.8.1.1 Property acquisition and model development for movement of waters and solutes in northern oceans

A physical oceanographic systems model is being developed which is composed of a bottom boundary layer submodel, a regional eddy-resolving general circulation submodel, and an ocean basin general circulation submodel. Components for this model are being obtained and will be upgraded at SNL as required. The physical oceanographic model will be interfaced with the biological transport model identified in 3.8.2.1 for the calculation of radionuclide concentration histories in the water and in biological organisms at any point of interest in the North Pacific or North Atlantic oceans.

3.8.1.2 Laboratory and/or field verification

Laboratory and in-situ physical oceanography experiments will be planned and executed to help verify both the submodels and properties needed for the submodels discussed in 3.8.1.1. Information and data will be collected on the movements of natural and man-made tracers such as radionuclides from weapon explosions, common natural radionuclides released into the water from the sediments, and chemicals released into the ocean through the atmosphere and the river systems.

*While the water column would be beneficial in that it will allow very large dilution and dispersion of radionuclides in worst-case accidents or long-term unexpected events, it is not considered an acceptable long-term confinement barrier to prevent the migration of radionuclides to man

3.8.2 Biological oceanography

The possible role of the ecosystem in transporting accidentally released radionuclides back to man must be determined. These studies must consider both deep and shallow-water organisms, so that all potential release scenarios can be addressed. Somatic and genetic effects on biota must also be quantified.

3.8.2.1 Property acquisition and model development for biological uptake and movement of radionuclides in the oceans

No models for radionuclide transport via the food web through the water column exist at this time. Therefore, a multicompartmental ecosystem model is being written, and parameter studies on important pathways and environmental effects will be performed. Experiments are under way which will allow the acquisition of necessary standing crop data, turnover rates, and uptake rates for organisms or groups of organisms considered to be primary links in the radionuclide transport path.

3.8.2.2 Laboratory and/or field verification

Laboratory and in-situ biology experiments will be planned and executed to verify the model and properties as soon as sufficient progress has been made in section 3.8.2.1 above to allow design of logical experiments.

3.8.3 Environmental impacts

Since the deep sea may contain undiscovered animals of major taxonomic or phylogenetic interest, additional studies of basic community parameters will be completed to better ascertain any potential impact of accidentally released radionuclides on the biota of the deep sea. We have assumed that the radiosensitivity of abyssopelagic biota is the same as for related epipelagic biota, because, in general, radiosensitivity is a function of the molecular size of DNA. This assumption will be tested by conducting radiosensitivity studies on deep sea organisms as well as on their shallow-water counterparts. Experiments to study the effects of heat on the benthos will be conducted as add-ons to the in-situ heat transfer experiment (ISHTE).

3.9 Instrumentation

3.9.1 Sandia Seafloor Research Platform (SFRP)

The SFRP is a tethered, unmanned deep-sea research platform being developed for use both as a near-bottom towed survey vehicle and as an on-bottom work vehicle in depths to at least 6500 m.

3.9.2 Penetrator Survey Instrument

A penetrator capable of carrying instruments designed to measure in-situ properties of the sediments is needed to verify lateral and vertical uniformity and coherence of a sedimentary geologic formation.

3.9.3 Long Corer Facility (LCF)

Standard piston coring systems are generally limited to less than 20 m of penetration, and disturbance of samples is such that they are not suitable for certain geotechnical studies, such as shear strength. In addition, complete stratigraphic information is needed down to the horizon at which the waste canister will be placed (~50 m). A long coring capability is needed by which at least 50 m of high-quality continuous cores of stiff red clay sediments can be obtained. The LCF presently being designed will provide this capability.

5.0 Regulatory and Institutional Studies

The radioactive disposal programs of most countries, including the U.S., are focused on investigation of geologic formations on land as possible containment media for nuclear wastes. However, in recent years several countries in addition to the U.S. have initiated programs to investigate use of geologic formations in the subsea floor.* Therefore, in addition to demonstrating technical, environmental, and engineering feasibility of subseabed emplacement, we must clarify national and international institutional definitions and legal implications. This study area is divided into four sections:

First, a U.S. capability to assess the technical and environmental feasibility of ocean disposal options undertaken by other nations must be developed, even though it is not a legal requirement for national implementation of a subseabed disposal option.

Second, current national and international legal and institutional aspects must be assessed. Later, if technical and environmental feasibility is established, attention will be given to resolving problem areas.

Third, the current U.S. policy and legal position must be defined. Then, if technical, environmental, and economic feasibility is established, assistance will be given in developing the national position to allow use of the option if such action is needed.

Fourth, important factors of concern to the public must be identified, after which the public must be

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

made aware of goals and progress, and must be involved to the greatest possible extent in all aspects of the program.

5.1 International Seabed Program

Technical aspects of subseabed disposal are being addressed on an international level via a series of international workshops. A Seabed Working Group (SWG) has been created, consisting of a (Nuclear Energy Agency-restricted) group of member countries under the Organization of Economic Cooperation and Development (OECD). These are the Comission of European Communities, France, Japan, the United Kingdom, the Netherlands, the U.S., Germany, and Canada. Belgium and Switzerland participate as observers. 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. The SWG meets annually.

5.2 Legal and institutional program

The institutional and legal implications of the subseabed disposal option cannot be brought fully into focus before the technical and logistic attributes of an actual program can be projected with more clarity. However, an ongoing legal review is being conducted to assure compliance with U.S. statutes, treaty law, and case law. Institutional aspects will also be assessed continuously.

On the international level, the London Dumping Convention (LDC) of 1972, a multinational treaty developed to protect the oceans from pollution by man, specifically addresses the disposal of both low and high level wastes into the ocean waters. The treaty, which was written before the concept of disposal of HLW in submarine geologic formations was devised, does not address such disposal. However, the LDC is a living treaty and is reviewed and updated every five years to keep it current with scientific advances. A chapter can be prepared which will protect the ocean waters and the environment from inadvertant release of radionuclides from the disposal of radioactive waste in geologic formations beneath the oceans. For example, it was determined that the environmentally safest way to dispose of certain chlorinated hydrocarbons was to burn them at sea. This change to the LDC took approximately five years. During the next few years, the SDP will actively pursue the preparation of additional clauses to the LDC which will deal specifically with HLW disposal in submarine geologic formations, and will investigate other international management possibilities for the concept.

The two regulatory agencies in the U.S. responsible for radioactive waste disposal are the Environmental Protection Agency (EPA) and the Nuclear Regulatory Commission (NRC). Insofar as subseabed disposal is concerned, their duties are not as clearly defined as with the land options; however, it is clear that EPA would license any U.S. ocean geologic repository. Both EPA and NRC will regulate the transportation of U.S. waste to the repository. The SDP will continue to work with both the EPA and the NRC to clarify all roles, to develop the necessary data base, and to assist in the development of the understanding and regulations necessary to allow the subseabed option to proceed, assuming it is found to be feasible from a technical, environmental, and engineering standpoint.

5.3 Education and participation

The NEPA process requires public involvement in decisions which may affect the quality of the environment. Most individuals (including scientists) are poorly informed about nuclear materials and about the oceans unless they are directly involved with research in these areas. Thus, the subseabed education efforts will have to begin by making available the necessary background material. The primary task is to convey technical information.

The methods for educating the scientific community include program involvement, reviewed publications, presentations, and workships. Much of the education process for this section has been completed. The methods for educating the decision-makers (e.g., National Oceanic and Atmospheric Administration, EPA, NRC, Office of Technology Assessment, Office of Science and Technology Programs, the U.S. House of Representatives, and the U.S. Senate), include briefings, hearings, workshops, publications in respected journals (such as *Science*) and information exchanges. The methods for educating the public (e.g., the news media, environmental groups, the League of Women Voters, etc.) include publications, briefings, workshops, and program involvement.

5.4 Review process

Reviews are conducted for the SDP in order to assure that the technical activities are being properly conducted, to meet NEPA requirements, and to provide reassurance to those who cannot themselves evaluate the research. Some of the reviews are to be conducted by experts within the program; however, the three remaining major reviews (scientific and environmental, engineering, and final concept reviews) will be completed by an external group such as the National Academy of Science or National Academy of Engineering.

Each year an annual meeting is held with all SDP principal investigators, at which the past year's research is discussed and reviewed by the other scientists within the SDP. When a piece of research has been completed, the program strongly encourages the investigators involved to publish their data and results in the open literature where they can be reviewed by the public and the scientific community at large.

In addition, an international Seabed Working Group has been established under the Nuclear Energy Agency/OECD. In addition to exchanging information on specific research topics of interest, this group annually review the research of the 8 countries involved in the assessment of geologic disposal beneath the oceans. This review has as one of its goals the identification of any uncertainties which might make the concept unacceptable.

Workshops are occasionally used to bring a group of scientists who are not funded by the program together to focus on a section of the program in great detail.

The scientific and environmental feasibility, engineering feasibility, and environmental impact statements for the program will accomplish two things: first, the reviewers will identify any problem areas which have been overlooked by the SDP; second, and more important, they will make an independent assessment of the validity and acceptability of the subseabed disposal concept at that phase of its development. If these assessments are positive and no major problem areas are identified, the program will proceed; if the reviewers determine on scientific, technical, or environmental grounds that the concept is unacceptable, further efforts will be devoted exclusively to demonstrating this unacceptability to other nations investigating the subseabed concept.

8.0 Program Management

The objective is to manage the SDP in the most cost-effective and scientifically sound manner, using new and existing tools such as activity charting, internal and external review committees, reviewed journal articles, workshops, etc. The quality assurance program is also included in this section.

8.1 Program management

The program will be managed by personnel at Sandia National Laboratories and by the Principal Investigators at various universities. The aims of the management function include, in addition to cost effectiveness and scientific soundness, a close coordination with the other sections of the NWTS program through the Albuquerque Operations Office of the Department of Energy.

8.2 Quality assurance

The quality assurance program will be developed in such a manner that if the subseabed option is found to be a feasible disposal option, acceptable quality assurance will be in force.

IV. Management Structure

Management Duties

The Subseabed Disposal Program management has two major program responsibilities:

- To assess the feasibility of disposal of high-level wastes or spent fuel into geologic formations beneath the sea floor, and
- To develop and maintain a viable program for assessing and cooperating with, where appropriate, the waste disposal plans of other nations.

Sandia National Laboratories has the prime responsibility for coordinating and managing these parts of the program, including contracting to many Principal Investigators at universities and private companies, and coordinating the efforts and/or monies from government agencies, including DOE, NOAA, and EPA. Following is a description of the responsibilities of the Subseabed Program management as shown in Figure 8.

Program Manager

The Program Manager is responsible to DOE's Division of Waste Isolation and the Albuquerque Operations Office for overall program planning, achievement of program goals and objectives, reviewing and presenting program results in accordance with HQ guidance, acquiring and directing the activities of the Principal Investigators needed to meet program goals and objectives, and reporting costs, progress, technical status, and program performance.

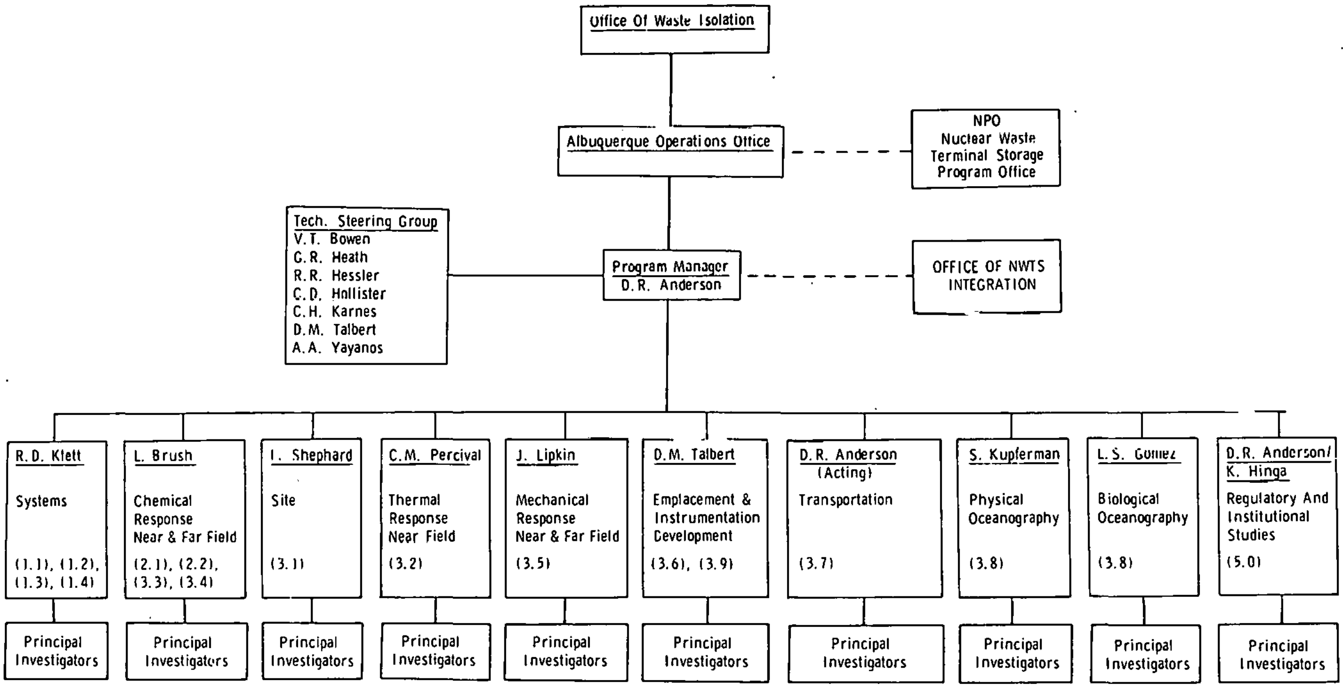


Figure 8. Subseabed Disposal Program Management. The DOE Division of Waste Isolation provides support to the Deputy Assistant Secretary for Nuclear Energy (not shown) and receives field support from the National Terminal Waste Storage Program Office (NPO). Responsibility for the administration of the SDP as an individual NWTS Project Element lies with the Albuquerque Operations Office (ALO) of the DOE. Specific activities are carried out by Principal Investigators under Technical Program Coordinators for each task. The TPC's are coordinated by the Program Manager at Sandia National Laboratories.

Technical Program Coordinators (TPC's)

Technical Program Coordinators are responsible to the Program Manager for accomplishing assigned tasks needed to reach an assigned goal or milestone. They develop and implement appropriate subtask plans in response to requests of the Program Manager, including reviews, technical status reports, and documentation of costs and progress as required, and coordinate and oversee the work of the PI's.

Principal Investigators (PI's)

The Principal Investigators carry out individual activities as agreed by the TPC and the Program Manager. These responsibilities, in addition to successful and timely completion of the activity, include periodical reports on their accomplishments, and provision of detailed technical guidance for the phase of the program in which they are involved.

Internal Technical Program Reviews

Participants in the program reviews will be made up of senior scientists from both the ocean science and engineering fields associated with the subseabed assessment program. They will report on their individual research activities, exchange information with other scientists representing other scientific disciplines and groups, and review the quality, completeness and relevance of the scientific tasks for the SDP. The reviews will include both scientific and institutional aspects of the SDP.

V. Major Milestone Schedule

Because of the large number of interactions and interfaces within the Seabed Disposal Program, network analysis techniques are used in the planning, control, and optimization of program management. Figure 9 is the Programmatic Activity chart, and includes the time-phased major milestones.

These schedules are very tightly interrelated with program costs. To project schedules beyond one year, an assumption must be made that adequate funding will be available to complete the program by 2010.

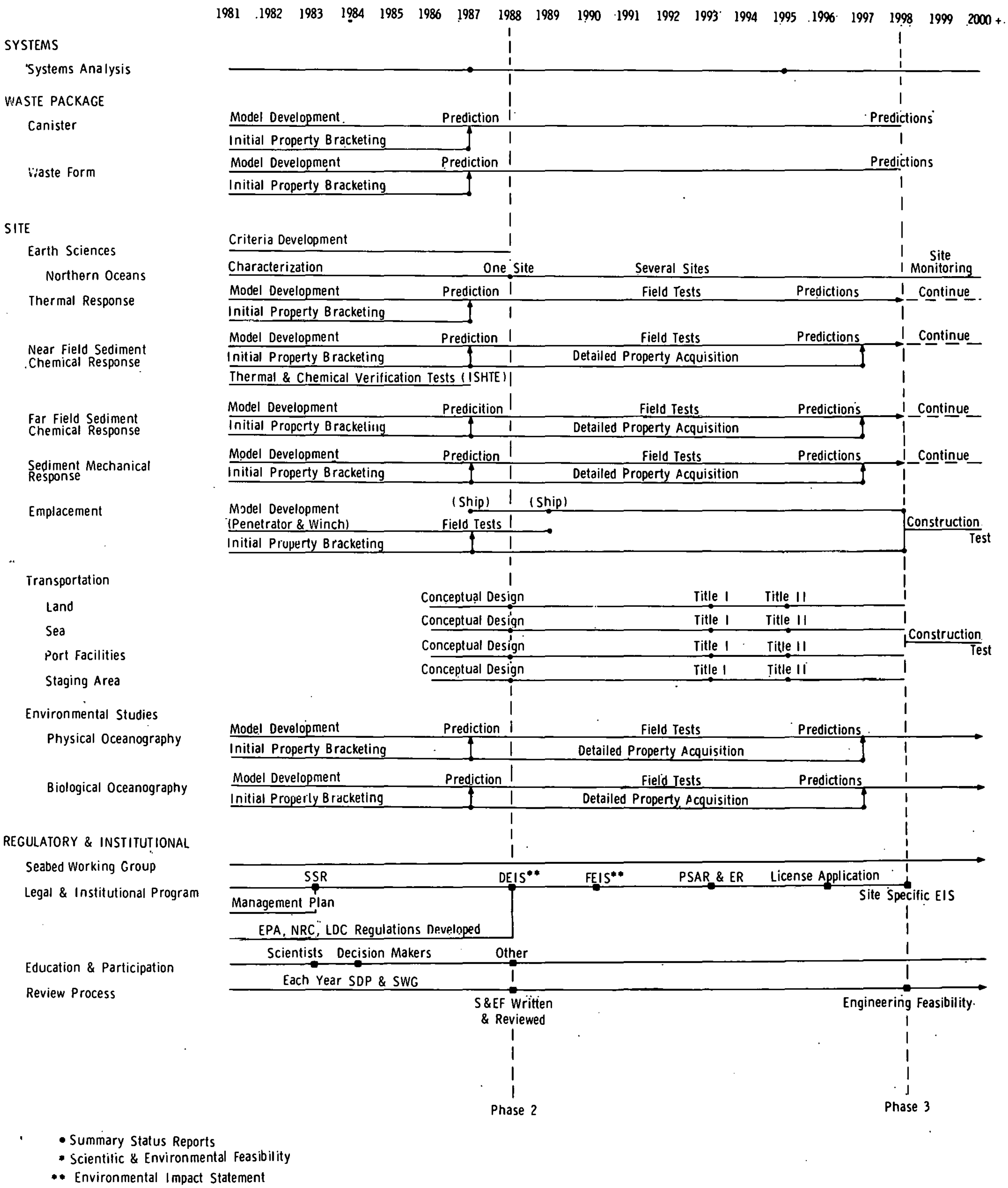


Figure 9. Programmatic Activity Chart. This chart shows the relationship of the phase description documentation to the conceptual and Title I and Title II designs, in accordance with the requirements of the National Environmental Policy Act of 1969, as amended.

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