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Volume 3

**HIGH-LEVEL RADIOACTIVE
WASTE MANAGEMENT ALTERNATIVES**

SECTION 5: ICE SHEET DISPOSAL
SECTION 6: SEABED DISPOSAL

May 1974

Battelle

Pacific Northwest Laboratories
Richland, Washington 99352

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SECTION 6: SEABED DISPOSAL

May 1974

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FOREWORD

This report is a comprehensive overview study of potential alternative methods for long-term management of high-level radioactive waste. The study includes a compilation of information relevant to technical feasibility, safety, cost, environmental considerations, policy conflicts, public response and research and development needs for:

1. Disposal in terrestrial locations
 - a. In geologic settings on land
 - b. In the seabed
 - c. In ice sheets
2. Disposal into space
3. Elimination by transmutation (nuclear transformation of certain waste constituents into nuclides having less long-term toxicity).

The study is limited to the management of high-level radioactive waste from nuclear power by variations of these alternatives. Consideration of alternative types of electrical power generation are not within the scope of the study. In addition, evaluation of interim storage of radioactive waste in retrievable surface storage facilities is not part of this study. Disposal of waste in bedded salt deposits was studied extensively in other AEC programs, and the concept is included here as part of the overall matrix of geologic disposal techniques.

To complement these studies, investigations were also conducted on waste partitioning (separation of radionuclides in radioactive waste into different elements or groups of elements according to their long-term toxicity or suitability for different disposal methods), and systems methodology was developed to assess the effects of radionuclides from waste introduced into man's ecological cycle, assuming some failure of the primary waste containment.

Information pertinent to evaluating the various potential waste disposal techniques was developed without promoting any single disposal concept. The study is concerned with management of the waste and does not consider the potential for recovery of resources within the waste, including the heat. Concepts are developed only to the detail necessary to describe them for the overall investigation and in general are studied on a systematic, generic basis. This information can be used in comparing and assessing the various disposal concepts as a basis for decisions regarding their further study.

The evaluations of feasibility are not restricted to currently available technology. Rather, the study attempts to take into account technology which can be developed or is expected to be available at least within the next four decades. Indeed, most of the concepts studied are estimated to require 15 to 30 years for full implementation.

The study includes most currently known waste management alternatives, but is not considered to be all-inclusive. As new data become available, and as new or varied concepts become evident (e.g., disposal in rocks in permafrost areas, isotopic dilution of selected materials, etc.,) comparable follow-on studies will be carried out.

This investigation has been performed largely by a multiple-discipline technical staff at the Pacific Northwest Laboratory of Battelle Memorial Institute with significant input from a large number of consultants and outside contributors. This wide involvement of persons was an attempt to assure up-to-date and accurate coverage of the broad scope of subject matter, including areas where there are diversities of opinions.

This report is issued as nine major sections in four volumes:

Volume 1	Section 1	Summary ^(a)
	Section 2	Background and Data Base
	Section 3	Evaluation Methodology
Volume 2	Section 4	Geologic Disposal
Volume 3	Section 5	Ice Sheet Disposal
	Section 6	Seabed Disposal
Volume 4	Section 7	Waste Partitioning
	Section 8	Extraterrestrial Disposal
	Section 9	Transmutation Processing

Appendix material is included with its own respective volume.

In general, metric system units are used in this report. Conversion factors to English units are given in Appendix 1.A.

-
- a. This section is almost identical to WASH 1297, High-Level Radioactive Waste Management Alternatives, US AEC Division of Waste Management and Transportation, May 1974.

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5.0 ICE SHEET WASTE MANAGEMENT SYSTEM

The concept for disposal of high-level radioactive waste in ice sheets, either Antarctica or Greenland, has been described previously in the literature.^(1,2) A copy of one of the latest proposals has been included as Appendix 5.A. For this study a generalized schematic of the operations that would be required for waste management in ice sheets is shown in Figure 5.1. The basic operations consist of truck, rail or barge transport of solidified waste from a fuel reprocessing plant or interim retriev-

able surface storage facility to specialized embarkation ports; marine transport during 1 to 3 months of each year by specially designed ship, with ice-breaker escorts near the ice sheet; off-loading of the waste canisters at a debarkation facility near the edge of the continent; over-ice transport by surface vehicles on a year-round basis; and off-loading and emplacement at the disposal site. Disposal of the high-level waste would be by one of three concepts described in the following sections.

FIGURE 5.1. Schematic of Operations in Ice Sheet Disposal Systems for High-Level Radioactive Wastes

5.1 Concepts Description

5.1.1 Meltdown or Free Flow

This disposal concept as shown in Figure 5.2 consists of selecting a location for disposal of each waste canister; preparation of a shallow hole in the ice sheet; and lowering the canister into the hole where it is released and allowed to melt down or free flow to the bottom of the ice sheet.

Pre-drilling of short surface holes to a depth of 50 to 100 meters would provide shielding for the operation during the initial phase of emplacement. At this depth, the snow (or firn) is transformed to ice having a density of approximately 0.8 g/cm^3 , with the air sealed into bubbles and the spaces no longer interconnected.⁽³⁾ The hole spacing would be

about 1.0 kilometers apart to preclude interference between individual canisters during descent or possible concentration at the ice sheet base after descent.

Each canister would melt its way down through the ice sheet to the bedrock at a rate of about 1 to 1.5 meters per day based on penetration rates of thermal ice probes.⁽⁴⁾ Assuming an ice thickness of 3000 meters as a typical value,⁽⁵⁾ the time required for meltdown to bedrock would be about 5 to 10 years.

Canister shape would be designed so that a vertical path from surface to bedrock could be assured. The canister design and materials would also consider potential problems that could result from pressure and possible saline water at the base of the ice sheet.

FIGURE 5.2. Ice Sheet Disposal Concepts

5.1.2 Anchored Emplacement

This disposal concept variation as shown in Figure 5.2 is somewhat similar to the free flow concept described previously except for the provision of interim retrievability. A hole is drilled in the ice sheet to a depth of 50 to 100 meters. A waste canister with cables 200 to 500 meters long attached is lowered into the hole. Meltdown begins and the descent is stopped at a depth of 200 to 500 meters by anchor plates on or near the surface, attached to the cables. The anchor cables or chains may also carry instrument leads that could be used to monitor the condition of the canister. The time for a canister to reach an anchored position, based on thermal probe rates,⁽⁴⁾ is estimated to be about 6 to 18 months.

Eventually, as new snow and ice accumulates on the surface, the anchor plates will be covered at a rate of about 2 to 10 cm/year in Antarctica and up to 20 cm/year or higher in Greenland. The use of 20-meter-high anchor markers would locate the waste canisters and make them potentially retrievable for 200 to 400 years. It is estimated that about 30,000 years would be required for the system to reach bedrock at a typical site. During that time, the waste and anchors would also tend to follow the ice flow pattern.

5.1.3 Surface Storage

5.1.3.1 Ice Sheet Surface

A potential concept for waste disposal storage in a surface facility with ultimate disposal into the ice

sheet is shown in Figure 5.2. The facility would be a large retrievable surface storage unit supported by jack-up pilings or piers resting on load-bearing plates within the ice. Waste canisters would be placed in cubicles inside the facility, with air cooling provided by natural draft. The facility would be elevated above the ice surface for as long as possible to reduce snow drifting and to provide for heat dissipation. Eventually, when the limit of the jack-up legs is reached, the entire facility would act as a heat source and begin to melt down through the ice sheet. It is estimated that the facility could be maintained above the ice sheet for up to 50 years after construction.

5.1.3.2 Ice-Free Dry Valleys

An alternative concept for interim storage of high-level wastes in Antarctica pending final disposal would be retrievable surface storage using air cooling and located in ice-free dry valleys. These ice-free dry valleys occur at several locales along the Transantarctic mountain ranges that separate the main ice sheet in East Antarctica from the ice shelves and from the probably younger ice sheet of West Antarctica.

These ice-free dry valleys appear to have been free from any glaciation or ice cover for the past 1 to 3 million years.^(6,7) Soil depths and permafrost are relatively thin. In general, a thin layer of glacial drift covers unweathered crystalline basement rocks.

The valleys could be used for staging and/or storage of high-level

waste canisters with a minimum of site preparation. The low average temperature would provide for air cooling and probably extend cask and canister life. Operations facilities could be built for year-round use; access by wheel-equipped aircraft could be made; and a remote site could be assured.

This concept is listed as a possible alternative for retrievable surface storage. However, since it is not currently considered as a concept for ultimate disposal, it will not be discussed further in this study.

5.1.4 Nature of the Disposal Medium and Areas

For several periods during the Pleistocene geologic epoch (approximately the last 2 to 3 million years), great ice sheets have covered nearly 30 percent of the earth's land surface. Today ice sheets are represented by the Greenland and Antarctic ice sheets, which together cover about 11 percent of the land surface of the earth. These two ice masses constitute the world's largest reservoirs of fresh water. About 78 percent of the world's non-oceanic water, or some 2.7×10^7 cubic kilometers (4.7×10^6 cubic miles) of water is held by the two ice sheets. In comparison, it is estimated that there is about 1.4×10^9 cubic kilometers (3.3×10^8 cubic miles) of water in the world's oceans and seas.⁽⁸⁾

5.1.4.1 Properties of Snow and Ice

The snow on all but the periphery of the ice sheet areas is deposited as a powdery, dry noncohesive aggregate. After deposition, intergranu-

lar bonds form between the grains, largely by sublimation, and the snow becomes firm and cohesive. As a result of the snow accumulation on the surface, a layer becomes buried deeper and deeper beneath the surface and the pressure on it steadily increases. As the snow is compressed, the density and intergranular bonding increase. In areas where no surface melting occurs, density of 0.8 grams per cubic centimeter is eventually reached at depths of 50 to 100 meters,⁽⁹⁾ and the air spaces, which had been interconnecting pores, become sealed off. This sealing off of the interconnecting pores is usually taken as the transition from snow (or firn) to ice.⁽¹⁰⁾

The transition from snow to ice is a result of thermal and pressure metamorphic processes, as well as repacking at low densities. The snow grains change their size and shape as a result of sublimation to become firn or snow that is undergoing metamorphism, which in turn becomes ice as it is buried more deeply. The process of transformation from snow to perennial ice occurs where environmental conditions are such that more snow is deposited than is dissipated by local wastage processes such as melting and evaporation.

As the mass of ice builds up, stresses created by its weight cause it to flow. This visco-plastic flow may permit a balance between accumulation and wastage to develop if conditions remain unchanged. The accumulation is then equal to the wastage caused by transport to coastal areas, where the ice may be lost mainly as

icebergs, or into warmer zones, where it melts.

5.1.4.1.1 Greenland. A general map of Greenland showing the topography of the ice sheet is given in Figure 5.3. The ice sheet covering Greenland represents about 12 percent of the total ice cover on the earth's surface. The surface area of the ice sheet is about 1.72×10^6 square kilometers (0.666×10^6 square miles), the maximum surface elevation is 3290 meters (10,800 feet), and the mean surface elevation is 2135 meters (7000 feet). The mean thickness of ice cover is 1515 meters (4979 feet) and the total volume of ice is estimated as 2.60×10^6 cubic kilometers (0.620×10^6 cubic miles). Average annual accumulation for the ice sheet is about 36.7 centimeters (14.4 inches) of water equivalent, which corresponds to an annual total volume deposit of about 636 cubic kilometers (152 cubic miles) of water.⁽¹¹⁾

Less than 0.03 percent of the total volume of ice is added to the ice sheet each year, and approximately 57 to 80 percent of this annual snow accumulation is lost each year by various ablational and wasting processes. These data suggest that the Greenland ice sheet has a slight positive mass balance; that is, ice is slowly accumulating.⁽¹²⁾

The Greenland ice sheet covers about 83 percent of the land area. The coastal areas surrounding the ice sheet are largely ice-free. The bedrock configuration, reasonably well known, consists of two domes separated by a low saddle between them, which is below sea level.⁽¹³⁾ The

ICE SURFACE ELEVATION ABOVE SEA LEVEL
(ADAPTED FROM BADER, 1961)

FIGURE 5.3. The Greenland Ice Sheet
(CRREL edition of map by
P. E. Victor)

southern and western coasts are extensions of the stable Canadian Shield, but the northern and eastern coasts are bordered by mountain ranges of younger sediments. The east coast particularly is bordered by high mountains, reaching altitudes of greater than 3,048 meters (10,000 feet).

The configuration of the land surface beneath the ice sheet has been fairly well determined by seismic methods and radio echo sounding. The central part of Greenland is depressed by the weight of the ice, and approximately 31 percent of the area underlying the ice is below sea level.⁽¹¹⁾ The upper ice surface is composed of two domes, a large one in the northern part and a smaller one at the southern end.

A more detailed description of the Greenland ice sheet has been included in Appendix 5.B.⁽¹¹⁾

5.1.4.1.2 Antarctica. A general map of Antarctica with the gross topography of the ice sheet is shown in Figure 5.4. Antarctica is a continental land mass lying, with minor exceptions, entirely south of the Antarctic Circle, and covered by a thick mantle of perennial ice. The land-based ice sheet is up to 4,250 meters (14,000 feet) in thickness.⁽³⁾ The ice mass rises steeply from the edges, becoming less steep further inland. In many of the bays and along certain stretches of the coast, ice shelves exist. The Ross Ice Shelf and the

Filchner Ice Shelf are the two largest.

The Ross Ice Shelf is about 518,000 square kilometers (200,000 square miles) in area, up to 800 kilometers (500 miles) wide and some 640 kilometers (400 miles) in north-south extent. Thickness varies from 240 to 600 meters (800 to 2000 feet). There is as much as 300 meters (1000 feet) of water beneath the ice shelf.

The Filchner Ice Shelf is about 414,000 square kilometers (160,000 square miles) in area.⁽³⁾ A large island, consisting of ice hills formed above an area of bedrock which extends above sea level, divides the ice shelf. The thickness of the floating ice is from less than

FIGURE 5.4. Antarctica

300 meters (1000 feet) to more than 600 meters (2000 feet).

The area of the Antarctic, excluding the ice shelves and offshore islands, is about 12.4×10^6 square kilometers (4.78×10^6 square miles). The ice shelves, islands and ice rises add another 1.58×10^6 square kilometers (0.61×10^6 square miles). More than 90 percent of this area is permanently covered with ice.⁽¹⁴⁾

Along most of the Antarctic coast, no land is visible. The continental or shelf ice terminates abruptly in vertical cliffs of 15 to 45 meters (50 to 150 feet). The ice-free areas of coast that do exist range from small islets of exposed rock to ice-free "dry valleys" to extensive hills or mountains.

The snow surface is hard and rough in the sloping fringe areas due to the persistent, strong winds which pack the snow and form dunes. In the less windy areas of the interior the snow is softer and less dense.

Crevasses may be found in any part of Antarctica but are more common near the coast and close to the mountains and isolated bare rock areas. East Antarctica exhibits crevasses over large, deeply-buried sub-ice mountains. The crevasses are often bridged by snow and difficult to identify. The width can vary from a few meters to a common width of 10 meters (30 feet) to more than 100 meters (300 feet).

Temperatures in the Antarctic are very cold. The Soviet Union's Vostok Station has recorded a minimum of -88.3°C (-126.9°F).⁽¹⁵⁾ The annual

average temperature at the South Pole is -50°C (-58°F).⁽¹⁵⁾ Winds are frequent and severe in Antarctica, with velocities reaching 200 km/hr in some places.

Antarctica can be divided into two parts: West Antarctica, south of the Americas, and East Antarctica, south of Australia and Africa. A line from the Filchner Ice Shelf to the Ross Ice Shelf generally separates these divisions. Geologically, West Antarctica consists of folded mountains and plateaus of sedimentary rocks, as well as extensive volcanic rocks. Sediments and scattered intrusive rocks have been traced from South America by way of the Antarctic Peninsula. East Antarctica is a continental shield of schists, gneisses and intrusives overlain by a series of sediments with igneous intrusive dikes, sills and sheets.

A more detailed description of the Antarctic Ice Sheet has been included in Appendix 5.C⁽³⁾ and 5.D.

5.1.4.2 Motions of Continental Ice Sheets

The motion of the continental ice sheets has been treated theoretically by several investigators,⁽¹⁶⁻²⁰⁾ but very little other than surface movement has been measured. Motion at depth within the ice sheet is largely unknown. Measurements made over a 4-year period in a 309-meter hole at Byrd Station, Antarctica, indicated accelerated rates of closure during that period and negligible inclination from the vertical.⁽²¹⁾ Thermal convection theory has been applied to

the Antarctic Ice Sheet and the conclusion drawn that upward-moving convection plumes may develop within the ice.⁽¹⁸⁾

The general form of the continental ice sheet is determined by major topographic features below the ice and by the visco-plastic properties of the ice itself. The ice tends to assume a dome-shaped form in dynamic equilibrium in regions of low subglacial relief. The thick inland ice dome tends to spread radially from high altitude centers. It is believed that the ice in an ice sheet may move almost as a rigid block by sliding over the underlying land, where bottom melting conditions exist, and by sheer displacement in a relatively thin basal layer. In shallow ice, and under frozen bottom conditions, differential movement throughout the thickness is believed to be more significant.⁽³⁾

Three general types of flow have been defined:⁽²²⁾

1. Sheet flow - general outward movement of ice over a bed of low relief.
2. Stream flow - relatively rapid movement of valley glaciers and ice streams.
3. Ice shelf movement - general seaward movement of an ice shelf.

Ice surface velocities for a number of locations in various parts of Antarctica are:⁽²²⁾

1. Sheet flow - 0.05 to 0.15 meters (2 to 6 inches) per day.
2. Stream flow - 0.3 to 2.7 meters (1 to 9 feet) per day.
3. Ice shelf movement - 0.9 to 1.2 meters (3 to 4 feet) per day.

Measurements of ice surface veloc-

ities in Greenland are in general lower for sheet flow--as low as 0.1 centimeters (0.25 inch) per day, and as high as 27 meters (88 feet) per day for outflow glaciers.⁽⁹⁾

In addition to the general types of ice motion are the surges and traveling waves that may occur in parts of a glacier as a result of controlling conditions that change with time. These conditions may change seasonally, irregularly from year to year or over long periods of time due to climatic changes. The changes cause disturbances that travel down a glacier from 2 to 5 times the average ice velocity.⁽²³⁾ Traveling waves and rapid advance of the "snout" of a glacier do not depend on changing basal conditions while surges are thought to be caused in part by the presence of a water layer of sufficient thickness at the base of the ice.⁽¹⁸⁾ The response time of the Antarctic ice sheet as a whole to changes is thought to be on the order of 10^3 to 10^4 years.

It is possible that the Antarctic Ice Sheet, or at least major portions of it, may surge.⁽²⁴⁾ The profile along a flowline from Byrd Station to the ocean suggests that this area is now recovering (retreating) from a surge.⁽²⁵⁾ Surges of a major portion of East Antarctica may cause rapid changes in sea level and the start of glaciation in the Northern Hemisphere.⁽²⁶⁾ Although the cause of surges is not fully understood, it is clear that the coupling of the ice to the bedrock in the presence of a water layer is crucial to the process.^(27,28,29) Thus a possibility exists that radioactive waste at the

interface, causing anomalous amounts of water, might precipitate surge-like behavior which could have global consequences.⁽³⁰⁾

The motion of the Greenland ice sheet has been measured along the edges at a number of locations. The motions are controlled by variable local conditions and are probably not typical of the ice sheet as a whole. The surface of the interior of the ice sheet has been estimated to move at velocities of no more than tens of meters annually.⁽¹¹⁾

In places the edge of the Greenland ice sheet consists of ice streams. The ice streams are similar to mountain glaciers, but instead of being bounded by rock slopes are bounded by slower moving ice. Many of the large outlet glaciers in Greenland are narrow outlets of ice streams that reach back miles into the ice sheet.

5.1.4.3 Meltwater at Base of Ice Sheet

The physical conditions at the ice-bedrock interface are essentially unknown. A few deep holes have been drilled through the ice sheets and have given information on conditions locally, but generally little is known about this interface.

Theoretical analyses of ice motion have in some cases included a layer of water at the bottom of the ice and its effects on ice sheet size and movement over the underlying material.⁽³¹⁾ Melting of the bottom surface of the ice sheet has been proposed as one of the mechanisms to account for extensive surging of the Antarctic ice sheet,⁽²⁶⁾ although

basal melting does not automatically produce surging. Most of these theories still await verification or disproof. The presence of a water layer or film at the bottom ice surface would undoubtedly affect the velocity at which ice would slide over its bed and also possibly affect the equilibrium thickness of the ice mass.

Various sources and methods have been proposed to account for the presence of a water layer at the base of the ice. Among these are:

1. The geothermal heat flux may raise the temperature to the melting point of the ice.
2. Frictional heat caused by the motion of the ice over the underlying rock may melt some of the ice.
3. Various combinations of 1 and 2 may occur.

Water was found at the ice-rock interface in a core hole through the Antarctic ice at Byrd Station.⁽³²⁾ The temperature was estimated to be -1.6°C . The presence of water was considered to be evidence that the bottom surface of the ice was at the pressure melting point. Calculations indicated that the water layer was at least 1 millimeter thick.

The temperature at the bottom of a 1,375-meter hole through the Greenland ice sheet at Camp Century was -13°C ,⁽³³⁾ well below the pressure melting point.

The presence of water beneath the ice sheets is no longer questionable.⁽³⁴⁾ Drilling through the ice sheets provides the only direct evidence on the conditions at the ice-bedrock interface. It is possible that indirect methods may be of use

when tied to known conditions. Radio-echo soundings of the ice sheet suggest that subglacial water may be present in some areas⁽³⁵⁾ and have established the existence of seventeen sub-ice lakes in East Antarctica.⁽³⁴⁾ The extent and distribution of subglacial water must be established before the questions of its effect on ice motion, its extent and distribution, and its hydraulic connections to the edge of the ice sheets can be determined.

5.1.5 Systems Requirements for the Concept

Overall systems requirements for the potential concept of ice sheet

disposal are summarized in Figure 5.5. As shown in this figure, storage of unconditioned high-level liquid waste arising from the chemical reprocessing of irradiated nuclear fuels is expected to be followed by conditioning (specifically solidification and encapsulation), interim retrievable storage of the resulting canisters, transport of the canisters in casks to the disposal area, and finally by emplacement in an ice sheet. Details concerning requirements for waste treatment and handling prior to emplacement in the ice sheet, site preparation, transportation of the canisters to the site, and final disposal operation follow.

FIGURE 5.5. Overall System Requirements for Managing High-Level Radioactive Waste by Emplacement in Ice Sheets

5.1.5.1 Prior Waste Treatment and Handling

The general system flow diagram, shown in Figure 5.5, starts with bulk high-level radioactive liquid waste from the nuclear fuel reprocessing plant. A number of potential options are shown, but for ice sheet disposal conventional solidification of the bulk waste to monolithic glass or ceramic forms within metal canisters, and disposal to the ice sheet are the basic steps required. Other options used will probably not be needed as a result of requirements for ice sheet disposal, but rather for other reasons. Examples of such options are: 1) the waste may be conditioned and stored as retrievable for some period of time; 2) chemical adjustment (such as neutralization) and storage as liquid in tanks for up to a 5-year cooling time may be done, or calcination and interim calcine storage may be practiced; 3) the waste may then be chemically separated into an actinide stream and one or more fission product streams. This might be done to manage by other options parts of the waste (e.g., those with short- or long-term biological hazards); to reduce heat transfer problems; or to recover useful constituents.

Only solidified high-level waste forms such as monolithic glasses or ceramics in metal canisters are considered for ice sheet disposal.

If the stability of ice sheets can be adequately verified, safe containment of waste forms for periods on the order of 10^5 years is possible. In this case, separation of actinides or long-lived fission products may

not be required. However, the difficulties and costs inherent in the system concerning the transportation, logistics and operations at the potential disposal site may suggest some separation of waste products. The actinides and long half-life fission products could be considered for disposal in the ice sheet areas, and the remaining waste forms handled in other disposal systems that may not have the same potential for safe long-term containment.

At the present time, the limited knowledge indicates that the ice sheets may not have sufficient stability to assure waste containment for periods of more than a few thousand years. In this case, separations would be required and the ice sheet should be considered for disposal of only the higher heat generating radionuclides having short half-lives. However, for this study, the reference case was assumed to be disposal of bulk solidified waste without chemical separation 10 years after separation from the reactor fuel.

Reference case canister dimensions are taken to be 30 centimeters in inside diameter by 3 meters long. Approximately 80 percent of canister volume is filled with about 170 liters of solidified high-level waste. Radioactive material in each canister is approximately 1 megacurie with a heat generation rate of about 3 kilowatts. The canister will be designed to assure proper penetration trajectories through the ice sheet, to withstand high pressure from surface loading, and of material to provide

resistance to corrosion from potential saline water that may be generated in the melt pool between the bottom of the ice sheet and bedrock.

5.1.5.2 Site Preparation

If either the meltdown or anchored emplacement concept is considered for disposal, minimum site preparation would be necessary. A support base would be established at the disposal area. Necessary equipment for a complete support base could be mounted on additional over-ice transport vehicles. This would include living facilities, drilling equipment, spare parts and supplies.

Prior site preparation will include selection of a disposal area on the ice sheet on the basis of ice stability, ice thickness, ice flow rates, and accessibility to the ice sheet margin. Selection will be followed by detailed exploration and mapping of the area for disposal and the access routes to the ice sheet margins. Shallow emplacement holes will be completed prior to arrival of the waste canisters.

In the ice surface storage concept, site preparation would require construction of a surface facility prior to shipment of the initial waste canisters.

In all concepts for ice sheet disposal, once a site has been selected and a disposal method established, embarkation ports, debarkation ports, supply bases and fuel stations would have to be built and operating prior to shipment of the first waste canister.

5.1.5.3 Transportation and Logistics

Figure 5.1 showed the basic system operational requirements for disposal of high-level waste in ice sheet areas. The lack of safe accessibility to either Antarctica or Greenland during a large part of the year would require that all waste be shipped on a campaign basis over about a 1- to 4-month period. For example, ports in Antarctica might be accessible for only a few weeks in any given year.

Transportation to the site would be accomplished in three steps. First the waste canisters would be loaded into conventional types of heavily shielded transport casks weighing 50 to 100 tons for shipment from the retrievable storage site to the embarkation port. At the embarkation port the canisters would be unloaded in a shielded cell facility for checking, repair and decontamination if required and transferred individually to specially designed casks of about 25 tons, which would be then loaded aboard the transport ship. (The smaller casks are used to facilitate over-ice transport.) The second stage of transport would be by special ship from the embarkation port to the ice sheet for unloading at debarkation facilities. Ice breaker escorts are required near the debarkation port.

At the debarkation area the casks and canisters would be inspected and the same casks would be off-loaded from the transport ship by crane directly onto over-ice transport vehicles. Upon arrival at the disposal

site, the canister is lowered from the cask into the ice sheet. If repair or decontamination were required, the cask and canisters could be loaded back onto the marine transport for handling in shielded cell facilities.

5.1.5.3.1 Overland Transport.

Transportation from the reprocessing plants or retrievable surface storage facility to the embarkation ports would be by rail, truck, or possibly barge. During this phase of transport, the waste canisters would be held in conventional overland transport casks, typically weighing around 50 to 100 tons and holding 6 to 12 canisters each. Existing railroad cars are designed to carry useful loads of 50 tons routinely and in special cases up to 100 tons.⁽³⁶⁾ Truck transport is limited by gross vehicle weight restrictions to loads of about 25 tons. Overweight permits can extend this limit to about 40 tons.⁽³⁷⁾

5.1.5.3.2 Embarkation Port. An embarkation port in the U.S. would serve to accumulate waste canisters on a year-round schedule, provide examination, recanning, and decontamination prior to shipment to ice sheet areas aboard specially designed transport ships. The embarkation facility would be similar in design to a Retrievable Surface Storage Facility (RSSF)⁽³⁸⁾ system with capacity for up to 1 year's capacity of waste canisters with additional modifications for canister transfer to the seagoing shipping casks.

The 50- to 100-ton overland transport casks containing the canisters

would be unloaded in a dock-side shielded cell facility where the canisters would be removed and examined for leakage, contamination, damage or other unsuitable conditions. Acceptable canisters would be either stored temporarily or transferred individually to specially designed casks of about 20 to 25 tons. These casks are then loaded aboard the marine transport ship. Any unacceptable canister would be placed back into the overland transport cask and returned to the reprocessing plant or to the nearest appropriate handling facility. On-land handling by crane could be accomplished by existing cranes with load capacities up to 300 tons.⁽³⁹⁾

An optimum system would use the same shipping cask for handling a waste canister first at the reprocessing plant, then for marine transport to the ice sheet and for over-ice transport to the disposal site.

5.1.5.3.3 Sea Transport. The second stage of transport would be by special ship from the embarkation port to the ice sheet area during a few months' period of each year. The transport ships envisioned would be capable of carrying at least 100 small casks, each weighing about 20 to 25 tons and containing 2 canisters. Additional hull strength would be required to protect the vessel from potential damage due to pack ice. Ice breaker escort ships would be required for routine travel through the ice to the debarkation site. The transport ship would be equipped with a shielded cell for examination and

handling of the canisters en route prior to off-loading at the ice sheet, if required.

The shipping casks would supply the radiation shielding, and the ship's facilities would supply artificial cooling. Any additional shielding required would be an integral part of the ship construction. Cooling could be accomplished by closed circulation water systems, or by filtered forced air systems. The coolant would be continuously monitored for radiation and temperature changes.

The transport ship would be equipped with a handling device capable of removing the waste canisters and their casks to a shielded cell facility (cuboid, about 4.5 meters on a side) for examining the condition of the canisters, either en route or at the debarkation port. Any canister unacceptable for disposal could be repaired on-board ship if it were a

relatively simple job. Alternatively, the canister could be returned to the shipping cask and back to the embarkation port for return to the reprocessing plant or other handling facility if necessary.

While aboard the transport ships, the casks could be fitted with locating devices and acoustically actuated flotation mechanisms if desired. The transport casks could be constructed so that, in the event the ship sank, part of the cask could be released from the ship and a flotation system with a collar could be activated to bring the canister and the recoverable part of the cask to the water surface. The release of part of the cask and the activation of the flotation device would be triggered by an acoustic signal from the surface. This conceptual system is shown in Figure 5.6.

FIGURE 5.6. Potential Cask-Canister Recovery System at Sea

5.1.5.3.4 Debarkation Port. Deep water ports with positive handling systems for off-loading 25-ton casks directly onto the over-ice transport system would be possible in the Antarctic or Greenland but may be impractical considering the potential port sites available in relation to disposal sites, cost of construction, and maintenance. The currently preferred alternative is to use 20- to 25-ton casks for each two canisters from the U.S. embarkation port, dock the transport ship at a land based port in an ice free area, and off-load the small casks directly onto over-ice transport vehicles.

5.1.5.3.5 Over-Ice Transport. Aircraft have been proposed as an efficient transport system for inland shipment of materials.^(2,40) However, several factors may preclude the use of aircraft. Construction of air fields on ice for wheeled planes is possible but would require extensive maintenance to keep open and would have a life span of around 2 to 3 years.⁽⁴¹⁾ Present ski-equipped C-130 Hercules transports are limited to about 10 tons of payload due to the added weight of the skis; they are subject to landing accidents because of problems with radar altimeters over ice fields; and their flying is highly dependent upon weather variables.⁽⁴¹⁾ Conventional tracked surface vehicles pulling sled trains may prove to be the most reliable means of over-ice transport.

An over-ice transport system using Surface Effects Vehicles (SEV) is considered as a possible alternative for

the present concepts. Self-propelled SEVs capable of speeds up to 80 kilometers per hour (50 mph), carrying a payload of 25 tons over ice, are in operation in northern Canada.⁽⁴²⁾

Barge-type SEVs with a payload capacity of 100 tons have been designed and are under construction. These larger SEVs require towing and would be limited to speeds of about 6 kilometers per hour (4 mph). Therefore, a self-propelled SEV with a payload of about 30 tons could be utilized to carry one 20- to 25-ton cask and support handling system.

A 1500-kilometer round trip to an interior disposal site could be made on an average of once each 7 days under normal conditions with allowances for maintenance, loading and unloading, and special problems. During the 3-month operating season, each SEV could be used to transfer approximately 24 high-level waste canisters to the disposal site. Therefore, about 25 of these SEVs would be required to handle the average yearly output from a 5 MT/day fuel reprocessing plant.

Petroleum fuel capacity of the 30-ton SEV vehicle is 2,500 gallons, which is enough to provide about 12 hours running time. Present aircraft operating in the Antarctic are limited to carrying 2,000 to 3,000 gallons extra fuel payload for resupply.⁽⁴³⁾ Four fuel resupply flights would, therefore, be required for each SEV round trip, or a total of more than 1,200 flights for waste from 1 year's processing of fuel at 5 MT/day. Four to five C-130 transport planes would be needed to make

the required 1,200 fuel resupply drops over a 12-month span or several times that number if operated over a several-month span, considering the problems that might be encountered with weather and equipment breakdown.

5.1.5.4 Operation of the Site

In both the meltdown and anchored emplacement concepts, site operations would consist primarily of surveying exact locations for the emplacement holes and of pre-drilling the holes to an approximate depth of 50 meters prior to arrival of the over-ice transports carrying waste canisters. Upon arrival, the canisters would be surveyed for leaks. If no leaks were found, the transport vehicle would be positioned over the pre-drilled hole and a waste canister lowered through the bottom of the cask. After release of the canister, the hole would be backfilled with ice, the surface location marked and monitoring established until such time as disposal operations are terminated. If anchored emplacement were used, the anchors would be deployed prior to release of the lowering cable.

In the ice surface storage concept, the transport vehicle with the cask and canister aboard would be brought into an air lock area of the shielded facility. The canister would be removed from the cask behind shielding, and transferred by an overhead remote operated crane to a permanent storage bay within the facility. Other operations consist of normal maintenance and repair of equipment, quality assurance control, engineering support and the management of any wastes

generated during the emplacement operation.

5.1.5.5 Final Sealing from Man's Environment

Emplacement and isolation of the waste canister is provided by the meltdown through the ice sheet caused by the thermal output of high-level waste. Calculations based on the reference waste canister 0.3 meters in diameter by 3 meters in length with an initial thermal output of about 3 kilowatts indicate a velocity due to melting of about 1 meter per day.⁽⁴⁰⁾ At this rate of melting, a free flow canister would reach the bottom of a typical ice sheet disposal site about 10 years after emplacement near the surface. Isolation is provided by ice thickness of between 3000 to 4500 meters and a distance of about 500 to 1000 kilometers from the edge of the ice sheet.

In the concepts with disposal by anchored emplacement or ice surface storage facility, the waste canisters would be at or near the ice surface for a period of up to 50 years. After this time the waste canisters would penetrate progressively deeper into the ice sheet but at a much slower rate than with the free flow concept. Horizontal isolation would be the distance from the disposal site to the ice sheet margin (500 to 1000 kilometers).

5.1.6 Heat Removal

At the time of canister loading, about 10 years after fuel reprocessing, the high-level waste will contain about 1 megacurie of radioactive

material with a heat generation rate of approximately 3 kilowatts. This amount of heat generation is sufficient to raise the waste temperature to its melting point in a relatively short time unless external cooling is provided. Casks for shipment from a retrievable storage location to the embarkation port would include provisions for adequate cooling. The marine transport ship used to move the waste canisters to the ice sheet disposal area will be able to provide adequate cooling by the use of seawater. In the ice sheet areas, the average ambient air temperature below 0°C should be adequate to provide air cooling of the waste. Once the waste is emplaced in an ice sheet, it is estimated that formation of a melt pool of about 70 meters diameter surrounded by ice will be more than adequate to maintain the waste well below melting temperatures. It should be noted that the melt pool water will have a higher density than the surrounding ice and may tend to move downward by plastic flow.

5.2 TECHNICAL FEASIBILITY

No information has been found that precludes the technical feasibility of high-level radioactive waste disposal in continental ice sheets. All systems required for waste management, transportation, logistics support and emplacement are available or could be developed through existing technology. The potential for a long-term containment and disposal system exists. However, today's limited knowledge of ice sheet physics and history makes prediction of the stability of the ice sheets for periods greater than

a few thousand years uncertain. Verification of the theories that support ice sheet disposal will require many years of extensive new data collection and evaluation.

From the limited data presently available, it appears that the ice sheet disposal concepts could offer potentially favorable features such as:

1. Geographical isolation,
2. Relative isolation and containment of wastes by the ice in the event of leakage or canister failure,
3. Low temperatures and high heat dissipation capacity, and
4. Relative safety from damage by storms, sabotage and other hazards once the waste is emplaced.

Potentially unfavorable features for ice sheet disposal in general are:

1. Extensive new data on all facets of ice sheet physics will have to be obtained.
2. The harsh environment and unpredictability of conditions on ice sheets will present severe problems in establishing safe operations.
3. Ice sheet areas are inaccessible during much of the year (8 to 11 months) because of storms, long periods of winter darkness, and freezing of surrounding seas.
4. Monitoring and evaluating waste disposal operations would be difficult.
5. Recovery from an unforeseen occurrence during transport to the disposal site would be difficult.

5.2.1 Containment Assurance

Assurance that the ice sheet will contain radioactive wastes for very long time periods is speculative at

this point. Containment is essentially a matter of the stability and physical properties of the disposal medium, with perhaps some augmentation by canister life and waste form.

A preliminary analysis of failure modes with ice sheet disposal concepts is discussed in Section 3.1, along with a listing of major failure modes.

In all of the ice sheet disposal concepts, it is considered that ultimately the waste canisters will be emplaced within the ice. Upon failure of a waste canister, the radioactive material is present in a potentially mobile system (i.e., the ice and the water that may be present beneath it, either naturally or melted by the waste canisters). The probability that the waste could reach man's environment while it is still in a hazardous form will depend on the rates of motion within the ice sheet, the physical state and rates of flow of ice or water at the base of the ice sheet, and the long-term stability of the ice sheet in total.

Numerous measurements have been made of the rates of surface motion of glacial ice. Most of these have been done in the valley glaciers, ice shelves and marginal areas of the ice sheets.⁽⁴⁴⁾ Rates vary from centimeters per day to kilometers per year.^(12,13) Mathematical models and theoretical studies have been made^(16,17,19,20) of ice sheets, but interior rates of movement are essentially unknown.

Physical conditions at the base of ice sheets are essentially unknown. Theoretical considerations suggest that the ice in the central areas is

sufficiently thick to cause melting.^(31,20) The presence of known basal water layers and under-ice lakes could possibly make the ice sheet less stable and increase the rate of movement.⁽¹⁷⁾ Any basal water layer could also form an active hydraulic system with the potential for more rapid transport of radionuclides to the ocean's and man's environment.

Long-term stability of the ice sheet is essential for disposal methods requiring waste isolation for periods of time of a few thousand years or longer. Stability depends on future rates of snow accumulation compared to ice losses by melting, evaporation, formation of icebergs, and future world climate. Present opinion^(34,44,45) suggests that the Antarctic ice cap is growing or at least is stable. Future stability, however, cannot be predicted from interpretation of past climates from the available ice cores.^(12,46) The occurrence of manmade or natural climatic changes which could change the long-term stability of ice sheets is highly possible. The magnitude of changes that might occur is unknown.

5.2.2 Siting Limitations

Siting limitations are determined in part by the disposal concept and in part by the physical dimensions and characteristics of the ice sheet. The meltdown concept would require, for maximum containment assurance, a site as far from the coast as possible and a location where the ice has the greatest thickness and stability.

It has been suggested⁽⁴⁰⁾ that the best locations for disposal in ice sheets would be near the tops of buried ridges in the underlying bedrock. In these suggested locations the ice thickness is greater than 1 kilometer, the ice-rock interface temperature is expected to be lower than in the ice basin areas, and lateral movement of the ice should be minimal.⁽²⁾

The anchored-storage and surface-facility concepts would require a site where the surface and upper 500 meters of ice are relatively stationary or slow moving. These concepts would also be applicable to areas of low accumulation of snow to maximize the time available for retrieval.

5.2.3 Prior Waste Conditioning

Solidified waste forms such as borosilicate glass encapsulated in metal canisters are the reference system considered for ice sheet disposal concepts. Physical characteristics of the waste and canister were given previously in Section 5.1.5.1. Beyond the 10-year interim storage time that provides for some thermal decay, no further waste conditioning is required in this reference concept. However, as discussed previously, waste partitioning may be used if only certain fractions of waste were to be disposed into the ice sheets.

5.2.4 Energy Requirements

Calculations indicate that the approximate net energy required for transport and emplacement of waste in an ice sheet is about 3 to 4 orders of magnitude lower than the

electrical energy generated by the nuclear power plants that supply the fuel.

The energy requirement in all ice sheet disposal concepts is almost totally committed in the transport and logistics associated with moving the waste from the reprocessing plant to the embarkation port and from the embarkation port to the disposal site.

Table 5.1 outlines the major fuel requirements for all transport systems that would be associated with ice sheet disposal.

5.2.5 Status of Technology

Present technology is adequate in general for emplacement of waste canisters under these concepts but will need further development in the areas of transportation, logistics and support facilities. The emplacement operations site for all disposal concepts would require transport of the wastes inland for a considerable distance. This transport would be over difficult and hazardous routes and, coupled to the short operating season, for the marine shipment, would require a fairly efficient form of transportation to carry the 20- to 25-ton casks being considered. Fuel depots would be required along the route, and these in turn would have to be supplied from other sources.

5.2.5.1 Emplacement

Because two of the disposal concepts are self-emplacing, there is little development needed for this actual operation once the wastes are on location. For emplacement within the ice, holes drilled to a depth of

TABLE 5.1. Fuel and Energy Requirements for Transport of High-Level Radioactive Waste to Ice Sheet Areas ^(a)

System	Liters Fuel	Equiv. Electrical ^(b) Energy (kW)
50-ton cask transport from reprocessing plant to port facility (1500 kilometers round trip; 2 km/liter; 2500 trips)	1.9×10^6	2.1×10^7
Marine transport (60 days round trip; 1.9×10^4 liters/day; 25 trips)	2.8×10^7	3.1×10^8
Over-ice transport (2000 kilometers round trip; 0.1 km/liter; 8000 trips)	1.6×10^8	1.8×10^9
Aircraft fuel resupply (2000 kilometers round trip; 1.2×10^4 liters/trip; 16,000 trips)	1.9×10^8	2.1×10^9
Total	3.8×10^8	4.2×10^9

- a. One plant reprocessing 5 MT/day of fuel with an average output of 600 waste canisters/year for 25 years. Electrical energy from the associated nuclear fuel is 10^{13} kW-hr.
- b. Electrical energy calculated by assuming 3.7×10^4 Btu/liter. Fuel converted in a power plant at 35% efficiency as 3.4×10^3 Btu/kW-hr or 11 kW-hr/liter.

50 to 100 meters would reach depths at which the interconnecting air spaces in the ice have been sealed off into bubbles. Drilling of holes to 400 meters below the ice surface by "dry bore" drilling (with no liquid in the hole) has been accomplished with existing equipment.⁽³³⁾ Cooled, compressed air serves as the drilling fluid.

The ice surface storage concept would require no drilling, and emplacement would be accomplished by handling equipment at the site. Equipment is available to handle the casks without difficulty.

5.2.5.2 Transportation

Transportation of the wastes from the embarkation ports to the areas of the disposal sites will be very difficult but should present no insurmountable problems. Ports would be designed for maximum safety, utilization and acceptability. Docking facilities for large ships would be taken into consideration during design.

Transport ships would be modifications of existing vessels or, if indicated by further investigation, would be fitted during construction with necessary safety features.

Crude oil tankers are currently being built in the 400,000-dead weight ton class,⁽⁴⁷⁾ which is considerably larger than necessary to transport the entire waste from 1 year's operation of a 5 MT/day reprocessing plant in one trip.

Transportation inland over the ice with presently available equipment would lead to several problems: slow travel, severe weather conditions, fuel supply, equipment maintenance, etc. The transportation is necessary for the within-ice sheet concepts to reach a disposal site as far from any coast as possible and where maximum thickness and stability of ice can be found, thus gaining as much isolation as possible. Even if sites were selected over the tops of buried bed-rock ridges to minimize lateral movement within the ice,⁽²⁾ some inland transport would still be necessary. In Antarctica, for example, the distance could be on the order of 1000 kilometers (600 miles).

Off-loading to the continent would probably be done by crane or possibly by helicopter.

Transportation inland from the points of off-loading could be accomplished by several methods. The use of surface sleds pulled by tracked vehicles has been a traditional method of supply and transport over the ice sheets and is used as the reference method in this study. This method has been essentially abandoned by the United States for supplying its permanent stations in favor of aircraft,⁽¹⁵⁾ although the method is still used by some nations. Surface tracked vehicles pulling sleds have

an average speed of 3 to 6 kilometers per hour (2 to 4 mph), and trips of 1000 kilometers (600 miles) using present equipment would require about 1 week of travel to the site and about an equal time to return.

Aircraft have been successfully used for transporting both personnel and supplies into Antarctica. C-130 Hercules transports, equipped with skis, regularly carry loads of 10 tons as a maximum operational load.⁽⁴⁸⁾ The use of aircraft reduces the time required for each round trip, but aircraft are subject to limitations such as high fuel consumption and navigational and operational difficulties over ice sheets and cannot operate at all during severe weather conditions. In addition, relatively drift-free landing areas must be maintained, requiring additional personnel and equipment.

Surface Effects Vehicles (SEV) are a possible means of over-ice transport although they have not been tested in high elevations of the Antarctic ice sheet. SEVs are discussed in Section 5.1.5.3.5.

Using any type of surface vehicle to transport the waste inland would require establishing a chain of fuel supply depots along the route. These in turn would have to be resupplied with fuel, possibly by aircraft drops. Fuel has been the largest single item of shipping in all expeditions to the Antarctic.⁽¹⁵⁾

Surface transportation in the Antarctic is also hindered by steep slopes inland from the edges of the ice sheet and by crevasses within the ice. Typical elevations in the ice

sheet surface at various distances inland are: 460 meters at 16 kilometers (1500 feet at 10 miles); 1800 meters at 160 kilometers (6000 feet at 100 miles); 2400 meters at 320 kilometers (8000 feet at 200 miles).⁽³⁾ The snow surface in the steeply sloping fringe areas around the ice sheet is frequently shaped by strong winds into snow dunes and drifts. These may attain heights of several meters and can present serious problems to surface travel.

Crevasses may be found in any part of Antarctica but are most common near the coast and close to mountains and the exposed rock knobs (nunataks).⁽³⁾ On ice shelves crevasses are commonly found at the junction of the shelf ice and land ice. Crevasses tend to form farther seaward on ice domes and in areas of sharp changes in elevation. In some areas such as east of Sonderstrom, Greenland, crevassing is so intense that surface travel is impractical.⁽⁴⁹⁾ Sigmoidal shear crevasses may exist in the vicinity of mountains and nunataks. Crevasses vary from less than a meter to over 100 meters wide. Because the crevasses often are concealed by snow, they present a considerable hazard to surface vehicles. Where the crevasses are bridged, electronic or infrared devices can be used to detect and define their pattern.⁽¹⁵⁾

5.3 ESTIMATED RESEARCH AND DEVELOPMENT REQUIREMENTS

In general, the Research and Development requirements for ice sheet disposal can be divided into those associated with obtaining basic

information on the ice sheet and those related to the handling, transport and emplacement of the waste.

The primary research need for ice sheet disposal of radioactive waste is for information on the rates of movement of the ice, its long-term stability, and the characteristics of the ice-bedrock interface. At present, little quantitative information is available on motion within the ice sheets. Stability of the ice sheets is of prime importance in assessing the suitability of the ice as a means of isolating and containing the wastes for the time periods required. The characteristics of ice-bedrock interface of either the Antarctic or Greenland ice sheet is almost completely unknown.

The need for further development of the transportation system for ice sheet disposal is primarily in the transporting of the wastes from the edge of the ice sheet to the disposal site. Existing ships could be adapted by installation of the necessary safety, cooling and handling facilities to provide transportation to the ice sheets. Operations would be limited to 3 to 4 months or less each year due to the climate and accessibility to the ports at the ice sheets.

Transportation to the disposal sites, either by air or on the ice surface, would require some development in vehicles and methods. Aircraft have replaced surface vehicles to a large extent in Antarctica,⁽¹⁵⁾ but would require additional modifications in cargo capacity, fuel load and navigational equipment for reliable operation during unfavorable weather conditions. Even during the

operational season, air transport would be at times impossible due to fog, blowing snow and winds.

Surface transport of wastes would require considerable development to be put into a practical and dependable system. Load capacity, fuel needs, speed of travel and capability to traverse rough surfaces and some grades would need consideration. Tracked vehicles have proved practical although slow. Surface Effect Vehicles (SEVs) or air cushion vehicles need further testing and development before they would be capable of routine use for transportation of waste over the ice sheets.

5.3.1 Geological/Geophysical Exploration

The determination of ice sheet movement and stability can be approached by a combination of geophysical, geologic and geodetic methods. Such research would provide in the shortest period of time the most complete and detailed knowledge of ice thickness and configuration of the underlying surface. Seismic and gravity surveys have been made in both Greenland and Antarctica for a number of years^(3,11) and have yielded information on ice thickness and configuration of the sub-ice surface. Radio-echo sounding from aircraft, used more recently,⁽³⁵⁾ covers large areas much more rapidly than previous methods.

Evaluation of a specific site for disposal in an ice sheet will require additional detailed geophysical mapping and geologic evaluation of a number of cores drilled through the ice

sheet and into the underlying bedrock.

To provide a thorough geologic evaluation of the ice core data, both regionally and at a specific site, geochemical techniques will have to be developed in the laboratory for age dating and stratigraphic analysis.

5.3.1.1. Ice Sheet Studies

A program of planned mapping of the ice sheets by radio-echo sounding would be needed to supply the information necessary to accurately delineate the parts of the ice sheet where the greatest thickness occurs. Radio-echo sounding in conjunction with aneroid or other methods of determining surface elevation would also yield information on what areas of the sub-ice surface are below sea level and on the configuration of the ice-rock interface. Areas where subglacial water is trapped beneath the ice have been found⁽³⁴⁾ and others may also be detected. The distribution of ice thickness is vital to determining the direction of movement in an ice sheet.

Ice motion, particularly at depth within the ice sheets, is essentially unknown. A number of measurements of ice surface motion have been made, for the most part on the surfaces of valley and outlet glaciers.⁽⁴⁴⁾ The motion of glaciers of this type is controlled by variable local conditions and does not yield much information on motion in the interior of the ice sheets as a whole.

Measurement of surface motion in the interior of the ice sheets is hindered by the lack of fixed landmarks.

The availability and use of navigational satellites, or use of radio-echo methods, can overcome this difficulty. A program of accurately determining the location of a number of points on the ice sheets would supply needed information regarding the movement of the ice. These surface measurements would supply not only data on motion of the points with respect to a fixed coordinate system, as well as relative motion among the points, but would enable workers to collect data on the differential movement of the ice at various depths, say in a drilled hole. Adequate information on ice movement would require a number of strain rate measurements at the ice surface and in holes within the ice sheet. Surface strain rates are relatively easy to obtain, but only average values have yet been obtained for vertical strain rates within the ice and near the base. The accurate determination of locations of the points would need to be made over a sufficiently long time period, probably a minimum of 5 to 10 years, to provide meaningful data on the gross motion of an ice sheet.

The stability of the ice sheets, that is whether they will exist continuously in the future or are expanding or shrinking, is at present not known. To assure isolation and containment of radioactive wastes in an ice sheet for a period of hundreds of thousands of years, the present trend in the balance must be known and a reliable estimate of future climatic conditions be determined. A program of study directed toward determining the mass economy or mass budget of

the ice sheet would be necessary to determine whether the ice sheet is growing or shrinking. Accumulation and wastage are difficult to measure, but must be determined to establish the order of magnitude of the surplus or deficit in a given time period.

The accumulation is compared to wastage or ablation, which includes ice lost as icebergs and oceanic melting, to determine if the ice sheet is losing or gaining substance. The large size of the Greenland and Antarctic ice sheets make studies difficult. At present nearly all of the Antarctic ice sheet is a region of positive balance with snow accumulation exceeding ablation,⁽¹⁴⁾ but the loss of ice as icebergs and by bottom melting on the ice shelves is not well known, and the overall state of balance may be positive or negative. Greenland also appears to have a surplus, with on-land accumulation exceeding ablation, but iceberg losses are not accurately known. Although the mass may be increasing, there is some evidence that the total area is shrinking.⁽¹¹⁾

The objective of the ice sheet studies would be to determine the effectiveness of the medium for containment of radioactive waste over the time period required. To accomplish this objective would require extensive new studies and data collection on the ice sheet proper, climatology, the atmosphere and oceans that surround and control the ice sheet, and the geologic history of both. The estimated time required for these studies is estimated to be in the range of 30 years provided that a

coordinated effort is established with a large number of scientific personnel and with adequate funds.

5.3.1.2 Site Evaluation

A number of cored or drilled holes through the ice sheet would be necessary, especially in areas selected as disposal sites. The holes would be required to supply definite values for ice thickness, provide information on ice motion and strain rates, and determine the physical conditions such as temperature and the presence or absence of water at the ice-rock interface. The presence of a water film or layer at the bottom of the ice is of considerable importance in determining the acceptability for a disposal site. A water layer at the base of the ice would definitely influence the basal velocity of the ice sheet over the underlying material and the travel time to the ocean,^(17,31) thus possibly affecting deleteriously the long-term waste containment. The basal water layer, if present, could possibly serve as a conduit or channel connecting the area beneath the disposal site to the edge of the ice sheet and to the ocean.

It is estimated that about 10 years after the ice sheet research has been in progress, enough data would be available to warrant tentative selection of the disposal site. Detailed evaluation of the site would primarily consist of core drilling a number of holes through the ice sheet over a 10,000 to 15,000 square kilometer area. Simultaneously the 800 to 1000 kilometer access route from

the disposal site to the ice margin would have to be explored, mapped, and evaluated for environmental impact. This phase is estimated to require 7 to 10 years.

5.3.1.3 Laboratory Studies

Ice cores from holes through the ice sheet will need to be taken for detailed laboratory study of oxygen isotope ratios, ice density, solid particles, ionic chemistry and the meteorological and climatological inferences that can be made. These factors would be necessary to determine the history of the ice sheet and provide data for modeling and developing estimates of the expected duration of the ice sheet in comparison to the time of containment necessary.

The major laboratory studies would be in support of the field studies and in evaluation of the data collected. Separate laboratory studies on age dating techniques for ice, effects of heat and radiation on the containment medium, and the effects of the containment medium on canister life would require about 5 to 7 years during the early phases of the program.

5.3.2 Transportation System

Transporting the wastes from the edge of the ice sheet to the disposal site in the interior for all concepts will require development to provide a safe, reliable system. Any transportation system designed for use in Antarctica, for example, must take into consideration the extreme nature of the setting. Low temperatures,

strong winds, snow storms, "white-outs" (in which diffused light confuses direction and distance perception), rough surfaces, crevasses and fairly steep slopes all make travel hazardous and difficult.

Development of marine transport systems for shipping waste from embarkation ports to the ice sheet could be accomplished readily by modification of existing ship design.

5.3.2.1 Transportation Vehicles

Several factors are important in developing a transportation system to the interior of the ice sheets:

1) Load capacity - as presently considered, the transport casks would weigh 20 to 25 tons, considered a minimum load capacity for whatever vehicle was used.

2) Speed of travel - the large distances of 800 to 1,600 kilometers (500 to 1,000 miles) to the disposal sites and a short operating season for marine transport make the round-trip time requirement very important. It is assumed that on the ice sheet proper year-round operation of the over-ice transport system could be achieved.

3) Fuel requirements - all fuel must be shipped in, and if refueling sites were needed along the route, they would need to be supplied and stocked.

4) Specialized requirements typical of type of transport - for example, snow free landing strips for planes.

Development of a transportation system should investigate the extending of available means of transport

to supply the needs for waste disposal. Tracked vehicles are slow and difficult to use over rough ice surfaces but are probably the most proven and reliable. Aircraft have proven valuable in saving time but are hindered by bad weather conditions and the need for good landing facilities. SEVs have potential in regard to load capacity, speed, and ability to traverse rough surfaces but have high fuel requirements and, in larger versions, require towing.

The most practical transportation system may be a combination of modes of transport, possibly tracked surface vehicles and SEVs with refueling stops along the route supplied by fuel drops from aircraft. Actual in-place testing would be necessary to demonstrate a workable system. Redesign and testing of over-ice vehicles to handle waste casks, construction of a prototype, and field testing are estimated to require 5 years.

Development of marine transport systems would consist primarily of designing existing ship types to include shielded cell facilities, special storage-handling facilities for casks and canisters, and hull strengthening to withstand transit through pack ice. Once the specifications were provided, it is estimated that design and construction would take about 5 years.

5.3.2.2 Embarkation Ports

Three years' time is assigned to the task of selecting embarkation ports for the collection of the waste

canisters and the shipping to the disposal areas. The selection would be based on the most safe and efficient relationship of all factors involved, including relative geographical location of the disposal site and embarkation port; location of waste reprocessing plants, available transportation networks; adequate harbor facilities; minimum interference with busy sea lanes; public acceptance and any other factors that might enter into the total concept.

Design, construction and installation of the port facilities are estimated to require 5 years after the port is selected. If, for example, major modification of the harbor is required, the time involved might need to be extended to 10 or more years.

Because the embarkation port would be considered a nuclear facility, filing of an environmental impact statement and compliance with siting regulations would be required. Based on present experience with siting nuclear plants, the total time required between site selection and operation could be about 10 years.

5.3.3 Containerization, Placement and Operating System

5.3.3.1 Containerization

Containerization is considered to be in metal canisters approximately 30 centimeters (1 foot) in diameter and 3 meters (10 feet) in length. Radioactive material in each canister would be approximately 1 megacurie with a heat generation rate of 3 kilowatts. Some research design would be required to develop a canis-

ter that could assure proper penetration trajectories through the ice sheet, withstand potential high pressure from ice movement and have maximum resistance to corrosion. Canister design should also consider the possible stresses developed by movement along a rough bed under the ice.

A summary discussion of the factors involved with canister materials selection for ice sheet and seabed disposal has been included in Appendix 7.A.

Relatively little new technology is required to design and construct an adequate waste canister for use in ice sheet disposal. Approximately 2 years would be needed for development of a prototype. Field testing could require an additional 10 years, depending upon the disposal concept considered.

5.3.3.2 Placement

Placement for the within-ice sheet methods of disposal would need study of the rate at which the canisters would sink by melting into the ice. The sinking rate will depend upon the final design of the canisters and the thermal output at the time and after emplacement. For the meltdown concept, the final position of the canister will be a result of the time required to melt down and the motions of the ice during that time.

For the anchored storage concept, research on the possibility and means of heating the suspending chains may be necessary if retrieval were considered. The study of internal ice motion would determine if there were

convective cells within the ice at the disposal site that might hinder use of this method.

Placement within the surface storage facilities would require only application of available techniques and equipment with modification to allow for radiation shielding during handling. Investigation should be conducted on the effectiveness of extensible "jack-up" legs for the loaded surface facility, as well as the sinking rate expected for the actual facility when in use.

The operating system would develop as the type of disposal was selected and the transportation system develops. Experience gained during the International Geophysical Year, Operation Deep Freeze I, Deep Freeze II⁽¹⁵⁾ and subsequently has answered many of the questions on support of personnel and equipment in the Antarctic. The results have shown what is necessary in the way of housing, clothing and supplies and should give considerable help in setting up an operating system.

5.3.3.3 Pilot-Scale Demonstration

Pilot-scale demonstration of the equipment and techniques would provide an actual operating test for the disposal system. For the demonstration, canisters of simulated waste would be transported over ice to the disposal area and emplaced. Heating elements within the canisters and connected to a power supply on the surface would be used to provide meltdown through the ice. Instruments attached to the canisters with telemetry to the surface would be used to

measure the condition of the canisters, temperature, salinity, and radius of the melt pool and the position of the canisters with respect to the surface site.

Demonstration time for the anchored emplacement concept is estimated to require about 5 years. Demonstration time for the meltdown or free flow concept is estimated to require 5 to 10 years.

5.3.4 Research and Development Costs

Research and Development costs for ice sheet disposal are very difficult to estimate. However, an estimate was made based on the information available compared to what would be needed to evaluate the ice sheet disposal concepts. It is recognized that during the estimated 25-year program significant accomplishments by any of the groups engaged in polar and ice sheet research might drastically reduce the time and cost requirements.

The research costs are based on the current yearly research cost in the Antarctic of about 40 million dollars per year.⁽⁴³⁾ It is felt that a fivefold increase in this effort and cost, to 200 million dollars per year, would be necessary to obtain the needed information and to develop the required equipment, considering the size of the area, number of personnel and variety of equipment involved.

The spending level is estimated to increase to about 200 million dollars per year by the fourth year. The spending level would remain at about 200 million dollars per year

until near the end of the program, when it would decrease. It is believed that the total Research and Development program would cost in the order of 5 billion dollars. At least 75% of this cost would be directed toward obtaining a thorough understanding of the ice sheets, and about 90% of these costs would be for logistics and support of the scientific personnel. The remaining 25% of the estimated total program cost would be more specifically concerned with disposal of the waste and would be directed toward transportation vehicles, shipping ports, containerization, placement and operating systems. These latter costs are estimated to be on the order of 600 to 1000 million dollars.

5.4 ESTIMATED TIME REQUIREMENTS FOR OPERATION

Research and Development needs are of two kinds: first a large amount of basic research on the nature, properties and conditions of the ice sheets to evaluate their suitability for radioactive waste over long periods of time and to make some estimate of their future existence; and second, development of equipment suitable for meeting the transportation needs safely and adequately.

Considering the results that may develop from the continuing U.S. research effort in the Antarctic directed by the Office of Polar Programs, National Science Foundation, and anticipated further results from the Deep Sea Drilling Project conducted by Scripps Institution for the National Science Foundation, a ten-fold increase in research rate over

the 1967-1972 levels could be required to develop a satisfactory model for definitive evaluation of radioactive waste disposal in an ice sheet. This estimate is based on the premise that the ongoing research programs would be directed toward the goal of evaluating waste disposal and that the personnel involved would form the nucleus of the expanded effort. At present, too few trained scientists are available for an effort of this size.

The duration of this expanded Research and Development program leading to the establishment of a commercial system for disposal of waste canisters in ice sheets is estimated to require a minimum of about 25 years. This estimate assumes that one of the ice sheet disposal concepts presented will be selected about 5 to 10 years after the program has been initiated. The key elements of the program will be the extensive new studies required to adequately evaluate ice sheets in general and the detailed studies necessary for specific site evaluations.

A summary Figure 5.7 shows the possible chronological sequence in ice sheet studies that could lead to a commercial disposal system.

5.5 ESTIMATED CAPITAL AND OPERATING COSTS

5.5.1 Systems Description for Cost Bases

Preliminary cost estimates were developed for the anchored emplacement disposal concept, as outlined in section 5.1.2 and shown in Figure 5.2,

FIGURE 5.7. Overall Research and Development Schedule - Waste Disposal in Ice Sheet

and assumed waste disposal in Antarctica. This section describes a conceptual disposal system which was used as the basis for the preliminary cost evaluation. A drilled hole to a depth of 50 to 100 meters in the ice sheet surface would be required for each canister. The total number of waste canisters from each reference reprocessing plant is assumed to be 14,522 or the amount of waste from one plant reprocessing 5 MT/day of fuel over a 25-year period. Unit costs for this system were then scaled up to meet the cumulative needs for U.S. nuclear power through the year 2000.

The reference waste will be aged 10 years prior to disposal and will then have a heat generation rate of

about 3 kilowatts of heat output per canister. The initial emplacement holes are considered to be on 1-kilometer centers. This spacing would require an area of about 11,000 square kilometers for the waste from each reference reprocessing plant or an area about 104 kilometers on a side.

5.5.1.1 Embarkation Facility

The embarkation facility includes a shielded cell and concrete block/steel roof buildings for the receiving facility; water cooled storage basins for the canisters; office buildings; laboratories; and maintenance facilities. The receiving facility would be equipped with a 100-ton bridge crane for handling the casks.

An in-cell 15-ton crane would manipulate the waste canisters and cell cover blocks. An electric/hydraulic, remotely controlled transfer cart would be used in the shielded cell to transfer canisters to the load-in, load-out areas below the cover block of the transfer cell. The shielded cell would be equipped with six viewing windows and six pairs of slave manipulators. Fans and filters would handle about 300,000 liters per minute ventilation air.

The embarkation port would also include the pier and docking facilities, as well as a 50-ton movable crane for use in moving casks from the storage area to the transport ship.

5.5.1.2 Transport Ship

The transport ship's construction or modification would be directed toward its primary purpose--transporting the waste canisters, in their shipping casks, from the embarkation port to the ice sheet margin or on-land port. Each cask, containing two waste canisters, is considered to weigh 25 tons.

The transport ship's capacity and dimensions would be determined by the final design size of the shipping cask; the type of debarkation or unloading used at the ice sheet; and the number of trips required or possible in 1 year. At present, a ship of 125 meters length and 25 meter beam is considered to be about the minimum size to accommodate 300 casks of 25 tons on one deck level. The waste from the reference reprocessing plant would require about 600 waste canisters to be transported per year with two canisters loaded in each cask

(see Section 5.5.1) and could be handled in one trip if desired. Further study may show the most efficient and economical marine transport systems to be several smaller ships carrying fewer waste canisters each trip.

The ship would be equipped with a small shielded cell, similar to but smaller than that described for the embarkation facility. The ship's shielded cell facility would be designed to permit entry and removal of the casks. A separate 50-ton capacity crane would be required for off-loading the casks at the debarkation port at the ice sheet.

Cask cooling equipment, decontamination holding tanks and monitoring equipment would be part of the ship's systems.

5.5.1.3 Over-ice Transport System

Surface Effect Vehicles were used as the bases for estimating over-ice transport costs. Over-ice transport vehicles could be simple adaptations of existing heavy haul hovercraft now in operation in the Arctic,⁽⁴²⁾ if further testing in Antarctica proves their suitability. Each hovercraft or Surface Effects Vehicle (SEV) would measure 19 meters long by 10 meters wide. SEV empty weight would be 14 tons. Payload weight would be 25 tons. Maximum gross weight would be 42 tons. Maximum performance speed over a flat surface carrying a 25-ton load would be 80 kilometers per hour. It should be noted that SEVs have been tested on the shelf areas but have not yet been proved under the more severe operating conditions of the interior.

Each cask-carrying SEV would be modified to allow a canister to be lowered directly from the bottom of the cask through the skirt deck into a pre-drilled emplacement hole. Approximately 30 SEVs would be required to transport the 600 waste canisters per year produced by one reference fuel reprocessing plant. Each SEV would make 10 round trips per season from the debarkation port to the disposal site carrying one cask with two canisters per trip.

Five additional SEVs would be used to transport temporary living facilities and operations staff to the disposal site each season, provide supplies during the season and serve as backup for the cask-carrying SEVs.

Normal fuel capacity of a SEV of this size is 2250 liters (600 gallons). Fuel consumption rate is approximately 9 liters per kilometer. Each round trip of 2000 kilometers would require approximately 1.8×10^4 liters of fuel. To meet this demand for fuel would require establishment of about six fuel supply depots spaced at 200-kilometer intervals. Fuel would be airlifted from McMurdo Base or other existing permanent fuel depots. Approximately 10 aircraft equivalent to a C-130 Hercules would be required to provide 640 fuel airlifts over a 90 to 120 day operating season.

5.5.1.4 Operations Staff

The operations staff for the ice sheet disposal system as visualized is estimated to be about 200. These personnel are associated with the handling and management of the waste and not with the auxiliary systems.

The operations staff is divided approximately as shown below:

Embarkation Port

8 supervisory, 26 nonsupervisory
Administration: 4 supervisory,
10 nonsupervisory (including
5 security guards)

Engineering/Operation: 4 supervisory, 16 nonsupervisory

Operation: 7 day week, 3 shift

Transport Waste Management Operations (incremental to normal ship's complement)

3 supervisory, 12 nonsupervisory
Operation (during time of actual transport): 7 day week, 3 shift

Ice Breaker Operations (2 required)

Ship's complement 45 men

Operation: 7 day week, 3 month operating period plus 1 to 2 month travel.

Debarkation Staff (incremental to Transport Waste Management Staff)

5 supervisory, 35 nonsupervisory
Operation: 7 day week, 3 shift
(4 months per year)

Over-ice Transport Operations

2 supervisory, 80 nonsupervisory
Operation: 7 day week, 2 shift
(4 months per year)

Drilling Crew at Disposal Site

2 supervisory, 30 nonsupervisory
Operation: 7 day week, 2 shift
(4 months per year)

Emplacement Operations at Disposal Site

3 supervisory, 24 nonsupervisory
Operation: 7 day week, 3 shift
(4 months per year)

5.5.2 Capital and Operating Costs

From the previous conceptual design bases, capital and operating

costs for the three ice sheet disposal concepts were developed as summarized in Table 5.2. The capital costs are associated primarily with transportation vehicles and equipment, which are essentially the same for the three disposal concepts. The operating costs for each disposal concept are summarized separately.

Capital costs are estimated to be about 410 million dollars to handle the output from one reference fuel reprocessing plant for the meltdown and anchored emplacement concepts. Associated operating costs are estimated at between 27 and 46 million dollars per year. The surface storage facility is estimated to have capital costs of about 415 million dollars and associated operating costs of about 23 million dollars per year for the disposal of waste from one reference plant.

Based on the charges assessed at the time of reprocessing, the total system unit charges including reprocessing, 5-year interim liquid storage, solidification and containerization, 5-year interim solid storage, transport to the disposal site and final emplacement are estimated to range between \$23,500/MT or 90×10^{-3} mills/kW-hr for anchored emplacement and \$19,800/MT or 75×10^{-3} mills/kW-hr for surface storage disposal.

Section 3.2 of this report discusses capital and operating costs in more detail.

5.6 PUBLIC RESPONSE, POLICY AND ENVIRONMENTAL IMPACT

5.6.1 Public Response

The overall question of public response and the public's perception of risk was discussed in Section 3.5. Key elements of public perception of risk are defined and the results from answers to a preliminary study questionnaire are presented. Because of the preliminary nature of the study, only tentative and qualitative indications can be derived. Some of the indications from the study are summarized below.

Ice sheet disposal was ranked by the in-house group of study participants, after a brief introduction to the disposal schemes, as being in the median range of publicly perceived risk level in overall rating of risk among the five generic disposal concepts. After a presentation of descriptive information on the disposal schemes, ice sheet disposal was perceived as having the highest risk level. In general, ice sheet disposal was ranked as being potentially dangerous with respect to protective measures considered achievable in the event of leakage. Similar reactions were recorded for retrievability, detectability and safety of emplacement operations. Ice sheet disposal was ranked as moderately dangerous with respect to stability and safety, once in place, and relatively safe with respect to distance and population density.

Table 5.2. Capital and Operating Cost
Items for Ice Sheet Disposal

Capital Costs, Million Dollars, for Meltdown and Anchored Emplacement:

1. Construction of Embarkation Port Facility	20.0
2. Sea Transport Vessel, Including Fully Equipped Hot Cell, 40-Ton Bridge Crane, etc.	100.0
3. Two Ice Breakers @ #60 x 10 ⁶	120.0
4. Over-ice Transport Vehicles	53.0
5. Drilling Rigs	12.0
6. Monitoring Equipment	2.9
7. Shipping Casks	45.0
8. Aircraft	50.0
9. Support Maintenance and In-Transit Facilities	5.0
Total Capital Costs	407.9

Capital Costs, Million Dollars, for Surface Storage Facility:

1. Construction of Embarkation Port Facility	20.0
2. Sea Transport Vessel, Including Fully Equipped Hot Cell, 40-Ton Bridge Crane, etc.	100.0
3. Two Ice Breakers @ #60 x 10 ⁶	120.0
4. Over-ice Transport Vehicles	53.0
5. Surface Facility	20.0
6. Monitoring Equipment	2.9
7. Shipping Casks	45.0
8. Aircraft	50.0
9. Support Maintenance and In-Transit Facilities	5.0
Total Capital Costs	295.9

Operating Costs, Per Year, Million Dollars:

Meltdown or Free Flow Concept

1. Operation of Embarkation Facility	1.0
2. Operation of Surface Facility with Hot Cell	8.1
3. Transport Vehicles Operation	10.5
4. Drilling Operations and In-Transit Facilities Operation	7.0
Total Operating Cost Per Year	26.6

Anchored Emplacement

1. Operation of Embarkation Facility	1.0
2. Operation of Surface Facility with Hot Cell	8.1
3. Transport Vehicle Operation	10.5
4. Surface Anchors, Cables, Chains	15.0
5. Drilling Operations and In-Transit Facilities Operation	7.0
Total Operating Costs Per Year	41.6

Surface Storage Facility

1. Operation of Embarkation Facility	1.0
2. Operation of Surface Facility with Hot Cell	8.1
3. Transport Vehicles Operation	10.5
4. Maintenance and In-Transit Facilities Operation	3.5
Total Operating Costs Per Year	23.1

5.6.2 Policy

Policy, restrictions and international treaty agreements are considered in Section 3.3 of this report. A number of treaties and agreements exist that could affect the use of the ice sheets for storage and disposal of radioactive material.

Because Greenland is Danish territory it was not considered with respect to policy restrictions.

Disposal of radioactive waste in Antarctica is specifically prohibited by the Antarctic Treaty of 1959, of which the United States is a signatory. The text of the Antarctic Treaty is included in Appendix 6.A. The treaty may be renewed after it has been in effect for 30 years or amended during this time. If the treaty were amended and ice sheet disposal demonstrated as feasible, Antarctica could become an international repository.

An example of one approach that may effect a possible change in international policy regarding disposal of radioactive waste in Antarctica is the resolution passed by the National Academy of Science, Committee on Polar Research, Panel on Glaciology at a meeting in Seattle, Washington, May 1973. The resolution reads as follows:

PANEL ON GLACIOLOGY
RESOLUTION NO. I
9 MAY 1973

"Whereas many nations of the world are now engaged in the production of high-level radioactive materials as a by-product of nuclear energy generation, and

whereas other nations will be engaged in similar activities before the end of this century,

whereas the inviolate storage/disposal of such materials poses the most serious environmental problem that is currently facing mankind and requires the location of suitable Earth "graveyards" that can be isolated from the biosphere for a period of 250,000 years, and

whereas the ice sheets of Antarctica and Greenland have been proposed as possible storage/disposal sites,

be it now resolved that the United States Committee on Polar Research convey to the Scientific Committee on Antarctic Research and to the International Commission on Snow and Ice, the urgent need to thoroughly investigate the geophysical basis for such an ice sheet disposal scheme so that its feasibility can be evaluated and its merits properly weighed against alternative methods of storage/disposal."

While this resolution neither favors nor opposes ice sheet waste disposal as such, it does indicate the objective concern of the scientific community for radioactive waste management and Antarctica. At the time of this publication, a working group of the Scientific Committee on Antarctic Research (SCAR) has the resolution on their agenda, for future action. The International Commission on Snow and Ice (ICSI) has responded and passed its own resolution.

5.6.3 Environmental Impact

The radiological studies for ice sheet disposal have only been started, as discussed in Section 3.1.3. Nonradiological environmental impact was discussed in Section 3.4 and is summarized in this section. The ice sheet disposal concepts and waste management system, if functioning as visualized, should have little impact on the environment with the possible exception of potential impact on the ice sheet itself. Until physical conditions within the ice sheet, and particularly at the ice-bedrock interface are better known, it is difficult to predict what effect the waste canisters would have and the effects of the interface conditions on the canister. In the meltdown and anchored emplacement concepts, the refreezing of the ice above the canisters forms the seal as long as the ice sheet retains its present form and properties, thus isolating the waste from man's environment as long as the bottom is nonmelting.

5.6.3.1 Land

The land would probably experience some environmental impact in connection with the embarkation port facility. The port facility would include a radioactivity handling shielded cell and, including dock and loading facilities, would require an area of about 1 square kilometer. For safety assurance, the port facility would be equipped with its own separate water, power and sewer systems. Noise and atmospheric emissions should be minimal.

The ice sheet disposal area and over-ice transportation routes can

also be considered land. These areas would include an area at the edge of the ice sheet, at an ice shelf edge, or at an ice-free area on land for off-loading the shipping casks; approximately six support and fueling stations along the route to the disposal area; and about an 11,000 square kilometer area of the ice sheet for the disposal area for the total output from each reference reprocessing plant. The area required for the retrievable surface storage concepts would be considerably smaller because each facility would contain a number of waste canisters. The area needed would depend on the final design capacity of each facility.

The disposal area for the meltdown and anchored storage concept are large because the canisters are emplaced singly on 1-kilometer centers. This separation is necessary to minimize the possibility of the melt pools around the canisters coalescing and forming a large water mass within the ice or at the ice-bedrock interface. The formation of such a large water body could affect the equilibrium of the ice sheet, particularly if it is at the bottom of the ice mass, where it might trigger an increase in velocity of the ice. Basal ice sheet water also could conceivably form a means of communication from the disposal area to the edge of the ice sheet, and thus to the ocean, for transporting waste material if any leakage from the canisters should occur.

Accidental spills of fuel would be a design danger. The over-ice transport vehicles would require over

12 million liters per year for the output from a reference reprocessing plant, most of which would be supplied by air drops. The probability of fuel bladders rupturing during the drops is moderately high. Such spills would penetrate into the surface snow and reach the underlying ice where it would remain until it evaporated or was buried by additional snow. It is unlikely that any would reach the ocean unless spilled near the edge of the ice sheet, although anything traveling with the ice will reach the ocean eventually.

5.6.3.2 Water

The use of seawater for cooling the canisters during sea transport to the ice sheet would include a closed circulating system for fresh water and a once-through system with seawater and thus would have no effect on the sea except for an almost undetectable temperature rise.

Use of water on the ice sheet would be primarily for consumption by and support of the 200 operating personnel. This water could be obtained by melting ice. No water would be used for cooling during the disposal operations.

5.6.3.3 Air

The major impact on air would be at the ice sheet and would come from the combustion products of the over-ice transport vehicles, support aircraft and the fuel consumed for heating the facilities. Though at present the effects of these products are not considered a major problem, a temperature inversion that persists above the ice sheet throughout most

of the year could cause ice fogs and result in the accumulation of exhaust fumes and vapors. By the year 2000 if Antarctica should become an international waste repository, the effects on the ice sheet could be several orders of magnitude larger than those from the reference plant studied here. It is conceivable that the cumulative effects of the heat and combustion products could affect the air to the extent that atmospheric circulation and weather patterns would be altered. Altered weather could affect the stability of the Antarctic ice sheet.

5.6.3.4 Ecologic Impact

The ecologic impact, through planning and consideration of the plant and animal life, should be small. The productivity of the shallow seas around Antarctica is very high, but Antarctica is relatively barren of life except in the coastal areas. The ice-free valleys away from the coast are barren by the standards of any other land area. Installations and access routes, including air traffic lanes, would be planned to avoid as much as possible the feeding, mating and nesting areas of the birds and animals.

5.6.3.5 Aesthetic Impact

Because of the remoteness of the area and lack of permanent population, the visual and aural impact on man would be very small.

5.6.3.6 Transportation Impact

Some transportation impact would result from the overland phase, from

the reprocessing plant to the embarkation port. Transportation will probably be by truck or rail, and would require about 100 trips per year for the reference fuel reprocessing plant. For the total United States' nuclear economy, the number of trips could increase to about 800 per year by the year 2010. Each trip is considered as a round trip from the reprocessing plant to the embarkation port and back to the reprocessing plant.

Transport by ship from the embarkation port to the ice sheet will require from one to four trips per year for the reference reprocessing plant, depending on the capacity of the ship. However, since there are usually less than 3 months when ships can reach the Antarctic continent, sea transport would have to be scheduled each year to arrive during this season. This phase of transportation would be largely on the open seas and thus have little impact on the environment.

The waste canisters could be equipped with flotation and other devices for recovering them in the event of a transport ship sinking. Eventually, most all waste canisters from a sinking transport ship should be recovered. However, a transport ship crushed in the ice pack and sunk could cause severe recovery problems. During transport, the canisters will be enclosed in casks to prevent radiation and high temperature effects on the immediate environment.

Over-ice transport should have little effect on the environment other than the possibility of fuel spills and the possible effects of combustion products already discussed.

In the event of power failure to a Surface Effects Vehicle, it would come to rest on the snow, and the canisters in their casks should be relatively undisturbed. In the unlikely event of a cask being dislodged by accident, the cask would remain sealed and sink slowly into the ice unless recovered.

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APPENDIX

SECTION 5: ICE SHEET DISPOSAL

APPENDIX 5.A

A PROPOSAL FOR THE ESTABLISHMENT OF A PERMANENT INTERNATIONAL
HIGH-LEVEL RADIOACTIVE WASTE DEPOSITORY IN ANTARCTICA

INTERNATIONAL RADIONUCLIDE DEPOSITORY
(INTERRAD)

A Proposal for the Establishment
of a Permanent International
High-Level Radioactive Waste
Depository in Antarctica

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ABSTRACT

The permanent disposal of high-level radioactive wastes^{*} accumulating from the growing production of nuclear energy is of vital concern to the international community and needs a world-wide commitment to a solution to this problem. The number of nations who are turning to nuclear energy as a power source increases and as the world's fossil fuel resources are depleted, there will be greater dependence on nuclear energy and a greater accumulation of waste materials. Before the problem of high-level radioactive waste disposal evolves into a serious problem, all possible solutions should be investigated on a long-term basis, beginning immediately.

Many waste disposal methods have been proposed and several are under investigation; however no permanent depository for these high-level radioactive wastes has been constructed in any country now accumulating the hazardous waste materials. Consideration must be given to the safety and world-wide environmental effects of the disposal method selected; thus as waste material buildup continues, the problem of its disposal assumes world-wide significance.

Permanent disposal of the waste under the Antarctic ice cap would remove the wastes from populated areas and — if the depository were properly designed — would remove the wastes from all contact with the biosphere. The polar climate and the low temperature of the ice would furnish a sink for the heat given off by the radioactive waste canisters, and the large subsurface area of the ice would provide adequate space so that the canisters would not be in close contact with each other.

All available evidence indicates that if the wastes were fused into a solid glass matrix, they could be practicably and safely transported to the interior of the ice cap. If placed on the surface of the ice, they would melt their own emplacement shafts which would rapidly reseal by freezing and plastic flow. The containers would sink slowly to the ice-rock interface where they would

^{*} Wastes with levels of radioactivity adequate to generate significant amounts of thermal energy.

5.A.3

remain safely isolated from the biosphere for more than 250,000 years.

Scientific studies have indicated that the average temperature in Antarctica has remained below freezing for more than a million years so that the large thickness of polar ice may be expected to provide a good seal for at least a similar period into the future.

Tentatively selected disposal sites are 600 to 1000 kilometers inland from the nearest natural flora or fauna, isolated from the sea by mountain ranges as well as by long horizontal thicknesses of ice and frozen ground. The sites were selected to effectively eliminate the chance of any harmful effects due to ice movements.

The Antarctica Treaty of 1959 prohibits radioactive waste disposal there, but it also provides specifically for amendments that are desired by the signatories, many of whom have or will have high-level waste disposal problems. This problem is one of truly international character, and Antarctica is the only "international" land territory which holds maximum promise of a practical and safe solution. Disposal under the Greenland ice cap also appears to be possible from the technical viewpoint. It is Danish territory and this discussion is concentrated on Antarctica because of its international accessibility. Similar technical considerations could be applied to the Greenland alternative.

The major problems to be solved to establish the feasibility of this approach include complete literature and laboratory studies of the basic principles involved, followed by field surveys and experiments to achieve the following: 1) determine ice/canister interactions; 2) survey detailed ice thicknesses, movements, and sub-ice topography; 3) determine temperature gradients down to the rock-ice interface; and 4) design, construct, and field-test both engineering models and prototypes of an operating fail-safe transport and emplacement system.

5.A.4

A brief comparison of the ice-cap approach with other methods which have been suggested for ultimate disposal indicates that it holds promise of being the most practical and safest solution. It thus deserves early and careful consideration by appropriate United States and international agencies.

1.0 INTRODUCTION

1.1 GENERAL

The safe, permanent disposal of high-level waste products accumulating from nuclear power reactor fuel-rod processing is an increasing problem. There is a growing concern about future accumulations of these wastes as nations turn to nuclear energy as a source of power. Fossil fuels are rapidly being depleted as an energy source, and the advent of theoretically clean nuclear fusion power is still far in the future. It is believed that nuclear fission reactors, particularly the breeder type, will provide the major part of our fixed-site energy requirements in the period from perhaps the year 1990 to 2100 A.D., or longer.

The ultimate disposal of high-level radioactive wastes from these plants is believed to be much more practical and economical over the long term than the controlled storage above ground as presently practiced, provided safe isolation can be assured. "High-level" radioactive wastes constitute approximately 1 percent by volume of all radioactive wastes, but contain approximately 90 percent of the total radioactivity (Ref. 1). They are produced primarily during the reprocessing of spent reactor fuel elements.

These high-level radioactive wastes are currently stored either in nitric acid or neutralized solutions in specially constructed and carefully monitored tanks, where they may literally boil from their own radioactive heating. Therefore, the containers must be continuously cooled. The activity decays with time according to the half lives of the included radionuclides and the relative quantities of each. The thermal output decays from 200 watts per kilogram of fission products, aged one year, to 10 watts per kilogram, aged

5.A.5

three years. Significant amounts of long-lived dangerous isotopes are present, however, and require safe containment in "permanent" storage for tens or hundreds of thousands of years.

The problem is not restricted to any one country but is truly international in scope. The United States has accumulated more than 80 million gallons of these liquid wastes over the past 30 years, and these remain above ground in "temporary" storage today (Ref. 2). Indeed, all countries with nuclear power capabilities, present or future, are faced with this disposal problem.

Table 1 indicates the most recent estimate of the capacity of nuclear power reactors in the nonweapon countries of the world. All of these countries now have, or shortly will develop, problems with disposal of high-level waste from their reactors. It seems unreasonable, impractical, and uneconomical to expect each individual nation to construct a permanent disposal facility which must be kept under constant surveillance for 250,000 years. Not only would the cost of such facilities become a major burden on society as a whole, but the hazards from dispersed high-level radioactive waste would be multiplied greatly over those arising from a single international depository.

In a number of countries that will have nuclear plants, it is literally impossible to find sites of any kind which meet the primary depository requirements because of their geological and geographical characteristics. For example, the earthquake intensity and frequency is so high in the Japanese Islands that it is doubtful that any location for a safe long-term depository could be found there, or constructed at reasonable expense.

The severity of this disposal problem can be expected to increase rapidly in future years as fossil fuel supplies dwindle and there is an increased reliance on nuclear power reactors. Figure 1 shows the relative future growth of nuclear power. The amount of high-level wastes produced annually will be roughly proportional to the annual power generation and is expected to increase about 100 fold between now (1972) and the year 2000.

5.A.6

Table 1

POWER REACTORS IN NONWEAPON COUNTRIES*

Name of Country	Being Built, Planned, or Proposed		Operating	
	Estimated Installed Megawatt Capacity 1976	Estimated Kilograms Plutonium Produced per Year	Estimated Megawatt Capacity 1971	Estimated Kilograms Plutonium Produced per Year
† Argentina	719	145		
† Australia	500	100		
Austria	700	140		
† Belgium	1600	320	10.50	2
Brazil	500	100		
Bulgaria	800	160		
Canada	3200	640	1496	300
† Chile	-	-		
China, Republic of	1200	240		
Czechoslovakia	110	20		
Finland	440	80		
Greece	450	90		
Germany, East	500	100	70	14
Germany, West	8500	1700	1019	200
Hungary	1000	200		
India	1100	220	580	115
Israel	-	-		
Italy	1300	260	597	120
† Japan	10000	2000	1300.75	260
Korea, South	560	110		
Mexico	-	-		
Netherlands	1000	200	51.50	10
† New Zealand	-	-		
† Norway	500	100		
Pakistan	200	40	125	25
Philippines	-	-		
Poland	200	40		
Portugal	-	-		
Rumania	600	120		
† South Africa	-	-		
Spain	2400	480	593	120
Sweden	4800	960	452	90
Switzerland	2200	450	1006.20	200
Thailand	300	60		
United Arab Republic	-	-		
Yugoslavia	-	-		

*From Safeguarding the Atom (UNA-USA Policy Panel, 1972)

† Indicates Antarctic Treaty Signatory.

Figure 1. Projected Nuclear Power Growth (after Figure 1, Ref. 3)

It is apparent that a safe permanent storage place and methodology for high-level radioactive wastes must be developed over the next 10 to 20 years to insure adequate protection of the world's future population and environment from this highly dangerous material. Otherwise, it may be necessary to slow drastically the development of nuclear energy with a consequent decrease in our available power supplies as the fossil fuels are exhausted.

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1.2 PERMANENT DEPOSITORY REQUIREMENTS

In the authors' opinion, any site for permanent storage of radioactive wastes must fulfill the following requirements:

1. If long-lived actinides are present, waste must be safely spatially separated from the biosphere for approximately 250,000 years, i. e., kept from entering ground or surface waters and the atmosphere.
2. Site must be safe from human sabotage or entry by accident for approximately 250,000 years.
3. Site must be safe from natural-disaster effects, i. e., earthquakes, floods, tornadoes, hurricanes, etc.
4. Site must not destroy or prevent the use of a potentially needed resource for the future.

The methods of transport and emplacement must fulfill these requirements:

1. Methods must be well within practical engineering capabilities as presently projected over the next 10 to 20 years.
2. All handling and transport mechanisms must be designed for fail-safe operation.
3. Methods must assume the possibility of container failure after a decade at most.
4. Methods must be reasonably economical.

1.3 SALT MINE WASTE DISPOSAL PLAN

Several approaches have been proposed for the ultimate disposal of high-level wastes. Of the various alternatives, only their disposal in salt beds has been studied in any depth and is seriously considered as a viable approach for ultimate disposal (Ref. 13).

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The Federal Republic of Germany has established a national waste repository in a salt mine and disposal of low- and intermediate-level radioactive wastes has begun. High-level waste will probably not be deposited at this facility until 1975, but planning and experimentation are now under way for the high-level radioactive waste storage facility (Ref. 16).

Although the United States has not moved as rapidly as West Germany to establish a functioning salt mine disposal facility, it has engaged in very extensive testing of the method in a salt mine at Lyons, Kansas and is considering locations in Southeast New Mexico. Experiments were begun in 1965 in which electric heaters and radiation sources were installed in the mine floor to test their effects upon the salt. The results obtained have clarified most of the uncertainties about the physical behavior of salt under heat and radiation.

Salt appears to be an attractive medium for the disposal of nuclear waste because of its ability to flow under pressure, permitting rapid sealing of fractures and void spaces. Salt formations also tend to be dry, and their existence implies that no large quantities of circulating ground water are present in the immediate area. Otherwise, the salt would have dissolved away. Salt has a fairly good thermal conductivity so that heat generated by the waste will be conducted away from the waste containers, thus preventing the development of excessively high local temperatures. Bedded salt is generally considered to be more suitable for waste repository sites than salt domes because of the tectonic activity of the domes. The practical feasibility of salt mine waste disposal for high-level nuclear waste remains to be tested. Plans for a pilot study are being made but no definite site has yet been selected.

It should be pointed out, however, that salt beds are not present in all countries which are producing nuclear wastes. Furthermore, deposits suitable for waste disposal are frequently located in populated areas, and hazards from accidental or intentional entry cannot be totally excluded. Finally, it seems unlikely that countries which have extensive salt deposits are likely to be willing to accept large amounts of nuclear wastes generated outside their borders.

1.4 ICE AS A STORAGE MEDIUM

Ice, if its average temperature can be maintained well below the freezing point, has, similar to salt, several advantageous features as a storage medium. Its fractures are self-healing through recrystallization or plastic flow. It is impermeable to water and has a heat conductivity comparable to common rock types. In Antarctica (Figure 2), ice occurs in large and pure contiguous masses. The central portion of the Antarctic ice cap is the largest area on earth that is essentially devoid of any flora or fauna, and it is the most remote region from normal human contact.

The Greenland ice cap is a possible alternate depository location. From the logistics viewpoint, it is more accessible than Antarctica and its environment is somewhat more moderate. It is Danish territory. This discussion has been concentrated on Antarctica because of its international accessibility. Similar technical considerations would apply also to the Greenland alternative.

The potential usefulness of large ice masses as sites for the storage of radioactive decay products was recognized by Bernhardt Philberth in 1958. At that time he was issued German Patent No. 1,043,535 titled "Storage of Radioactive Decay Products in Polar Ice." The patent proposes that radioactive decay products be stored in Arctic or Antarctic ice which receives constant mass increment by precipitation. In 1959, Philberth was granted an addition to his first patent which proposed that alkaline-earth or alkali metals be used as an external sheath for the waste containers to provide sufficient reaction heat to permit the containers to sink into the ice. In 1961, Philberth published a detailed and very complete review of his proposal for the use of ice caps of the earth as sites for disposal of radioactive decay products. In this paper he anticipated many of the problems which began to develop in the following decade (Ref. 14).

Ice has a further potential advantage in that it could be possible to place the hot containers of solidified high-level wastes on the surface of the ice and let them melt their own emplacement shafts to a final resting place as much as one or

Figure 2. Anarctic Ice Cap (from Meteorological Plotting Chart 6843, South Polar Area, 1956)

5.A.12

two kilometers beneath the surface. Containers can be designed to sink slowly and vertically. Snow, melt water, and plastic flow of the ice should permanently seal the "shafts" behind the sinking containers.

Preliminary rough calculations, based on a cylindrical can 30 centimeters in diameter by 3 meters in length with a thermal output of 5400 watts, indicate a probable sinking rate of approximately 1 meter per day with an ambient ice temperature in the range of -50°C . This would mean a total sinking time of about 3 to 5 years for an ice depth of about 1.5 kilometers.

Electrically heated probes have been used successfully to "sink" temperature sensors into the ice in Antarctica (Ref. 4). Observations made of the rates of closure of drill holes in ice near Byrd Station indicate that any residual openings in the shafts melted by the waste containers may be expected to seal themselves by the squeezing in of the walls at depths greater than about 300 meters by unbalanced overburden pressure and plastic flow of the ice. This may take several years or longer at depths of less than 300 meters, but the rates of closure appear to increase rapidly with depth below that level (Ref. 5, Fig. 12B).

The specific characteristics of the Antarctic ice fields will be considered in the waste disposal context from both the technical and political viewpoints in the following sections. Some of the problems to be solved are outlined, and a tentative plan to investigate this approach is presented.

2.0 ANTARCTIC ICE SHEET DEPOSITORY

2.1 GENERAL

The Antarctic ice sheet is believed to present the best opportunity for disposal of high-level radioactive wastes from both a political and technical viewpoint in spite of the fact that the transportation logistics may be difficult. From the technical viewpoint, preliminary studies undertaken to date indicate no identifiable unsolvable problems in achieving safe permanent waste storage.

The Antarctic Treaty of 1959* sets that continent aside for international use for a 30-year period. Of all the land territory on earth, it is the closest to being generally considered to be truly international territory. Thus, it could provide an international solution to the international problem of high-level waste disposal. Although the treaty specifically prohibits the emplacement of nuclear wastes in Antarctica, it also provides for amendment procedures if desired by the signatories as described in Article V, Section 2:

"1. Any nuclear explosions in Antarctica and the disposal there of radioactive waste material shall be prohibited.

"2. In the event of the conclusion of international agreements concerning the use of nuclear energy, including nuclear explosions and the disposal of radioactive waste material, to which all of the Contracting Parties whose representatives are entitled to participate in the meetings provided for under Article IX are parties, the rules established under such agreements shall apply in Antarctica."

Because most of the signatory nations already have or will develop disposition problems with high-level wastes (see Table 1), it is believed that amendments necessary for waste disposal are practically achievable.

2.2 TENTATIVE DEPOSITORY LOCATION

It has been suggested by Turner (Ref. 4) that the best locations would be near the tops of ridges in the underlying bedrock. Here, the ice cover is thick enough (more than 1 kilometer) for an adequate seal, and the temperature at the ice/rock interface would be lower than in the basins. The lateral movement of the ice in these areas would be minimal and not subject to the occasional ice "surges" thought by some to occur in the basins roughly every 100,000 years. Figure 3 (adapted from Ref. 6) shows a tentative depository area (cross-hatched) selected on the basis of sub-ice topography (shown by contours) where the ice flow paths to the sea are longest. Data on the age of ice cores have shown that even the relatively younger ice in a very active ice stream in the

* See Appendix A.

Figure 3. Tentative Antarctic Repository (dashed lines)
(Map adapted from Ref. 6)

vicinity of Byrd Station is approximately 100,000 years old at depths of about 2200 meters (Ref. 17). These values are estimated from measured accumulation rates and calculations of thinning through flow.

Ice thickness in the suggested area ranges from about 1000 to more than 3000 meters. Annual precipitation is generally less than 10 centimeters of water, and average annual surface temperatures range from -50°C to -60°C . Surface elevations on the ice cap range from about 3000 to 3800 meters (Ref. 5). All of the area is more than 800 kilometers inland from the edge of the continent. USSR scientific tractor-train expeditions have traversed the area to the South Pole and the pole of inaccessibility as shown in Figure 3 by the dotted lines from the Mirny Base. Several others have crossed this area since then.

2.3 SATISFACTION OF DEPOSITORY REQUIREMENTS

Within the limitations of our present knowledge about the ice cap, it seems essentially certain that placement of waste on the ice/rock interface on the ridges of the sub-ice topography would most effectively separate it from the biosphere. Paleoclimatology studies have demonstrated that the average temperatures in Antarctica have not risen above 0°C for more than 1 million years (Refs. 9, 10, and 11); thus the ice cap has maintained its entity throughout the warming periods occurring between periods of continental glaciation. It may therefore be concluded that it is highly improbable that the ice cap would melt within the next 500,000 years. The average amount of thermal energy added by the radioactive wastes would be negligible when compared to the normal meteorological and geothermal processes, and it may be concluded that there would be no danger of causing significant melting of the ice cap through waste storage. Waste containers could be widely spaced to insure that no large local "hot" spots are formed.*

* Our calculations indicate that the placement of one 5400-watt container every 10 km^2 would add only about 1 percent to the normal geothermal gradient in east Antarctica. This assumes the normal geothermal gradient to be $1.2\text{ }\mu\text{cal/cm}^2/\text{sec}$. (Ref. 15).

An extensive study on ice sheet dynamics, thermal profile characteristics and heat transfer in the Antarctic ice cap has been conducted by the Australian National Antarctic Research Expeditions (ANARE) as part of the Antarctic Division of the Department of Supply. This study incorporates data from Soviet, Belgian, Japanese and United States traverses which have provided information about East Antarctica. Computer models have been prepared which indicate that ice flow rates are so low in East Antarctica that 500,000 years would be required before snow grains falling as precipitation could reach the sea from the most stable parts of the area (Figure 4). The estimates used in the preparation of this map are clearly conservative. A recent report (Ref. 17) indicates that ice as old as 100,000 years was encountered in the borehole at Byrd Station, but the ANARE map shows no ice older than 50,000 years in any part of West Antarctica.

Even if each container forms a local surrounding lens of melt water, it would be sealed in by the ice or underlying permafrost and stabilize as do the permanently frozen lakes in Antarctica where the underlying water is above freezing while the surface has a permanent ice cover (Refs. 7, 8). Figure 5 shows representative temperature profiles for Lake Vanda (Ref. 7).

We have assumed that it would be safest to permit the waste containers to melt their way completely through the ice sheet so that they come to rest on the rock below. This would be the choice if the temperature at the ice/rock interface is found to be substantially below freezing. If this is not the case, problems could arise because of the existence of a thin water layer between the ice and the rock. Release of radioactive wastes into this thin layer might occur after breakdown of the waste container and uncontrolled dispersal of the wastes might then take place by slow lateral migration along the water layer. From ice thickness, accumulation rate, surface temperature and basal stress data, it has been possible to prepare a map of the ice temperature at the ice/rock interface as shown in Figure 6 (Ref. 15). These data have been contoured with the numbers indicating the temperature below 0°C at the base of ice cap.

Figure 4. Residence Time in the Ice Cap for a Snow Particle Falling on the Surface in Thousands of Years

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Figure 5. Temperature Profile for Lake Vanda (After Ref. 7)

Figure 6. Average Calculated Temperature at Base of Ice Cap Countoured for Each -10°C (Shaded Zones Are at the Pressure Melting Point)

The shaded zones in Figure 6 are regions where water layers are to be expected at the ice/rock interface. The lowest temperatures are to be found in east Antarctica in the region selected for the proposed depository site. Because of the low basal temperatures, it is unlikely that there could be any communication by liquid water flow between waste containers resting on the rock below the ice cap. This low temperature also precludes the existence of any extensive interconnected groundwater system which could transfer dissolved radioactive wastes to the ocean under the ice cap. Drilling and thermal probe testing would, however, be conducted to determine the exact ice/rock interface temperature in the disposal site.

Under some circumstances it may prove undesirable to permit the waste containers to melt their way through the entire ice thickness. A plan has been developed by which the density and thermal output of the containers could be controlled in such a way that they would reach an equilibrium position in the ice somewhere above the ice/rock interface (Ref. 12). As the total heat output of the waste decreased through decay of the radionuclides, the pod of water surrounding the container would shrink and eventually the wastes would be totally confined within the ice and could not contaminate any groundwater which might be present below the ice. This plan has the disadvantage that it would require careful control of the thermal output and density of each waste container and might require that the individual container size be kept to only a few hundred kilograms.

The central portion of the Antarctic ice cap is — and can be expected to continue indefinitely to be — the most remote land area on the earth with regard to normal human activities. The underlying rocks might be considered a possible source of minerals; however, there is little possibility of their being discovered under thousands of feet of ice. Even if found, their mining would be under the most severe climatic conditions through ice shafts that would be unstable due to slow surface ice movements and closure through plastic flow at depth. Therefore, it is felt that the ice cap of Antarctica is the most unlikely spot on earth for even distant future mining activity.

With regard to the area being a potential water resource, the central portion of the ice cap would be the last to be "mined" since the edges of the continent receive the most precipitation and are the most accessible, if indeed the recovery of fresh water from Antarctic ice is ever seriously contemplated. The origin of this ice (or icebergs formed from it) is far removed from any of the proposed radioactive waste sites and would not be expected to be contaminated by any known glacial mechanism.

It is therefore concluded that the radioactive waste depository would not destroy or prevent the exploitation of any practically useful natural resources. Located in the Antarctic, it would be completely safe against accidental entry and fail-safe against natural disaster. The area selected for the proposed disposal site is almost totally free of volcanic or earthquake activity. Should any occur, the thick ice cover seal would be completely fail-proof against leakage from earthquake-caused fractures since self-healing would occur by rapid recrystallization and plastic flow. Obviously, the site would also be fail-proof against all other forms of natural disaster such as tidal waves, hurricanes, tornadoes, or floods.

Disposal under the ice constitutes true ultimate disposal in that retrieval is probably impossible with present technology. Retrieval is considered to be unnecessary if it can be assured there is no change capable of impairing waste containment for a period of several hundred thousand years (Ref. 13).

2.4 PRELIMINARY TRANSPORTATION PLAN

Preliminary consideration of the transportation problem has resulted in the following tentative approach:

Containers (encapsulation shells designed for maximum life before failure by corrosion, radiation damage, or mechanical stress) would be transported to a port in the country of origin via railroad and would be loaded on a special

ship for ocean transport. A ship with the capacity and ice-breaking capabilities of the MANHATTAN is envisioned as being suitable for this purpose. The ship should be designed with compartments and foam flotation units included in its construction. Water transportation could be routed to Antarctica from any major port in the world.

After arrival at an appropriate staging site, waste containers could be off-loaded from the ship by high-lift helicopters and transported to a ground-based interim storage facility. Marble Point in Victorialand, Antarctica, is an appropriate location for construction of a major staging site. An all-season air field could be constructed at Marble Point. The Bechtel Corporation operating under contract to the U.S. National Science Foundation has already completed evaluation and engineering studies for potential development of an airport large enough to handle Boeing 747 size aircraft.

Transportation from the interim storage site to the ice plateau could be most efficiently conducted by aircraft of appropriate design and capacity. If a landing field could be constructed on the ice cap, the waste containers could be off-loaded from the aircraft and transported to the disposal area by sledge. If landing is not possible, parachute-drop techniques might be feasible but would require special design of the waste containers to permit this deployment technique.

Air transport is clearly the fastest and probably the cheapest method of transfer of the waste containers from the deep water port to the disposal area in East Antarctica. If, however, the responsible agency should decide that hazards associated with air transport are excessive it would be possible to move the wastes by sledge from the coast to the disposal site. This method is currently in use and re-supply of the Soviet Vostok Base is routinely accomplished by tractor train from the port at Mirnyy. The use of special arctic Surface Effects Vehicles should also be considered.

All transport and transfer operations would be designed to be fail-safe, with provisions for safely correcting any accidents or errors in procedure. A complete radiation monitoring system would be designed to detect any accidental contamination occurring enroute and to assure that the waste cylinders, when emplaced, sink into the ice as planned. It is anticipated that a sub-ice monitoring system would be developed to insure that no undetected migration of the wastes occurs from the immediate sites of burial. All of these operations with fail-safe designs are well within the state-of-the-art and present engineering capabilities.

The number of containers, ships, and debarkation facilities required for this disposal operation would be expected to increase with time as the number of nations participating increases.

2.5 POLITICAL CONSIDERATIONS

In order to put an international waste depository into operation, the Antarctic Treaty would require ammendments

- To allow radioactive wastes to be placed in Antarctica
- To set aside defined territories for permanent international use as repositories for high-level radioactive wastes. (The present treaty of 1959 reserved only 30 years for international exploration. The tentative repository location lies in territory claimed originally by Australia.)

This action will involve conclusive demonstration that:

- The plan described is the most effective and reasonable solution to the high-level waste problem, and
- The environment will not be harmed by the wastes.

Direction of the operation of an International Radionuclide Depository (INTER-RAD) could only be performed effectively by an international agency. It is presumed that the actual operations would be carried out under contract by international private organizations and national agencies with capabilities in Antarctic operations, ship operations, and support engineering.

3.0 ORGANIZATION AND FUNCTION OF INTERRAD

- INTERRAD is envisioned to be established as a subagency of the International Atomic Energy Agency *
- Initial funding could be provided by a levy upon member nations of I. A. E. A. in proportion to the present rate of nuclear energy utilization of the individual nations.
- Operational funding could be provided from a per-curie levy on each waste container sent to the depository for final disposal. The amount of the levy would be fixed at a rate which permits full payment of all costs associated with INTERRAD.

The basic functions of INTERRAD would be:

1. To set all standards for form, concentration, and encapsulation of high-level nuclear wastes that can be shipped to the depository for disposal.
2. To provide monitoring facilities to assure that wastes and container design conform to established standards at each port of pick-up.
3. To supervise transportation of wastes from pick-up at ports of the participating countries to ultimate placement at the disposal site in Antarctica.

* See Appendix B for relevant portions of the I. A. E. A. statute.

- To contract with national or private agencies to furnish safe ship transport of waste containers from pick-up ports to staging areas in Antarctica.
 - To contract with national or private agencies for transfer of waste containers from staging areas in Antarctica to the disposal site of sites.
4. To construct and maintain, or to contract for construction and maintenance of all permanent installations in Antarctica which are needed for operation of INTERRAD; e.g., laboratory and administrative buildings, interim storage facilities at staging sites, air fields, communication facilities, etc.
 5. To provide continuous monitoring facilities at the disposal site or sites to determine environmental effects of the disposal operations — these services to be provided either directly by INTERRAD or by contract with or through the various responsible government agencies of the Antarctic treaty signatory nations.
 6. To conduct and maintain research on polar nuclear waste disposal through I.A.E.A. facilities and/or through funding of external agencies.

4.0 CONCLUSIONS

It is concluded that the polar ice cap disposal method holds promise of being a highly practical solution to the permanent high-level radioactive waste disposal problem, both from the technical and political viewpoints. It deserves early and careful consideration by both the appropriate national and international agencies. There are many problems to be investigated and solved, but our best judgment indicates that all are well within present engineering capabilities.

The first step in determining the feasibility of this approach should be an exhaustive literature review and theoretical study, supported by laboratory and model studies as necessary to:

- Examine the heat flow and material conditions to be expected after emplacement
- Prove the feasibility of self-melted shafts
- Determine the best theoretical disposal site locations, and
- Create a preliminary design for a complete transport and emplacement system.

Follow-up studies should include field surveys and experiments to:

- Survey ice thicknesses, movements, and sub-ice topography in detail near the preliminary sites*
- Study the actual temperature gradients down to the ice/rock interface at selected site locations in drill holes or utilizing Philberth probes.
- Demonstrate a self-melted shaft
- Construct and field-test an engineering model of the transport system
- Design, construct, field test, and demonstrate a prototype model of an operating transport and emplacement system
- Obtain detailed radiation and climatic environmental surveys of the sites prior to emplacement of any wastes

* Radio echo studies of ice thicknesses in East Antarctica to date are summarized by Evans and Robin (Ref. 18) and are shown to agree very well with available seismic measurement control.

The general magnitude of the program to demonstrate clearly the technical feasibility of the plan is envisioned as involving the expenditure of at least 30 million dollars over several years. This should carry through the design of an engineering mode. At least 200 - 300 million dollars would probably be required to construct and demonstrate a fully-engineered prototype system.

The total cost of a fully operational high-level waste depository in Antarctica can only be estimated, but it might cost as much as 500 million dollars. Although this is certainly a major expenditure, it should be emphasized that it represents less than 1 percent of the value of the nuclear power industry projected for the next 10 years in the United States alone and surely less than 0.1 percent of the value of the world-wide nuclear power 10-year cost projections. Furthermore, it appears that the establishment of an INTERRAD facility on a cooperative basis should be very much less costly than the construction of independent facilities in every nation which produces high-level waste.

Finally, some of the subsidiary benefits of the program should also be considered. They include (but are not limited to) the following:

- The construction of an international depository located in Antarctica permits the consolidation of future high-level wastes in a single unoccupied area under the direct control of a single responsible international agency, the I. A. E. A. The establishment of the facility would greatly reduce the hazards attendant upon the proliferation of national deposit sites.
- The development and maintenance of the site would yield significant scientific data related to geophysics, paleoclimatology, oceanography, glaciology, and meteorology.
- The establishment of INTERRAD would serve as a basis for genuine international cooperation on a large scale basis to provide a practical solution to a world problem of steadily increasing magnitude.

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5.A.30

APPENDIX A
TEXT OF ANTARCTIC TREATY

APPENDIX A

TEXT OF ANTARCTIC TREATY *

The Governments of Argentina, Australia, Belgium, Chile, the French Republic, Japan, New Zealand, Norway, the Union of South Africa, the Union of Soviet Socialist Republics, the United Kingdom of Great Britain and Northern Ireland, and the United States of America,

Recognizing that it is in the interest of all mankind that Antarctica shall continue forever to be used exclusively for peaceful purposes and shall not become the scene or object of international discord;

Acknowledging the substantial contributions to scientific knowledge resulting from international cooperation in scientific investigation in Antarctica;

Convinced that the establishment of a firm foundation for the continuation and development of such cooperation on the basis of freedom of scientific investigation in Antarctica as applied during the International Geophysical Year accords with the interest of science and progress of all mankind;

Convinced also that a treaty ensuring the use of Antarctica for peaceful purposes only and the continuance of international harmony in Antarctica will further the purposes and principles embodied in the Charter of the United Nations;

Have agreed as follows:

* Reprinted from the Department of State Bulletin, December 21, 1959
Office of Public Services, Bureau of Public Affairs.

ARTICLE I

1. Antarctica shall be used for peaceful purposes only. There shall be prohibited, *INTER ALIA*, any measures of a military nature, such as the establishment of military bases and fortifications, the carrying out of military maneuvers, as well as the testing of any type of weapons.
2. The present Treaty shall not prevent the use of military personnel or equipment for scientific research or for any other peaceful purpose.

ARTICLE II

Freedom of scientific investigation in Antarctica and cooperation toward that end, as applied during the International Geophysical Year, shall continue, subject to the provisions of the present Treaty.

ARTICLE III

1. In order to promote international cooperation in scientific investigation in Antarctica, as provided for in Article II of the present Treaty, the Contracting Parties agree that, to the greatest extent feasible and practicable:
 - (a) information regarding plans for scientific programs in Antarctica shall be exchanged to permit maximum economy and efficiency of operations;
 - (b) scientific personnel shall be exchanged in Antarctica between expeditions and stations;
 - (c) scientific observations and results from Antarctica shall be exchanged and made freely available.
2. In implementing this Article, every encouragement shall be given to the establishment of cooperative working relations with those Specialized Agencies of the United Nations and other international organizations having a scientific or technical interest in Antarctica.

ARTICLE IV

1. Nothing contained in the present Treaty shall be interpreted as:
 - (a) a renunciation by any Contracting Party of previously asserted rights of or claims to territorial sovereignty in Antarctica;
 - (b) a renunciation or diminution by any Contracting Party of any basis of claim to territorial sovereignty in Antarctica which it may have whether as a result of its activities or those of its nationals in Antarctica, or otherwise;

(c) prejudicing the position of any Contracting Party as regards its recognition or non-recognition of any other State's right of or claim or basis of claim to territorial sovereignty in Antarctica.

2. No acts or activities taking place while the present Treaty is in force shall constitute a basis for asserting, supporting or denying a claim to territorial sovereignty in Antarctica or create any rights of sovereignty in Antarctica. No new claim, or enlargement of an existing claim, to territorial sovereignty in Antarctica shall be asserted while the present Treaty is in force.

ARTICLE V

1. Any nuclear explosions in Antarctica and the disposal there of radioactive waste material shall be prohibited.

2. In the event of the conclusion of international agreements concerning the use of nuclear energy, including nuclear explosions and the disposal of radioactive waste material, to which all of the Contracting Parties whose representatives are entitled to participate in the meetings provided for under Article IX are parties, the rules established under such agreements shall apply in Antarctica.

ARTICLE VI

The provisions of the present Treaty shall apply to the area south of 60° South Latitude, including all ice shelves, but nothing in the present Treaty shall prejudice or in any way affect the rights, or the exercise of the rights, of any State under international law with regard to the high seas within that area.

ARTICLE VII

1. In order to promote the objectives and ensure the observance of the provisions of the present Treaty, each Contracting Party whose representatives are entitled to participate in the meetings referred to in Article IX of the Treaty shall have the right to designate observers to carry out any inspection provided for by the present Article. Observers shall be nationals of the Contracting Parties which designate them. The names of observers shall be communicated to every other Contracting Party having the right to designate observers, and like notice shall be given of the termination of their appointment.

2. Each observer designated in accordance with the provisions of paragraph 1 of this Article shall have complete freedom of access at any time to any or all areas of Antarctica.

3. All areas of Antarctica, including all stations, installations and equipment within those areas, and all ships and aircraft at points of discharging or embarking cargoes or personnel in Antarctica, shall be open at all times to inspection by any observers designated in accordance with paragraph 1 of this Article.

4. Aerial observation may be carried out at any time over any or all areas of Antarctica by any of the Contracting Parties having the right to designate observers.

5. Each Contracting Party shall, at the time when the present Treaty enters into force for it, inform the other Contracting Parties, and thereafter shall give them notice in advance, of

(a) all expeditions to and within Antarctica, on the part of its ships or nationals, and all expeditions to Antarctica organized in or proceeding from its territory;

(b) all stations in Antarctica occupied by its nationals; and

(c) any military personnel or equipment intended to be introduced by it into Antarctica subject to the conditions prescribed in paragraph 2 of Article I of the present Treaty.

ARTICLE VIII

1. In order to facilitate the exercise of their functions under the present Treaty, and without prejudice to the respective positions of the Contracting Parties relating to jurisdiction over all other persons in Antarctica, observers designated under paragraph 1 of Article VII and scientific personnel exchanged under subparagraph 1 (b) of Article III of the Treaty, and members of the staffs accompanying any such persons, shall be subject only to the jurisdiction of the Contracting Party of which they are nationals in respect of all acts or omissions occurring while they are in Antarctica for the purpose of exercising their functions.

2. Without prejudice to the provisions of paragraph 1 of this Article, and pending the adoption of measures in pursuance of subparagraph 1 (c) of Article IX, the Contracting Parties concerned in any case of dispute with regard to the exercise of jurisdiction in Antarctica shall immediately consult together with a view to reaching a mutually acceptable solution.

ARTICLE IX

1. Representatives of the Contracting Parties named in the preamble to the present Treaty shall meet at the City of Canberra within two months after the date of entry into force of the Treaty, and thereafter at suitable intervals and places, for the purpose of exchanging information, consulting together on matters of common interest pertaining to Antarctica, and formulating and considering, and recommending to their Governments, measures in furtherance of the principles and objectives of the Treaty, including measures regarding:

- (a) use of Antarctica for peaceful purposes only;
- (b) facilitation of scientific research in Antarctica;
- (c) facilitation of international scientific cooperation in Antarctica;
- (d) facilitation of the exercise of the rights of inspection provided for in Article VII of the Treaty;
- (e) questions relating to the exercise of jurisdiction in Antarctica;
- (f) preservation and conservation of living resources in Antarctica.

2. Each Contracting Party which has become a party to the present Treaty by accession under Article XIII shall be entitled to appoint representatives to participate in the meetings referred to in paragraph 1 of the present Article, during such time as that Contracting Party demonstrates its interest in Antarctica by conducting substantial scientific research activity there, such as the establishment of a scientific station or the dispatch of a scientific expedition.

3. Reports from the observers referred to in Article VII of the present Treaty shall be transmitted to the representatives of the Contracting Parties participating in the meetings referred to in paragraph 1 of the present Article.

4. The measures referred to in paragraph 1 of this Article shall become effective when approved by all the Contracting Parties whose representatives were entitled to participate in the meetings held to consider those measures.

5. Any or all of the rights established in the present Treaty may be exercised as from the date of entry into force of the Treaty whether or not any measures facilitating the exercise of such rights have been proposed, considered or approved as provided in this Article.

ARTICLE X

Each of the Contracting Parties undertakes to exert appropriate efforts, consistent with the Charter of the United Nations, to the end that no one engages in any activity in Antarctica contrary to the principles or purposes of the present Treaty.

ARTICLE XI

1. If any dispute arises between two or more of the Contracting Parties concerning the interpretation or application of the present Treaty, those Contracting Parties shall consult among themselves with a view to having the dispute resolved by negotiation, inquiry, mediation, conciliation, arbitration, judicial settlement or other peaceful means of their own choice.

2. Any dispute of this character not so resolved shall, with the consent, in each case, of all parties to the dispute, be referred to the International Court of Justice for settlement; but failure to reach agreement on reference to the International Court shall not absolve parties to the dispute from the responsibility of continuing to seek to resolve it by any of the various peaceful means referred to in paragraph 1 of this Article.

ARTICLE XII

1. (a) The present Treaty may be modified or amended at any time by unanimous agreement of the Contracting Parties whose representatives are entitled to participate in the meetings provided for under Article IX. Any such modification or amendment shall enter into force when the depositary Government has received notice from all such Contracting Parties that they have ratified it.

(b) Such modification or amendment shall thereafter enter into force as to any other Contracting Party when notice of ratification by it has been received by the depositary Government. Any such Contracting Party when notice of ratification is received within a period of two years from the date of entry into force of the modification or amendment in accordance with the provisions of subparagraph 1 (a) of this Article shall be deemed to have withdrawn from the present Treaty on the date of the expiration of such period.

2. (a) If after the expiration of thirty years from the date of entry into force of the present Treaty, any of the Contracting Parties whose representatives are entitled to participate in the meetings provided for under Article IX so requests by a communication addressed to the depositary Government, a Conference of all the Contracting Parties shall be held as soon as practicable to review the operation of the Treaty.

(b) Any modification or amendment to the present Treaty which is approved at such a Conference by a majority of the Contracting Parties there represented, including a majority of those whose representatives are entitled to participate in the meetings provided for under Article IX, shall be communicated by the depositary Government to all the Contracting Parties immediately after the termination of the Conference and shall enter into force in accordance with the provisions of paragraph 1 of the present Article.

(c) If any such modification or amendment has not entered into force in accordance with the provisions of subparagraph 1 (a) of this Article within a period of two years after the date of its communication to all the Contracting Parties, any Contracting Party may at any time after the expiration of that period give notice to the depositary Government of its withdrawal from the present Treaty; and such withdrawal shall take effect two years after the receipt of the notice by the depositary Government.

ARTICLE XIII

1. The present Treaty shall be subject to ratification by the signatory States. It shall be open for accession by any State which is a Member of the United Nations, or by any other State which may be invited to accede to the Treaty with the consent of all the Contracting Parties whose representatives are entitled to participate in the meetings provided for under Article IX of the Treaty.

2. Ratification of or accession to the present Treaty shall be effected by each State in accordance with its constitutional processes.

3. Instruments of ratification and instruments of accession shall be deposited with the Government of the United States of America, hereby designated as the depositary Government.

4. The depositary Government shall inform all signatory and acceding States of the date of each deposit of an instrument of ratification or accession, and the date of entry into force of the Treaty and of any modification or amendment thereto.

5. Upon the deposit of instruments of ratification by all the signatory States, the present Treaty shall enter into force for those States and for States which have deposited instruments of accession. Thereafter the Treaty shall enter into force for any acceding State upon the deposit of its instrument of accession.

6. The present Treaty shall be registered by the depositary Government pursuant to Article 102 of the Charter of the United Nations.

ARTICLE XIV

The present Treaty, done in the English, French, Russian, and Spanish languages, each version being equally authentic, shall be deposited in the archives of the Government of the United States of America, which shall transmit duly certified copies thereof to the Governments of the signatory and acceding States.

IN WITNESS WHEREOF, the undersigned Plenipotentiaries, duly authorized, have signed the present Treaty.

DONE at Washington this first day of December, one thousand nine hundred and fifty-nine.

For Argentina:

Adolfo Schilingo

F. Bello

For New Zealand:

G D L White

For Australia:

Howard Beale

For Norway:

Paul Koht

For Belgium:

Obert de Thieusies

For the Union of South Africa:

Wentzel C. du Plessis

For Chile:

Marcial Mora M

E. Gajardo V

Julio Kscudero

For the Union of Soviet Socialist Republics:

V. Kuznetsov (Romanization)

For the United Kingdom of Great Britain
and Northern Ireland:

Harold Caccia

For the French Republic:

Pierre Charpentier

For the United States of America:

Herman Phleger

Paul C. Daniels

For Japan:

Koichiro Asakai

T. Shimoda

APPENDIX B
RELEVANT PORTIONS OF I. A. E. A. STATUTE

APPENDIX B

RELEVANT PORTIONS OF I. A. E. A. STATUTE

A brief resumé of the pertinent functions of the I. A. E. A. together with excerpts from the statute which relate to the operations that might be involved in radioactive waste disposal is included. It is clear that the Agency does have the authority and capability for the development and operation of an International Radionuclide Depository (INTERRAD).

THE INTERNATIONAL ATOMIC ENERGY AGENCY (I. A. E. A.)

The International Atomic Energy Agency (I. A. E. A.) came into being on 29 July 1957, the necessary instruments of ratification of the Agency's Statute having been deposited in Washington. The Agency's main objectives are: to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world; and to insure that assistance provided by it or under its aegis is not used in such a way as to further any military purpose.

In carrying out its functions, I. A. E. A. is authorized: to encourage and assist research on, and the development and practical application of, atomic energy; to act, if requested to do so, as an intermediary for securing the performance of services or the supplying of materials, equipment or facilities by one member of the Agency for another; and to perform any operation of service likely to contribute to the peaceful application of atomic energy.

The Agency is also authorized to make provision for the materials, services, equipment, and facilities necessary for the production of nuclear power and for research in that field, with due consideration for the needs of the under-equipped areas of the world.

ANNEX I. STATUTE OF INTERNATIONAL ATOMIC ENERGY AGENCY

ARTICLE I. ESTABLISHMENT OF THE AGENCY

The Parties hereto establish an International Atomic Energy Agency (hereinafter referred to as "the Agency") upon the terms and conditions hereinafter set forth.

ARTICLE II. OBJECTIVES

The Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health, and prosperity throughout the world. It shall insure, so far as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose.

ARTICLE III. FUNCTIONS

A. The Agency is authorized:

1. To encourage and assist research on, and development and practical application of, atomic energy for peaceful uses throughout the world, and, if requested to do so, to act as an intermediary for the purposes of securing the performance of services or the supplying of materials, equipment, or facilities by one member of the Agency for another; and to perform any operation or service useful in research on, or development or practical application of, atomic energy for peaceful purposes;
2. To make provision, in accordance with this Statute, for materials, services, equipment, and facilities to meet the needs of research on, and development and practical application of, atomic energy for peaceful purposes, including the production of electric power, with due consideration for the needs of the underdeveloped areas of the world;
3. To foster the exchange of scientific and technical information on peaceful uses of atomic energy;
4. To encourage the exchange and training of scientists and experts in the field of peaceful uses of atomic energy;
5. To establish and administer safeguards designed to insure that special fissionable and other materials, services, equipment, facilities, and information made available by the Agency or at its request or under its supervision or control are not used in such a way as to further any military purpose; and to apply safeguards, at the request of the parties, to any bilateral or multilateral arrangement, or, at the request of a State, to any of that State's activities in the field of atomic energy;

6. To establish or adopt, in consultation and, where appropriate, in collaboration with the competent organs of the United Nations and with the specialized agencies concerned, standards of safety for protection of health and minimization of danger to life and property (including such standards for labor conditions), and to provide for the application of these standards to its own operations as well as to the operations making use of materials, services, equipment, facilities, and information made available by the Agency or at its request or under its control or supervision; and to provide for the application of these standards, at the request of a State, to any of that State's activities in the field of atomic energy.

7. To acquire or establish any facilities, plant and equipment useful in carrying out its authorized functions, whenever the facilities, plant, and equipment otherwise available to it in the area concerned are inadequate or available only on terms it deems unsatisfactory.

B. In carrying out its functions, the Agency shall:

1. Conduct its activities in accordance with the purposes and principles of the United Nations to promote peace and international cooperation, and in conformity with policies of the United Nations furthering the establishment of safeguarded world-wide disarmament and in conformity with any international agreements entered into pursuant to such policies;

2. Establish control over the use of special fissionable materials received by the Agency, in order to insure that these materials are used only for peaceful purposes.

ARTICLE IX. SUPPLYING OF MATERIALS

The Agency is specifically authorized to construct facilities for storage of fissionable materials and this could most probably be extended to include nuclear waste.

H. The Agency shall be responsible for storing and protecting materials in its possession. The Agency shall insure that these materials shall be safeguarded against (1) hazards of the weather, (2) unauthorized removal or diversion, (3) damage or destruction, including sabotage, and (4) forcible seizure. In storing special fissionable materials in its possession, the Agency shall insure the geographical distribution of these materials in such a way as not to allow concentration of large amounts of such materials in any one country or region of the world.

I. The Agency shall as soon as practicable establish or acquire such of the following as may be necessary:

1. Plant, equipment, and facilities for the receipt, storage, and issue of material
2. Physical safeguards
3. Adequate health and safety measures
4. Control laboratories for the analysis and verification of materials received
5. Housing and administrative facilities for any staff required for the foregoing

J. The materials made available pursuant to this article shall be used as determined by the board of Governors in accordance with the provisions of this Statute. No member shall have the right to require that the materials it makes available to the Agency be kept separately by the Agency or to designate the specific project in which they must be used.

ARTICLE XI. AGENCY PROJECTS

The Agency may also supply services.

C. The Agency may arrange for the supplying of any materials, services, equipment, and facilities necessary for the project by one or more members or may itself undertake to provide any or all of these directly, taking into consideration the wishes of the member or members making the request.

APPENDIX 5.B

THE GREENLAND ICE SHEET

5.B.1

COLD REGIONS SCIENCE AND ENGINEERING

F. J. Sanger, Editor
Part I: Environment
Sect B: Regional

I-B2
Sept 1961

The Greenland Ice Sheet

by Henri Bader

**U. S. ARMY COLD REGIONS RESEARCH
AND ENGINEERING LABORATORY**
Corps of Engineers

PREFACE

This monograph summarizes existing knowledge of Greenland for the use of professional engineers engaged in design or construction in that region.

The paper has been reviewed and approved for publication by the Office of the Chief of Engineers, U. S. Army.

W. L. NUNGESSER
Colonel, Corps of Engineers
Director

Manuscript received 1 March 1961
Department of the Army Project 8S66-02-001

5.B.3

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EDITOR'S FOREWORD

This is the second section of "Cold Regions Science and Engineering" to appear. As part of the larger work, it is not a complete dissertation on Greenland but presents basic information, with a minimum of theorizing, about the particular ice sheet. General geology, physiography, environment and glaciology are dealt with in other sections; history and exploration are not included in a work written to give background material for engineering on the polar land ice sheets.

Sections of the work will appear as they become ready, not necessarily in numerical order, but fitting into this plan:

- I. Environment
 - A. General
 - B. Regional
- II. Physical Science
 - A. Geophysics
 - 1. Micrometeorology
 - 2. Exploration Geophysics
 - B. The Physics and Mechanics of Snow
 - 1. Properties of Snow
 - 2. Snow Mechanics
 - C. The Physics and Mechanics of Ice
 - 1. Ice on the earth's surface
 - 2. Ice as a material
 - D. The Physics and Mechanics of Frozen Ground
 - 1. Properties of frozen soils
 - 2. Permafrost
- III. Engineering
 - A. Snow engineering
 - B. Ice engineering
 - C. Frozen-ground engineering
 - D. General engineering
- IV. Miscellaneous

F. J. SANGER

29 September 1961

5.B.5

THE GREENLAND ICE SHEET

by

Henri Bader

The Greenland ice sheet, covering most of the island of Greenland, lies between the parallels of $60\frac{1}{2}^{\circ}\text{N}$ and 82°N , and meridians 20°W and 72°W (Fig. 1).

DIMENSIONS

Linear dimensions

The greatest length is almost 2400 km (1500 miles) along the 44°W meridian, and the greatest width is some 1100 km (700 miles) at latitude 77°N . A point located near $43\frac{1}{2}^{\circ}\text{N}$ $77\frac{1}{2}^{\circ}\text{W}$ has the maximum distance of 430 km (270 miles) from the nearest land. The mean east-west width between latitudes 63°N and 81°N is 920 km (460 miles), and the mean north-south length between 24°W and 60°W is 1370 km (860 miles).

Surface areas

Areas were measured² by planimetry of 15 sheets of the World Aeronautical Chart, scale 1:1,000,000.

	<u>km²</u>	<u>Miles²</u>
Area of Greenland, including its islands	2,186,000	843,800
Area of the ice sheet (inland ice, ice cap)	1,726,400	666,400
Area of isolated peripheral glaciers (examples, Flade Isblink, Sukkertoppen)	76,000	29,300
Area of ice-free land	383,600	148,100

Thus 5/6 of Greenland is covered by glaciers, 4/5 by the main ice sheet. In elevation, the area of the ice sheet is distributed as follows:²

<u>Elevation above sea level</u>		<u>Area</u>		
(ft)	(meters)	(km ²)	(mile ²)	(%)
0-1000	0-305	27,000	10,400	1.6
1000-2000	305-610	37,200	14,400	2.2
2000-3000	610-915	64,000	24,700	3.7
3000-4000	915-1220	93,400	36,000	5.4
4000-5000	1220-1525	124,000	47,900	7.2
5000-6000	1525-1830	174,000	67,300	10.1
6000-7000	1830-2135	237,300	91,600	13.7
7000-8000	2135-2440	290,000	112,000	16.8
8000-9000	2440-2745	310,500	119,900	18.0
9000-10,000	2745-3050	254,200	98,100	14.7
10,000-10,800	3050-3290	114,200	44,100	6.6
		1,726,400	666,400	100.0

The mean elevation of the ice sheet is 7000 ft (2135 m).

Thickness

There is a good seismic coverage of the area south of latitude 73°N by the French expeditions, and of a cross-section strip between 76°N and 79°N by American and British expeditions. The French maps² given here (Fig. 2, 3) make use of a single profile at 79°N , and would not be significantly changed by incorporation of the more recent thickness data. The bed may be deeper in the central area where there is no coverage.

THE GREENLAND ICE SHEET

Figure 1. The Greenland ice sheet (CRREL edition of map by P. E. Victor).

5.B.7

THE GREENLAND ICE SHEET

Figure 2. Cross sections and volume of the inland ice (From Holtzschler, 1954, Fig. 19).

5.B.8
THE GREENLAND ICE SHEET

Figure 3. Map of bed of southern part of the inland ice
(From Holtzscherer, 1954, Fig. 18).

5.B.9

The areas of the base of the ice sheet show the following distribution in elevation.²

<u>Elevation above sea level</u>		<u>Area</u>		
(ft)	(meters)	(km ²)	(mile ²)	(%)
-1300 to 0	-400 to 0	529,000	204,000	31
0-3300	0-1000	632,000	244,000	37
3300-6600	1000-2000	419,000	162,000	24
6600-9900	2000-3000	123,000	47,000	7
9900-12,000	3000-3700	17,000	7,000	1
		1,720,000	664,000	100

The values should not be considered precise, being based on very sparse seismic coverage over large areas.

The mean elevation of the bed of the ice sheet is 620 m (2060 ft), and almost $\frac{1}{3}$ of its area lies below sea level. The mean thickness of the ice sheet (equal to the difference between the mean elevations of surface and bed) is 1515 m (4970 ft). The ice volume is 2,600,000 km³ = 620,000 miles³. The water equivalent is 2,350,000 km³ (560,000 miles³). If distributed over the world's oceans, it would raise the sea level by 6.5 m (21 ft). The maximum thickness of the ice sheet is about 3000 m (10,000 ft).

REGIMEN

Precipitation (Accumulation)

For practical purposes, all the precipitation on the ice sheet is in the form of snow. Only summer rain very near to the edge can run off immediately. Annual accumulation and precipitation can be equated when considering large areas. The magnitude of inequality of precipitation and accumulation caused by snow drifting is not known but is unlikely to be very large; the effect is to remove snow from the interior downslope towards the edge.

The contour map of accumulation (Fig. 4) was drawn from data gathered largely by SIPRE* Expeditions^{3,7,9}. The reader is warned that the isohyets (lines connecting points of equal precipitation) are likely to be inaccurate in many places, particularly to the east of 40° meridian.

Table I is the result of measuring individual areas and calculating the accumulations. The mean precipitation is 36.7 cm water equivalent over the whole area of the ice sheet, corresponding to a volume of 636 km³ of water equivalent. Figure 4 and Table I are interesting. It appears (the values are probably not very accurate) that the southern part (south of 66° lat which cuts through the saddle between the two domes), with $\frac{1}{8}$ of the area, receives almost $\frac{1}{4}$ of the snowfall. The region north of 78°, $\frac{1}{5}$ of the whole area, receives only $\frac{1}{10}$ of the snowfall. The mean temperature at 10 m depth is about -14C in the southern area and about -24C in the northern. In the northern area the slopes are less steep than in the south. This all points to a highly dynamic situation in the south, against a relatively static situation in the north.

Latitude 73 $\frac{1}{4}$ °N bisects the area of the ice sheet. The colder northern half receives $\frac{1}{3}$ of the precipitation; the warmer southern half receives $\frac{2}{3}$.

The existence of the saddle between the south and north domes could be partly due to low accumulation in the area.

Long-term accumulation rates have been determined by stratigraphic studies at only one point (Site 2: 77°N 56°W). Because of the difficulty of locating layers exactly one year apart, the annual values given in Figure 5a can have large errors, but the 5-year means are fairly accurate.

Figure 5b is more informative. The residual mass curve rises when the annual accumulation is greater than the mean (40.7 cm water equivalent between 1885 and 1954), and falls when accumulation is less than the mean. The curve shows that the rate of accumulation was predominantly low from 1885 to 1890 (6-year mean 38.2 cm),

* U. S. Army Snow Ice and Permafrost Research Establishment, Corps of Engineers, now the Cold Regions Research and Engineering Laboratory (CRREL).

THE GREENLAND ICE SHEET

Figure 4. Mean annual accumulation.

Table I. Distribution of annual accumulation on the Greenland ice sheet.

Annual accumulation in cm of water equivalent	North of 78°N latitude		Between 78°N and 75°N latitude		Between 75°N and 72°N latitude		Between 72°N and 69°N latitude		Between 69°N and 66°N latitude		Between 66°N and 63°N latitude		South of 63°N latitude		Total area		Total annual accum.	
	Area km ²	Accum. km ³	Area km ²	Accum. km ³	Area km ²	Accum. km ³	Area km ²	Accum. km ³	Area km ²	Accum. km ³	Area km ²	Accum. km ³	Area km ²	Accum. km ³	km ²	%	km ³	%
10-15	93,800	11.7	95,600	12.0	-	-	-	-	-	-	-	-	-	-	189,400	11	23.7	3½
15-20	64,700	11.3	73,300	12.8	44,300	7.8	2,400	0.4	-	-	-	-	-	-	184,700	11	32.3	5
20-30	140,500	35.1	101,900	25.5	102,300	25.6	63,300	15.8	20,500	5.1	-	-	-	-	428,500	25	107.1	17
30-40	13,800	4.8	22,800	8.0	78,100	27.3	80,500	28.2	103,800	36.3	35,200	12.3	-	-	334,200	19	116.9	18½
40-50	3,800	1.7	30,500	13.7	35,700	16.1	67,100	30.2	53,800	24.2	32,400	14.6	-	-	223,300	13	100.5	16
50-60	3,300	1.8	24,300	13.4	30,500	16.8	50,900	28.0	15,200	8.4	20,900	11.5	1,400	0.8	146,500	8½	80.7	12½
60-70	-	-	11,900	7.7	7,100	4.6	10,000	6.5	10,400	6.8	17,600	11.4	5,700	3.7	62,700	3½	40.7	6½
70-80	-	-	-	-	-	-	6,200	4.7	13,300	10.0	11,000	8.3	12,800	9.6	43,300	2½	32.6	5
80-90	-	-	-	-	-	-	5,200	4.4	20,000	17.0	12,400	10.5	24,800	21.1	62,400	3½	53.0	8½
90-100	-	-	-	-	-	-	3,300	3.1	10,500	10.0	15,700	14.9	21,900	20.8	51,400	3	48.8	7½
Total area %	319,900 18½		360,300 21		298,000 17		288,900 17		247,500 14		145,200 8½		66,600 4		1,726,400 100			
Total accum. %		66.4 10½%		93.1 14½%		98.2 15½%		121.3 19%		117.8 18½%		83.5 13%		56.0 9%			636.3 100%	
Mean accum.		21cm		26cm		33cm		42cm		48cm		58cm		84cm			36.7cm	

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Figure 5a. Annual accumulation at 77°N 56°W.

Figure 5b. Residual mass curve for accumulation at 77°N 56°W.

from 1899 to 1913 (15-year mean 36.3 cm) and from 1935 onward (20-year mean 37.8 cm). Rate of accumulation was high from 1891 to 1898 (8-year mean 46.0 cm), and 1914 to 1934 (21-year mean 45.5 cm). The general decrease in accumulation since the middle thirties has been emphasized previously.⁴ Accumulation trends over hundreds of years should soon become available from analysis of cores from deep drill holes made by USA SIPRE (now USA CRREL).

Ablation

The loss of mass by runoff of melt water and by calving off of icebergs is very difficult to estimate. Recent estimates^{2,3} are 315 km³ and 272 km³ loss by water runoff, based on loss of 110 cm³ and 107 cm³ over ablation areas of 286,600 km²

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and 254,600 km² respectively. Loss by calving is estimated² at 215 km³. A new appraisal can be made using Figures 4 and 8. Figure 8 is based on a glacier surface area of 254,600 km² lying below the firn line. This was reduced somewhat by lowering the firn line in the south.

Areas below the firn line and annual precipitation thereon

	Area (km ²)	Precipitation (km ³)
North of 78°	51,700	13.9
Between 78° and 75°	28,600	8.6
Between 75° and 72°	25,600	8.0
Between 72° and 69°	36,600	19.2
Between 69° and 66°	54,200	34.2
Between 66° and 63°	26,000	16.9
South of 63°	<u>24,100</u>	<u>21.6</u>
	246,800	122.4

The firn line, which in a temperate glacier separates the areas of net accumulation and net ablation, does not do so in a cold polar glacier. A portion of the melt water here refreezes at the base of the snow cover, with the result that much of the bare ice exposed at the end of the summer below the firn line is superimposed ice, which represents net accumulation. Thus a part of the 122 km³, which is the water equivalent of the annual snowfall on the area below the firn line, is retained in the form of superimposed ice. But, in the areas near the edge, the superimposed ice plus older ice is melted after the snow has gone. There is also significant runoff from areas above the firn line. It has not been estimated.

Measurements¹¹ indicate that north of 76° the melt may not remove all of the year's accumulation below the firn line, but there is little doubt that it more than does so in the south, so that 120 km³ is a fair minimum value for ablation by melt, while the previously mentioned estimate of 315 km³ is probably too high, being based on an ablation area of 286,600 km², which is now known to be on the high side. Adding the 240 km³ of estimated iceberg discharge, we obtain a small or a large over-all positive mass budget depending on the chosen values. There remains no doubt that the northern half of the ice sheet is gaining mass, while the southern half may be gaining or losing. It is easy to demonstrate that, in the north, ice flow does not remove more than a small fraction of the volume added by accumulation, so that the volume of the ice sheet is increasing although the area is decreasing. Consider, for instance, a vertical cross section from the edge of the ice sheet at Thule to the crest 700 km to the east. The mean accumulation along the line is at least 25 cm of ice, a total of 175,000 m², which must be removed by ice flow if the glacier is to be stationary (not change its shape). This means that, for instance, an ice cliff 175 m thick should be advancing over the land at a rate of 1000 meters per year all along the edge of the ice sheet in this region. The 7-km wide Moltke Glacier removes the accumulation from a strip only two or three times its own width. Such large fast-moving calving glaciers are few and far apart along the ice edge.

In summary, the mass budget of the Greenland ice sheet is estimated as follows:

Accumulation:	630	km ³
Ablation:	120 to 270	km ³
Loss by iceberg calvings:	<u>240</u>	<u>km³</u>
Annual gain in mass:	120 to 270	km ³

Previous estimates^{2,3} indicated a net annual loss of mass. This is unlikely to be the case, unless iceberg calving has been greatly underestimated. It must be admitted, however, that the errors in estimating the mass budget parameters can be large.

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Figure 6. Drainage basins of the ice streams (From Bauer 1954, Fig. 40).

Glaciers

1. Jakobshavn	7. Ryder	12. Hamberg
2. Torssukatak	8. C. H. Ostenfeld	13. Daugaard Jensen
3. Grand Karajak	9. Academy	and West
4. Rink and Umiamako	10. Zachariaes and	14. Kangerdlugssuaq
5. Humboldt	Nioghalvfjerd	15. Sermilik (Helheim)
6. Petermann	11. Heinkel	16. Tingmiarmiut

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Ice streams

An "ice stream" is something akin to a mountain glacier consisting of a broad accumulation basin and a narrower outlet valley glacier: but a mountain glacier is laterally hemmed in by rock slopes, while the ice stream is contained by slower moving surrounding ice. The edges of the ice stream are often crevassed, and the surface tends to be concave as the ice is "funnelled" down. Many of the large outlet glaciers in Greenland, particularly in the south are the narrow outlets of large ice streams which reach back many scores of miles into the ice sheet. The largest ones flowing into Disko Bay have corresponding depressions in the glacier floor. An interesting question is whether the ice stream makes the depression, or vice versa; and an interesting hypothesis is that the ice stream, once started, is self-perpetuating because its ice mass, warmed up by heat of internal friction, has a lower viscosity than the surrounding ice.

Figure 6 shows the main ice streams.² It is estimated that eight ice streams south of latitude 72°N annually discharge 120 km³ of icebergs, which is one-third of the total accumulation of this southern half of the ice sheet. It has been pointed out⁴ that the high north-south crestline of the ice sheet lies far to the east of the area of maximum accumulation. Between latitudes 69°N and 75°N, the area lying to the west of the crest (363,000 km²) receives an annual accumulation of some 140 km³ (mean 39 cm water). If this part of the ice sheet is to remain stationary, the major portion of this large volume of ice must drain out through the ice streams of Jakobshavn, Torssukatak, Grand Karajak, Rink and Umiamak. The ice streams of the great northern glaciers, for instance the Humboldt, move more slowly and remove less ice. The estimate² is for a total of only 10 km³ north of 78°N.

Variability

Table I shows that the mean rate of accumulation increases from north to south. The rate of increase is 2.5 cm water equivalent for each 1° of latitude from 80°N to 63°N. Then there is a sharp increase at the south tip of the ice sheet. It is evident that the flow picture of the ice sheet must be quite complicated owing to the great regional variations in thickness, temperature, slope and rate of accumulation, and it is further disturbed by the existence of the ice streams. Since all these factors are also temporal variables, one must conclude that the Greenland ice sheet is a mass of ice in a constantly mobile state of local readjustment to ever-changing local conditions. At present the whole ice sheet seems to be gaining mass, while the total area is shrinking. In comparison to Greenland, the much colder and much larger Antarctic ice sheet should be changing much more slowly.

TEMPERATURES

Near the surface

Figure 7 is a map of mean temperature of the upper snow layers. Where melting is insignificant, the mean snow temperature is within 1C or 2C of the mean air temperature. In the peripheral zone of net ablation by melting, the mean ice temperature must be lower than the mean air temperature, because the ice surface temperature cannot exceed 0C. In the percolation zone, where melt water refreezes to form superimposed ice or ice layers in the firn, the relation between air temperature and firn temperature is not known, because there are no long-term measurements and no theory. If the calculated^{3,4} air temperatures on the southern dome are correct, then the snow temperatures measured during the SIPRE expedition of 1959 show that here the snow temperatures are also lower than the mean annual air temperature. A difference of 1C-4C is indicated.

The warming up of the Arctic (perhaps mainly higher summer temperatures) during the last few decades is clearly evident in the ice sheet. The stratigraphic record from the deep pit and drillhole at 77°N 56°W shows much evidence of summer melting back to about 1920, but almost no ice-layer formation during the preceding several hundred years. The temperature measured⁵ in the drillhole shows a decrease with depth, which is also indicative of a warming up of the surface. The temperature is 1C lower at 300 m depth than near the surface. At Eismitte Station Centrale (71°N 40°W) the warm-up between 1930 and 1950 appears to have been 1C. Coastal stations

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Figure 7. Mean annual snow temperatures.

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south of 70°N show an increase of from 1/2C to 3C of the mean air temperature from the period 1907-1920 to the period 1921-1940.^{3,4} The ice sheet seems to be somewhat less affected than the coastal land.

Internal

The energy of flowing is converted into heat at the rate of 2.34×10^{-3} cal per gram per meter drop in elevation. The corresponding temperature increase is 0.47C per 100 meters. Now consider an idealized ice sheet: the surface temperature is equal to the air temperature; the atmospheric lapse rate is equal to the above-mentioned 0.47C per 100 m; the heat from the flow energy is evenly distributed throughout the whole ice mass; and there is no earth heat flow into the ice. The ice will then reach the coast with a temperature equal to the mean air temperature there.

In Greenland only the very southern tip, south of 62°N, would show wet ice: the ice sheet would be cold (i. e., temperature below the melting point). In comparison to this model, the real Greenland ice sheet is colder, because

- a) the lapse rate is higher (0.6 to 0.8)
- b) near-surface snow or ice temperatures in the melt zone are lower than the mean air temperatures
- c) it is probable that most of the flow energy is liberated near the bed.

This means that the ice near the surface is colder than the atmosphere and absorbs heat from it. Thus a negative temperature gradient does not necessarily indicate climatic amelioration.¹⁰

The earth heat flow of some 40 cal/cm² per year can escape through the ice only by conduction if the temperature gradient at the bottom is greater than 2.5C per 100 m. If the gradient is smaller, the bottom of the ice sheet must be wet, and since wet (isothermal) ice does not conduct heat, only a very thin layer can be wet from geothermal heating. A somewhat thicker layer can become wet from internal generation of frictional heat, but it is unlikely to be thicker than a very small fraction of the glacier thickness. A number of icebergs in the fjord at Narssarssuak near the south tip of Greenland were inspected, and none showed any trace of the large ice crystals usually found in bottom wet ice.

The conclusion is that the Greenland ice sheet is cold, except for a very thin bottom layer. It is hoped that very deep core drilling will soon partly clear up the problem of internal temperatures.

In the Thule area, as proved by core drilling, the ice near the edge is frozen to the bed: in this case there is no erosion under 200 ft of ice. An interesting question is whether there can be any erosion under thick ice if the bed is frozen.

SURFACE MOTION

Motion near the edge of the ice sheet has been measured in a number of locations, but since it is completely controlled by the greatly variable local conditions, it throws almost no light on the motion of the ice sheet as a whole. In the interior, where there are no visible fixed landmarks, the determination of motion is difficult and expensive. Accurate "Hiran" fixes were made at six stations in 1956, but are unlikely to be repeated. A fairly large number of astronomical fixes with varying degrees of accuracy have been made, but not yet repeated at sufficiently long time intervals to yield good motion data.

Presently, the best estimate is that surface points in the interior of the ice sheet move with velocities of no more than tens of meters annually.

This subject of motion of the ice sheet is not yet ripe for useful summarizing.

SURFACE CONDITIONS

Bare ice is exposed near the edge of the ice sheet, where all the snow melts away, and in the summer there is also a peripheral strip of wet snow. Saturated slush forms on flats, which are quite extensive, for instance, in the area east of

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Sondre Stromfjord. Here slush fields are found as far as 100 km from the ice edge. Most of the peripheral zone is crevassed, but there are few crevassed areas more than 100 km inland, and perhaps none more than 200 km from the nearest land. Most of the common morphological features of glaciated areas can be found in Greenland, but those associated with morainal material are not prominent. Glacial erosion appears to be generally weak, and most of the land area is only thinly covered with debris.

The interior of the ice sheet, $\frac{1}{2}$ to $\frac{2}{3}$ of its area, shows only very surficial summer melt features. It is a monotonous snow landscape with generally low slope gradients. Here there are two interesting morphological features awaiting explanation.

The first is that on many routes one notes, on traveling inland, a succession of relatively steep rises tens of miles apart alternating with relatively flat areas. The second is the wavy surface of the high interior. The wave length is several kilometers and the amplitude several meters. It is unlikely that either of these features is controlled by the shape of the bed. The first may be in part correlatable with accumulation rates, more probably it will have to be explained in terms of ice flow mechanics. The second must be a snowdrift phenomenon.

The snow surface changes from day to day with the weather; strong winds can produce hard sastrugi, very seldom higher than 1 ft. Surface snow density varies from about 0.2 to 0.4 g/cm³, essentially the same as winter snow elsewhere, except that very light snow is rare because snowfall is usually associated with wind. High winds are rare in the interior at most stations: it blows in excess of 20 mph only some 5% of the time. But very strong winds up to 120 mph in gusts occur in North Greenland at the edges of the ice sheet. Four facies (geological term for different aspects of a formation) of upper layers can conveniently be distinguished³ (Fig. 8, 9).

1. The ablation facies - extends from the edge of the ice to the firn line. Above the firn line, there is a permanent snow cover, i. e., the snow does not all melt away. Bare ice characterizes the area of the ablation facies, which covers no more than 15% of the ice sheet area.

2. The soaked facies - extends from the firn line to the saturation line. Summer melting produces sufficient water to soak at least the whole snow accumulation of the past year. Thus all the snow of the soaked facies has been wet at least once. Average density of the upper 5 meters is greater than 0.50 g/cm³. The soaked facies belt covers about 10% of the ice sheet area.

3. The percolation facies - extends from the saturation line to the dry snow line. Summer melting is insufficient to soak all of the past year's accumulation. Percolation in pipe-like vertical channels can, however, penetrate to and past the previous summer layers and spread to form ice lenses and layers in older snow. The average density of the upper 5 meters varies from 0.43 to 0.39 g/cm³. The percolation facies covers some 45% of the ice sheet area.

4. The dry-snow facies - is characteristic of the whole area lying above the dry-snow line. Melting and percolation are negligible; the snow remains permanently dry, and the average density of the upper 5 meters is less than 0.375 g/cm³. Snow of the dry facies covers 30% of the ice sheet area.

Figure 10 shows a pit dug in the dry snow (dry-snow facies). The pit walls have been brushed to reveal the succession of hard and soft layers.

SNOW DENSIFICATION

Figure 11 shows a typical 10-meter snow profile¹ at 77°N 56°W near the upper limit of the percolation facies. There are almost always some low-density layers deposited in the summer, and down to about 7 meters the general increase in density is almost linear with depth. The slope of the depth-density line varies with location. The smaller the rate of accumulation, and the higher the temperature, the greater the density increase over a given depth increment.

Figure 8. Distribution of facies (Benson, 1960, Fig. 48). The location of facies boundaries is most certain along the west side of the crest between 66 and 79°N. Away from this region, the dry-snow line may be extrapolated with confidence because it is independent of accumulation. The dry-snow line on this map was drawn along the intersection between a plane sloping 1.15 m/km to the north, and the surface of the ice sheet. Location of the firn line and saturation line in south and east Greenland is highly speculative.

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Figure 9. Schematic of facies (Benson, 1960, Fig. 15).

Figure 10. Pit in dry snow (Benson, 1960, Fig. 4b). The walls have been brushed to reveal succession of hard and soft layers.

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Figure 11. Snow density profile at 77°N 56°W (Bader, 1958, Fig. 4).

Figure 12. Depth-density curve 77°N 56°W (Bader, 1958, Fig. 3).

Figure 12 shows the increase of density with depth¹ as determined on cores from a drill hole at 77°N 56°W. At about 80 m depth, the pores in the snow have become isolated and there is impermeable ice with a density of about 0.8 g/cm³, and an air bubble volume of about 10%. Further densification takes place at the expense of air bubble volume, causing a rise in bubble pressure.⁷ The resulting glacier ice is fine-grained (1 mm to 1 or 2 cm) and milky in appearance due to inclusion of hundreds of bubbles per cm³.

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APPENDIX 5.C

THE ANTARCTIC ICE SHEET

5.C.1

COLD REGIONS SCIENCE AND ENGINEERING

F. J. Sanger, Editor

Part I: Environment

Sect B: Regional

I-B1

Feb 1961

The Antarctic Ice Sheet

by Malcolm Mellor

**U. S. ARMY COLD REGIONS RESEARCH
AND ENGINEERING LABORATORY
Corps of Engineers**

PREFACE

This monograph summarizes existing knowledge of the Antarctic continent for the use of professional engineers engaged in design or construction in that region.

The paper has been reviewed and approved for publication by the Office of the Chief of Engineers , U.S. Army.

W. L. NUNGE~~S~~SSER
Colonel, Corps of Engineers
Director

Manuscript received November 1960

Department of the Army Project 8S66-02-001

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EDITOR'S FOREWORD

"Cold Regions Science and Engineering" consists of a series of monographs summarizing existing knowledge and providing references for the use of professional engineers responsible for design or construction in Cold Regions, defined as those areas of the earth where frost is an essential consideration in engineering.

Sections of the work will appear as they become ready, not necessarily in numerical order, but fitting into this plan:

- I. Environment
 - A. General
 - B. Regional
- II. Physical Science
 - A. Geophysics
 1. Micrometeorology
 2. Exploration Geophysics
 - B. The Physics and Mechanics of Snow
 1. The snow cover
 2. Snow as a material
 - C. The Physics and Mechanics of Ice
 1. Ice on the earth's surface
 2. Ice as a material
 - D. The Physics and Mechanics of Frozen Ground
 1. Properties of frozen soils
 2. Permafrost
- III. Engineering
 - A. Snow engineering
 - B. Ice engineering
 - C. Frozen-ground engineering
 - D. General engineering
- IV. Miscellaneous

F. J. SANGER
Special Assistant
to the Director

7 February 1961

5.C.5

THE ANTARCTIC ICE SHEET

by
Malcolm Mellor

Physiography and surface characteristics

Antarctica consists of a continental-type land mass covered by a thick mantle of snow-formed ice. The land surface beneath the ice is below sea level in many places, but since troughs and basins are solidly filled with permanent ice, the rock depression is partly due to imposed ice load, and the earth's crust is of continental type, Antarctica can be regarded as a continent having some major basal troughs. The surface area of the continent and its fringing ice shelves is about 5,500,000 square miles.

Antarctica can conveniently be divided into two distinct parts: West Antarctica, lying south of the Americas, and East Antarctica, south of Australia and Africa and divided from West Antarctica by a line joining the Ross and Filchner Ice Shelves. Geologically, West Antarctica consists of folded mountains and plateaus, with sedimentary deposits in older geosynclines. Sediments and intrusives can be traced from South America via the Palmer Peninsula. East Antarctica is a continental shield comprising a basement of schists, gneisses, and intrusives overlain by a series of sediments intruded by dykes and sills. Thick flat-lying sediments are exposed along the south-west edge of the Ross Ice Shelf, but most of the ice-free areas in the coastal belt between 0° and 170° E long. are formed solely of old basement complex.^{7, 8 *}

The land-based ice sheet is up to 14,000 ft thick, and its surface form is influenced by features of the underlying terrain, by the visco-plastic properties of the ice and, to a small extent, by snowfall distribution. Stresses developed by the ice cause it to deform into a dome-like shape and flow outward to the sea, where it is dissipated mainly by iceberg calving. In coastal areas where the subglacial relief is gentle, the ice flows slowly as a featureless sheet at a rate of inches per day; where higher relief exists, the flow can be channeled and accelerated to form out-flow glaciers and ice streams which move feet per day.²² In many of the larger bays, and along certain other stretches of coast, ice shelves exist. The two largest are the Ross and the Filchner ice shelves, which move seaward at rates of feet per day near the ice front.

Ice shelves are nourished partly by the inflow of glacier ice from the land and partly by snow accumulation on the surface. As the thickness of a floating ice shelf increases, it tends to spread laterally and this spreading, coupled with the flow of land ice, leads to a relatively rapid seaward movement. The response of an ice shelf to tidal motion produces relative movement between the floating shelf and the fixed land-ice, so that hinge and shear cracks form around the shelf boundaries.^{6, 28, 45, 46}

The Ross Ice Shelf is about 200,000 square miles in area, up to 500 miles wide, and about 400 miles in north-south extent. Its southern extremity comes within 300 miles of the South Pole. Away from the seaward edge, or the ice front, the thickness ranges from 800 to 2000 ft and there is 1000 ft of water beneath the base of the shelf. Near the ice front the shelf rises and falls several feet with the tides. The horizontal movement seaward is estimated at 3 - 5 ft/day. The over-all change of surface elevation on the shelf is no more than 60 ft, but it has ice anticlines, or "rolls," with amplitudes of 15 - 50 ft and wavelengths of 300 - 350 ft.⁶⁰

The Filchner Ice Shelf is approximately 160,000 square miles in area. It is divided by a large "island" consisting of ice hills formed above an area of bedrock

* See References.

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ENVIRONMENTAL: REGIONAL

Figure 1. Approximate contours of the surface of the ice sheet (meters). (After Crary, ref. 64). Stipple pattern represents regions in which there is much exposed land.

which juts up to sea level. Another island lies near the western edge of the shelf. The thickness of the floating ice ranges from less than 1000 ft to more than 2000 ft.⁴⁶

The continental land-based ice rises steeply from the edges, slopes becoming progressively smaller further inland. Typical rises are as follows: 10 miles inland - 1500 ft, 50 miles - 4500 ft, 100 miles - 6000 ft, 200 miles - 8000 ft. The maximum height of the ice surface is about 14,000 ft and the highest areas are in the region 75° - 85°S lat, 20° - 90°E long.

Along most of the Antarctic coastline no rock is visible and the continental ice or shelf ice terminates abruptly in vertical cliffs, which are generally 50 - 150 ft high. The exposed rock areas which do exist range in size from small isolated nunataks or islets to extensive ice-free hills or mountains. There are many stretches of coast, 100 miles and more in length, where exposed rock is completely absent.

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Figure 2. Thickness of the Ross Ice Shelf (in meters). (After Crary, ref. 6).

Most of the sea ice which forms around Antarctica during the winter breaks up in summer and is dissipated by movement into the open ocean. Thus there is little tendency in most places for refreezing of old ice and subsequent development of great thickness, such as occurs in the Arctic. In some local areas the sea ice is protected from summer break-up, or broken ice is restrained; in such places thick "bay ice" can build up. The maximum thickness of one-year old ice is about 5 - 7 ft, but bay ice and re-frozen pressure ice may be much thicker.²⁶

In steeply sloping fringe regions the snow surface is hard and rough due to the strong and persistent winds, which pack the snow and form dunes and sastrugi. Long rounded dunes are laid down periodically during cyclonic blizzards and their orientations indicate the directions of snow-bearing winds. Katabatic winds, which are not normally associated with precipitation, cut the dunes into jagged shapes, and form sharp-edged sastrugi from blowing snow.

Katabatic winds flow down the steepest regional slopes, a certain deflection towards the west being produced by the Coriolis effect. Sastrugi directions, therefore, can give some indication of regional contours. The height of old sastrugi in a given area is often taken as an indicator of the maximum wind speed at that place. In Mac-Robertson Land, sastrugi 5 ft high have been measured, and in Queen Mary Land sastrugi are up to 6 ft high. Movement over this kind of terrain severely taxes surface vehicles.

In relatively wind-free areas of the interior, and in places where regional contours nullify the katabatic effect, surface snow is softer and less dense, so that heavily-loaded vehicles easily become bogged.

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Crevasses may be encountered in any part of Antarctica, though they are most common near the coast and close to mountains and nunataks. On ice shelves the most serious crevassing is near the junction of shelf ice and land ice. Although most crevasses are bridged by drifted snow there is usually adequate indication of their presence on the inland ice, provided that drifting snow or whiteout conditions are not prevailing. Inland, crevasses tend to form on ice domes, which are themselves associated with subglacial peaks and ridges. Ice domes are obvious from the ground in clear weather and there is often direct indication of the crevasses in the form of slightly depressed snow bridges and "haycocks" (hard snow mounds) along the crevasse edges. From the air, ice domes only stand out in favorable low-angle light, but the crevasses show up well in clear weather conditions. In the vicinity of mountains and nunataks, numerous sigmoidal shear crevasses may exist; it is more difficult to pick a safe route through a field of concealed sigmoidal crevasses than through an area of simple straight-line crevasses, since probing does not reveal a general pattern. In some places crevasses are so well concealed that they cannot be traced visually even after a vehicle has broken through and the eye has been directed to the precise location. In such cases only electronic and infrared devices can define the crevasse system. Antarctic crevasses can be very wide; 30 ft is common and crevasses more than 100 ft wide have been encountered on the inland ice. There are no measurements to show that Antarctic crevasses are appreciably deeper than those of Arctic regions.

Figure 3. Accretion and decay rates of sea ice at Mawson Station
(67°36'S, 62°52'E). (Mellor, ref. 26).

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Snowfall is light compared with that in Greenland; it is estimated that the average precipitation over the whole Antarctic ice sheet is no more than 5 inches of water per year, little more than the rainfall on the arid deserts of the earth. The distribution is by no means uniform. Air over the high, cold interior contains very little precipitable moisture and most of the snowfall is a result of cyclonic penetration from the coast. There is generally a fall-off of accumulation towards the interior, and in the heart of the continent the average accumulation seems to be only about 2 inches of water, or something like 6 inches of snow. In the outer zones accumulation varies from place to place, changing mainly with wind speed and relative location of cyclone tracks. Generally speaking, accumulation is greatest on ice shelves, where snow is not blown away by katabatic winds and where snow blowing from the continental slopes may be deposited. The annual accumulation in these places can be up to several feet of snow.

Where katabatic winds are especially fierce and persistent, such as on steep slopes and in valleys which funnel the wind, all new snow may be blown away so that melting and evaporation actually lower the surface. The relatively low albedo of snow-free ice permits radiation melting even far inland during the summer, and melt streams and lakes are common features in some regions.

Wind velocities vary widely from place to place, both regionally and locally. Much of the interior is free from katabatic and pressure winds, while coastal areas are subject to both. Big differences sometimes exist between places only tens of miles apart, usually due to local topographic effects but sometimes because of persistent meteorological factors governing cyclonic movements. The highest velocities seem to be reached where the katabatic wind reinforces cyclonic winds. Commonwealth Bay (67° S, 143° E) is believed to be the windiest place on earth, with a mean annual wind velocity of 44 mph and gusts up to 200 mph. At Pointe Géologie, 50 miles to the west, the mean annual wind speed is only 21 mph. At Mawson (67° 36' S, 62° 52' E), another windy place, peak gusts of 150 mph have been recorded and the average velocity is 24 mph. Mirny and Pionerskaya have annual averages of 26 mph and 24 mph respectively. By contrast, the Russian inland stations Vostok and Komsomol'skaya have average wind speeds of 10 and 9 mph respectively, and the South Pole has an annual average of about 15 mph, with peak gusts less than 60 mph.

Brisk winds blowing over a loose surface pick up snow, and the resulting drift reduces visibility and piles snow around stationary objects. Blowing snow is a menace to surface installations, burying everything under deep drifts and putting heavy snow loads on buildings. It limits all outdoor work, prevents flying operations, and precludes surface travel on unmarked routes; drift frequency is therefore an important parameter for the assessment of local conditions. At Port Martin and Cape Denison (Commonwealth Bay area) drifting snow prevails for more than 50% of the time.

Another condition which restricts air and surface travel is whiteout, a condition resulting from the elimination of all shadows by multiple light reflections between the snow and an overcast. In many areas, whiteout is more prevalent than drifting snow.

Temperatures around the coasts vary with latitude and with local conditions, mean annual temperatures ranging from +26F to -12F (Fig. 49). The warmest coastal stations are on the Palmer Peninsula, the coldest on the edges of the Ross and Filchner Ice Shelves. Stations situated on extensive areas of ice-free rock have somewhat enhanced mean annual temperatures due to solar radiation effects, while stations swept by strong and persistent winds off the ice sheet are cooler than average for their latitudes. For coastal stations over-all, there is a fall of mean temperature with increasing latitude of roughly 2.5F per degree of latitude.

Away from the coast, temperature falls rapidly with increasing surface altitude; mean annual temperature drops about 5.5F/1000 ft. The temperature

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Table I. Annual means of wind speed and temperature.

Station	Co-ordinates		Mean annual temperature (F)	Mean annual wind speed (mph)
	Lat	Long		
Port Martin	66 49 S	141 24 E	+10	40
Cape Denison	67 00 S	142 40 E		44
Pointe Géologie	66 39 S	140 01 E	+12	21
Dumont d'Urville	66 40 S	140 01 E	+12	26
Station Charcot	69 22 S	130 01 E	-35	21
Little America V	78 11 S	162 10 W	-12	14
Cape Hallett	72 18 S	170 18 E	+5	18
Wilkes	66 15 S	110 31 E	+16	12
Ellsworth	77 43 S	41 08 W	-12	14
Byrd	80 00 S	120 01 W	-18	17
Camp Michigan	78 34 S	163 57 W	-13	-
Wilkes Site 2	66 28 S	112 17 E	-3	-
Amundsen-Scott	90 00 S	-	-56	15
Mirny	66 33 S	93 00 E	+15	26
Vostok	78 27 S	106 52 E	-72	10
Oasis	66 16 S	100 44 E	+16	14
Vostok I	72 08 S	96 35 E	-53	15 (est.)
Pionerskaya	69 44 S	95 30 E	-38	24
Komsomol'skaya	74 S	99 E	-65	9
Lazarev	69 58 S	12 55 E	+5	-
Pole of Inaccessibility	82 06 S	55 00 E	-72	7 (est.)
Mawson	67 36 S	62 52 E	+12	24
Davis	68 34 S	77 57 E	+13	10
Maudheim	71 03 S	10 55 W	+1	17
Syowa	69 00 S	39 35 E	+14	16
Roi Baudouin	70 30 S	23 E	+15	15 - 20
Halley Bay	75 36 S	26 41 W	0	15
Shackleton	77 57 S	37 16 W	-14	-
Southice	81 56 S	29 30 W	-24	-
Hope Bay	63 24 S	56 59 W	+20	14
Marguerite Bay	68 11 S	67 01 W	+19	10
Argentine Islands	65 15 S	64 16 W	+22	9
Port Lockroy	64 50 S	63 31 W	+26	12
Scott Base	77 51 S	166 45 E	-4	11

drop with distance from the sea (or latitude) is around 3F/100 miles on the inland ice of East Antarctica between 70° and 75°S latitude.

Except on the extreme coastal fringe, monthly mean air temperatures remain below freezing for the whole year, and even on relatively warm coastal rock areas temperatures for December and January are seldom more than 2F above freezing. The lowest recorded temperature is -125F at Vostok (78° 27'S, 106° 52'E; 11,500 ft a.s.l.), where the mean annual temperature is -72F. The minimum temperatures experienced at coastal stations are around -63F. The highest temperatures occur on the Palmer Peninsula - up to +53F - but summer air temperatures as high as +46F are reached over rock areas on the coast of East Antarctica, and rain falls occasionally.

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Figure 4a. Smoothed annual temperature variations for some Antarctic coastal stations. (After Hisdal, ref. 58).

Figure 4b. Unsmoothed annual temperature variations for two coastal stations. (From ANARE meteorological records).

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Figure 5. Mean density of surface snow layers plotted against mean annual temperature. (After Schytt, ref. 39 and Mellor, ref. 61).

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Snow accumulation

Precipitation over the ice sheet of Antarctica is closely associated with the penetration of low pressure systems. Since these depressions move mainly around the periphery of Antarctica, being blocked from crossing by the high icecap, most of the precipitation falls within a few hundred miles of the coastline, on the ice shelves and the steep marginal slopes of the icecap. Snowfall in the high, cold interior is relatively slight.

The pattern of snow deposition is further complicated by the redistribution which results from wind-drifting. Snow may be carried long distances and deposited in preferred locations both by pressure winds and katabatic winds. Katabatic winds, which are gravity winds created by temperature inversions over the snow surface, flow down the steepest slopes, their speeds and directions influenced by regional contours. They often transport loose snow from the steep slopes to flat-lying areas where wind velocities decline.

The rate of snow accumulation is in itself an essential glaciological parameter but on wind-swept polar snowfields, measurements of net accumulation are of necessity substituted for precipitation measurements. It is, therefore, important to realize what net accumulation really represents; it can be expressed as follows for the inland ice:

$$\text{Accumulation} = \text{Precipitation} + \text{snow blown in} + \text{hoar formation} \\ - \text{snow blown away} - \text{evaporation.}$$

Hoar formation (crystallization) and evaporation are both small quantities which approximately balance, and they can be neglected in most cases. In marginal zones of the ice sheet where melting is appreciable:

$$\text{Accumulation} = \text{Precipitation} + \text{snow blown in} + \text{hoar formation} \\ - \text{snow blown away} - \text{evaporation} - \text{melt-water run-off.}$$

Melt water which soaks into the snow and refreezes is part of the accumulation.

Accumulation is measured in Antarctica by direct stake measurements and by interpretation of the snow stratigraphy revealed in pit sections and drill cores. Some of the results obtained so far are presented in Table II and Figures 6 to 8.

Figure 6. Accumulation in Queen Mary Land plotted against distance from the coast. (After Vialov, ref. 49).

Figure 7. Accumulation along the route of the Commonwealth Trans-Antarctic Expedition. (After Lister and Pratt, ref. 15). The lower line is the ice surface profile; vertical distance from this to the upper line gives snow accumulation.

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Figure 8. Accumulation in the Weddell Sea area and in Marie Byrd Land. Average net annual accumulation (cm of water). (After Giovinetto, ref. 11).

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Table II.

Location	Annual accumulation	
	in. of water (approx.)	in. of snow (approx.)
Mac-Robertson Land (150-200 mi. inland)	6	15
Queen Mary Land (within 40 mi. of coast)	up to 33	up to 83
" (45-280 mi. inland)	8 - 12	20 - 30
" (500 mi. inland)	3	8
Terre Adélie (10-30 mi. inland)	8 - 12	20 - 30
" (190 mi. inland)	4	10
Dronning Maud Land (ice shelf)	14	35
" (continental slopes)	10	25
" (180 miles inland)	5	13
Davis Bay, Wilkes Land	15	38
South Pole	3	7
Byrd Station	6	15
Ellsworth Station	9	23
Wilkes Satellite Station (50 miles inland)	5	13
Lazarev Station	12	30
Halley Bay	13	33
Southice	4	10
Victoria Land Plateau	6	15
Little America V	9	22
Sentinel Mountains region	6 - 15	16 - 38
Horlick Mountains region	5 - 6	13 - 15
Palmer Peninsula (west coast)	17	43
Norway Station	17	43
Roi Baudouin Base	7	19

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Ablation

The loss of ice by evaporation and meltwater run-off is only a small proportion of the total ice loss from Antarctica, but it is locally significant in some regions. The indications are that melting and evaporation are insignificant on ice shelves, and quite negligible in the high interior of the ice sheet. In relatively warm coastal zones, however, and in areas where the surface albedo is reduced by wind-scouring (wind-swept "blue ice"), summer melting can occur on a large scale, streams, rivers, and lakes being formed by the meltwater. Evaporation is likely to occur wherever drift-free katabatic winds flow down the steep marginal slopes, warming and increasing their water-bearing capacity as they go.²³

Although most of the surface of Antarctica can be classed as accumulation area (net accumulation of snow each year), there are a number of net ablation areas. These are represented by the ice-free "oases" of East Antarctica (e.g. Bunger Hills, Vestfold Hills) and the "blue ice" ablation areas (found in certain coastal regions of East Antarctica and in mountain regions).

Annual net ablation as high as 2 ft of water per year has been measured along the coast in East Antarctica, but the ablation rate falls off rapidly with increasing altitude of the ice surface - about one-third of the sea level rate at a height of 1500 ft.

Figure 9. Ablation from a snow-free ice surface (200 ft a.s.l.) near Mawson (67° 36'S, 62° 52'E). (Based on Crohn, ref. 7, and Mellor, ref. 23).

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Drifting snow

Drifting snow is sufficiently intensive and persistent in many parts of Antarctica as to constitute a major problem of both science and logistics. Research has been directed at elucidation of the mechanics of drifting snow, measurement of drift density at various heights, estimation of the mass transport of blowing snow, and the control of drifting at surface installations.

Drift may be due to horizontal transport of snow during the course of precipitation, by predominantly pressure winds, or to transport of previously-deposited snow by winds which are mainly

katabatic in origin. Severe wind and drift conditions appear to prevail at locations where katabatic and pressure winds reinforce each other. The density of drift and the rate of snow transport are dependent on wind velocity and also on the supply of loose snow (drift is lifted from an age-hardened surface only by very strong winds).

Blowing snow is carried along by two principal mechanical processes: turbulent suspension, in which turbulence transports upwards as much snow as settles down under gravity, and saltation, in which particles close to the ground move by successive impact with, and rebound from, the surface.^{29, 2}

In the turbulent diffusion range, drift density falls off with increasing height above the surface because of the height dependence of the coefficient

Figure 10. Drift snow transport as a function of height at Mawson. (Based on Mellor and Radok, ref. 29).

Figure 11. Variations of snow transport at the 2 m level shown against variations of wind speed. (Mellor and Radok, ref. 29).

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Figure 12. Drift density as a function of height at Wilkes Station. (After Dingle and Radok, ref. 9).

Figure 13. Average drift snow density as a function of height (for heavy drift and high winds). (Mellor and Radok, ref. 29).

Figure 14. Drift snow transport as a function of the wind velocity at 10 m height. (After Dingle and Radok, ref. 9).

Figure 15. Size distribution of drifting snow particles at Southice. (After Stephenson and Lister, ref. 43).

of exchange. The drift density at a given height appears to be an exponential function of the reciprocal of the wind velocity at that height. The drift snow increments transported in different horizontal layers are exponential functions of the wind velocity at a given level (usually the standard 10-m anemometer level) (Fig. 14).^{29,9}

The saltation process takes place in a surface layer which is only a few inches deep, but because of the high drift density in this layer and the prevalence of saltation (it frequently occurs when wind speeds are too low for turbulent transport), significant amounts of snow are moved in this way. For one windy station on the coast of East Antarctica it has been estimated that 6% of the annual mass transport by drifting is due to saltation; where winds are generally lighter, the corresponding percentage would be higher.²³

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Snow transport is estimated by totaling the mass of snow moved through a unit-width vertical strip normal to the wind direction. The rate of mass transport is measured for a number of layers, and the consideration is taken to greater heights by extrapolation of the measurements from the wind profile. The average rate of transport corresponding to each of the drift reporting codes (the meteorologists' groups 36, 37, 38, 39) is found, and so the annual mass transport along the wind direction can be estimated with fair accuracy. The cross-coast transfer is simply the component of flow normal to the local coastline.²³

Measurements at Mawson and Wilkes stations give rates of mass transport for a 62 mph wind (at the 10-m level) of 10 lb/sec and 9 lb/sec respectively through a 1-ft wide vertical strip. In the case of Mawson station, the estimate for annual mass transport in the wind direction is 39 million short tons per 1 mile wide strip. The amount of snow crossing the coastline (which is not normal to the wind direction) is 28 million tons per year.^{23, 9}

Port Martin, in Terre Adélie, suffers drifting snow of some kind for 50% of the time,¹⁶ compared with Mawson's drift frequency of 14%. The average wind speed at Port Martin is 42.5 mph compared with the Mawson average of 23.5. This indicates an enormous annual mass transport of wind-blown snow at Port Martin according to current estimating methods.

Table III.

<u>Station</u>	<u>Percentage of time with drift of some kind</u>
Cape Evans	20
Hut point	19
Little America	18 (13% light drift)
Port Martin	53
Mawson	14

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Ice flow

The general form of the continental ice mass is determined by major features of the subglacial terrain and by the visco-plastic properties of the ice itself. The shape of the ice sheet conforms to the shape of the land mass beneath, but the tendency of the ice to assume the dome-shaped form of dynamic equilibrium is apparent in regions of low subglacial relief. In such areas the ice surface rises from the coast with a radial profile approximating to an elliptic arc. Wherever subglacial topographic features are large compared with the ice thickness, the ice surface is modified and distorted in an irregular manner.

The thick inland ice tends to spread radially towards the coastlines from high-altitude "flow centers." Velocity generally increases with distance from the flow center and the ice depth decreases. The effects of subglacial features are most pronounced in the coastal regions where the ice is thin and velocities are relatively high. In these places mountains and nunataks may project through the ice surface, channeling the ice into valley glaciers and blocking the general seaward movement. Submerged hills and mountains produce ice domes at the surface, and subglacial valleys allow ice streams to form.

The land-based ice commonly terminates in continental ice cliffs or glacier tongues which calve directly into the sea, but much of it flows into ice shelves. The major ice shelves usually occupy large embayments and receive nourishment from inflows of continental ice and from surface snow accumulation. Lateral spreading of the floating ice occurs and the shelf moves towards the open sea with relatively high velocity.

It is thought that the deep continental ice moves almost as a rigid block by slipping over the base and by shear displacement in a relatively thin basal layer. In shallow ice the differential movement through the thickness is believed to be more significant.

Figure 16. Ice movement near coastal mountains in East Antarctica - disturbed sheet flow. (Mellor, ref. 22).

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Figure 17. Ice movement on the coast of East Antarctica - sheet flow around a rock exposure. (Mellor, ref. 22).

Figure 18. Movement of the Taylor Glacier, a small ice stream in Mac-Robertson Land. (Mellor, ref. 22).

Figure 19. Ice movement in a mountain area of Dronning Maud Land - Advance Base of the Norwegian-British-Swedish Expedition. (After Swithinbank, ref. 44).

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On the almost featureless expanses of the inland ice, precise barometric leveling has revealed surface profiles which are "stepped" along the flow direction. These are believed to be surface perturbations caused by deeply submerged hills and ridges.³⁰

For the purpose of reporting ice flow velocities, three types of flow have been defined:²²

"sheet flow" - general outward movement of the continental ice over a bed of low relief.

"stream flow" - the relatively rapid movement of valley glaciers and ice streams.

"ice shelf movement" - general seaward movement of an ice shelf.

Few large-scale flow measurements have been made in Antarctica so far, partly because of the absence of fixed control points for surveys in most areas, but enough data have been secured to define the order of magnitude of each main type of flow. Table IV gives surface velocities for a number of locations in various parts of Antarctica.

Table IV.

Terre Adélie coast ¹⁶	Sheet flow	3 in/day
Mac-Robertson Land coast ²²	"	2 "
Cape Folger ⁴⁷	"	6 "
Dovers Glacier, Mac-Robertson Land ²²	Ice stream	7 ft/day
Hoseason Glacier, " " ²²	"	3 "
Jelbart Glacier (west tongue) " ²²	"	3 "
" " (east tongue) " ²²	"	1 "
Taylor Glacier " ²²	"	1 "
Helen Glacier, Queen Mary Land ¹⁰	"	5 "
Denman Glacier, " ¹⁰	"	9 "
Scott Glacier, " ¹⁰	"	4 "
Reed Glacier, " ¹⁰	"	4 "
Obroutschew Glacier, " ¹⁰	"	3 "
Apfel Glacier, " ¹⁰	"	3 "
Mirny, " ¹⁰	"	2 "
Gaussberg, Kaiser Wilhelm II Land ⁵⁷	"	1 "
Vanderford Glacier, Wilkes Land ⁵	"	6 "
Glacier de Zélée, Terre Adélie ¹⁶	"	3 "
Skelton Glacier, Victoria Land ⁵⁵	"	1 "
Maudheim Ice Shelf, Dronning Maud Land ⁴⁴	Shelf movement	3 "
Ross Ice Shelf, Ross Dependency ⁵⁴	"	3 - 4 "

Figure 20. Movement of the Skelton Glacier. (After Wilson, ref. 55).

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Figure 21. Closure of the Byrd Station borehole. Hole drilled January 1958. (After Bender & Gow, ref. 3).

Recent research has also aimed at determining the flow properties of Antarctic glacier ice, i. e., the relationships between strain rate, stress, temperature, and ice type. Figures 21 and 22 show the results of large-scale closure measurements on a borehole. Deformation measurements have also been made in horizontal circular tunnels. Laboratory creep tests have been made on small specimens.

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Figure 22. Relationship between load and hole diameter in the unrestrained Byrd Station borehole. 14.630 cm (5.760 in.) is initial diam - January 1958; d is new diam. (After Bender & Gow, ref. 3).

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Ice thickness

Extensive programs of ice depth measuring have been undertaken in Antarctica in recent years. Seismic sounding has been the standard method, with gravimeter observations being used for filling in detail between seismic shot points. New equipment, based on the radar altimeter, is under development for rapid measurements of ice depth, possibly from the air.⁵³

Measurements have revealed that the subglacial terrain has a high relief in many areas, and major mountain blocks have been discovered beneath the ice. Much of the rock base is below sea level, but since the earth's crust is largely of continental thickness and is also isostatically depressed by the ice load, it seems reasonable to regard Antarctica as a continent (with some major troughs) rather than as an archipelago.

Figure 23 shows the routes covered by parties measuring ice thickness. Figures 24 to 33 are profiles resulting from these traverses. Figure 35 is a speculative structural diagram of the Antarctic land mass based on seismic soundings and mapped features.

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Figure 23. Routes followed by seismic traverse parties of various nationalities.

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Figure 24. Ice depth profile along the route of the Commonwealth Trans-Antarctic Expedition. (After Lister & Pratt, ref. 15).

Figure 25. Ice depth profile along the meridian 62° E. (After Goodspeed, ref. 12).

Figure 26. Ice depth profile in Terre Adélie. (After Imbert, ref. 13).

Figure 27. Ice depth profile from Little America to Byrd Station. (After Woollard, ref. 56).

Figure 28. Ice depth profile in Dronning Maud Land. Vertical scale exaggerated 20 times. (After Robin, ref. 37).

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Figure 29. Ice depth profile from the Filchner Ice Shelf to Byrd Station.
(After Thiel *et al.*, ref. 46).

Figure 30. Ice depth profile on the Filchner Ice Shelf.
(After Thiel *et al.*, ref. 46).

Figure 31. Ice depth profile on the Victoria Land Plateau.
(After Crary, ref. 6).

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Figure 32. Ice depth profile from Mirny to Vostok.
(After Shumsky, ref. 42).

Figure 33. Ice depth profile from Komsomol'skaya to Pole of Inaccessibility.
(After Shumsky, ref. 42).

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Figure 34. Approximate distribution of ice thickness in Antarctica (1000-m intervals).
(After Crary, ref. 64).

Heavy dashed lines are routes of U.S. oversnow traverses; light dashed lines indicate approximate borders of shelf ice. SP = South Pole, LA = Little America, B = Byrd, M = McMurdo, W = Wilkes, E = Ellsworth, H = Hallett.

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Figure 35. Speculative structural diagram of the subglacial Antarctic land mass. (Adapted from a compilation published by "Life" magazine, November 1960).

5.C.35

THE ANTARCTIC ICE SHEET

Variation of ice properties with depth

Surface melting is extremely rare on Antarctic snowfields, and the transition from snow to ice is a dry process consisting of slow compaction by successively deposited layers, and intergranular migration of water molecules. As a result of these processes, density, air bubble pressures, and crystal size increase with depth.

The density of a given snow layer increases with depth mainly due to sustained visco-elastic deformation under the gradually increasing overburden load. In the layers near the surface, say the uppermost 30 ft, deformation occurs largely as a result of grain rearrangement to give the best geometry for close packing. Thereafter, the grains and their bonds must be deformed to allow further density increase. At depths in the region of 200 ft a density of 0.82 g/cm^3 is achieved, and at this stage the previously interconnecting air spaces seal off to form bubbles. Further compression of the material reduces the bubble volume, with consequent increase of the pressure of entrapped air.

Figure 36. Depth-density profile for Maudheim. (After Schytt, ref. 39).

Figure 37. Depth-density curve for Maudheim (detail of upper 12 m). (After Schytt, ref. 39)

Figure 38. Depth-density curve for Byrd Station.
(After Bender & Gow, ref. 3).

Figure 39. Depth-density curve for Little America V.
(After Bender & Gow, ref. 3).

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Figure 40. Depth-density curve for Southice. (After Stephenson & Lister, ref. 43).

The crystalline structure of the ice changes with depth under the action of sublimatory metamorphism and stress on the crystal lattice. The most rapid changes occur in the layers nearest the surface, where the amplitude of temperature variations is appreciable. The smallest snow grains of the original deposit gradually evaporate, with re-deposition causing larger grains to grow, become less angular, and acquire mutual bonds.

Observed changes of ice properties with depth are shown in Figures 36 to 47.

Figure 41. Depth-density curve for Wilkes satellite station (Site 2). (After Cameron et al., ref. 5).

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Figure 42. Depth-density curve for South Pole. (After Giovinetto, ref. 62).

Figure 43. Depth-density curve for Ellsworth Station. (After Aughenbaugh, Neuburg & Walker, ref. 63).

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Figure 44. Grain size vs depth in the ice shelf at Maudheim. (After Schytt, ref. 39).

Figure 45. Grain size vs depth at Southice. (After Stephenson & Lister, ref. 43).

Figure 47. Crystal size vs depth at Southice. (After Stephenson & Lister, ref. 43).

Figure 46. Crystal area vs depth at Maudheim. (After Schytt, ref. 39).

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Ice sheet temperatures

Temperatures in a thick, land-based ice sheet are influenced by the surface heat balance, geothermal flux from the earth below, and liberation of heat by ice shearing in the basal layers. The temperature distribution is complicated by movement of the ice, the shape of its upper surface, and accumulation of snow. Temperatures in a floating ice shelf are largely dependent on the surface heat balance and the heat flow from the sea beneath, with disturbances of the temperature profile being caused by ice movement, surface accumulation and basal melting.^{4, 16, 24, 34, 38, 54}

On a cold, non-melting ice sheet, temperatures of the snow layers within 50 ft of the surface respond to changes of air temperature. Since horizontal temperature gradients in the ice are small compared with vertical gradients, vertical heat flux in the upper layers can be considered as a case of linear conduction. Periodic variations of surface temperature can be expressed as a Fourier series, and the linear conduction equation solved for this temperature boundary condition to give the temperature in the snow at any depth and time. Temperature changes penetrate the ice with a velocity dependent on the thermal diffusivity of the ice, and the amplitude of a temperature wave decreases exponentially with depth. There is a progressive time lag dependent on depth and diffusivity.

Observations in Antarctica confirm this theory and it is found that diurnal temperature variations penetrate 2 or 3 ft into the snow, while annual temperature variations are detectable to depths of 40 - 50 ft, where the amplitude of the annual wave reduces to zero. Snow temperatures measured 40 ft or so below the surface therefore give a good approximation to the mean annual surface air temperature in a particular locality.

In Figure 49 mean annual surface temperatures, derived from "40 foot temperatures" and meteorological observations, are plotted on a map of Antarctica. It is immediately apparent that the wide spread of temperatures has little connection

Figure 48. Annual temperature changes in the upper 12 m of the snow at South Pole.
(After Giovinetto, ref. 62).

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Figure 49. Mean annual surface temperatures in Antarctica — derived from meteorological observations and borehole temperatures.

5.C.42

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Figure 50. 15 m ice temperature plotted against surface elevation (Queen Mary Land). (After Bogoslovski, ref. 4).

Figure 51. 15 m ice temperature plotted against surface elevation (Mac-Robertson Land). (Mellor, ref. 24).

Figure 52. 10 m ice temperature plotted against surface elevation (Wilkes Land). (After Cameron et al., ref. 5).

5.C.43

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Figure 53. 15 m ice temperature plotted against distance from the coast (Queen Mary Land).
(After Bogoslovski, ref. 4).

Figure 54. 15 m ice temperature plotted against distance from the coast (Mac-Robertson Land).
(Mellor, ref. 24).

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Figure 55. Borehole temperatures to 1000 ft depth at Byrd Station. (After Bender & Gow, ref. 3).

with latitude, and Figures 50 to 52 bring out the fact that surface temperature is mainly influenced by altitude. The observations made in East Antarctica indicate that the temperature change with altitude is about 5.5F/1000 ft from sea level to 6000 ft a.s.l. (steep slopes), and about 7F/1000 ft from 6000 ft upwards (gentle slopes). Figures 53 and 54 show surface temperature changes with distance from the sea (roughly equivalent to latitude change). These, taken with the previous figures, suggest that the temperature variation with latitude in this part of East Antarctica is about 1.6F/degree of latitude.^{4, 24}

Below the 50-ft level, ice temperature at any given depth remains constant over a period of many years. The temperature profile at a fixed geographical position can only be slowly disturbed by long-duration climatic fluctuations or changes in the physical structure of the ice sheet, but the temperature distribution in a given vertical element of ice gradually changes as that element flows coastwards.

Figures 55 to 61 show temperature profiles for a number of points on the land-based Antarctic ice sheet. At first sight the negative temperature gradients (tem-

Figure 56. Ice temperature profile at South Pole. (After Giovinetto, ref. 62).

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Figure 57. Temperature profile at Mirny. (After Bogoslovski, ref. 4).

Figure 58. Temperature profile in the ice 5 km inland from Mirny. (After Bogoslovski, ref. 4).

perature decreasing with depth) exhibited in these profiles are puzzling, since the upward geothermal flux and the heat released in the basal layers suggests that a positive gradient should exist. However, it can be shown that negative temperature gradients are formed by ice flow and surface accumulation, and by climatic warming at the surface.

Temperature profiles in the Ross and Maudheim Ice Shelves show positive temperature gradients throughout.^{3, 40} Temperature increases with depth, the rate of temperature rise becoming progressively greater as the base of the shelf is approached (Figs. 62, 63). An apparently anomalous profile was measured on the Filchner Ice Shelf (Fig. 64), temperature falling with increase of depth in the top 160 ft.⁵⁴ This reversed gradient was believed to be due to the rapid rate of flow of the shelf from a colder "upstream" environment.

Figure 59. Temperature profiles in the ice at Komsomol'skaya and Vostok I. (After Bogoslovski, ref. 4).

Figure 60. Temperature profiles in the continental ice of Queen Mary Land (locations are given in km from the coast near Mirny). (After Bogoslovski, ref. 4).

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Figure 61a.

Figure 61b.

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Figure 61c.

Figure 61. Temperature profiles in the continental ice of Mac-Robertson Land (on the meridian 62°E - profiles measured in summer). (Mellor, ref. 24).

Figure 62. Borehole temperatures through the Ross Ice Shelf. (After Bender & Gow, ref. 3).

Figure 63. Temperature profile in the Maudheim Ice Shelf. (After Schytt, ref. 40).

5.C.49

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Figure 64. Temperature profile in the
Filchner Ice Shelf.
(After Wexler, ref. 54).

5.C.50

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The mass budget and fluctuations of the ice margins

One of the ultimate aims of glaciological research in Antarctica is a determination of the ice mass budget, from which it will be possible to tell whether the ice sheet is losing or gaining mass, or whether it is in equilibrium.

The mass balance for the ice sheet can be expressed in the following way:

$$(\text{Gain or loss}) = (\text{precipitation over the ice sheet}) - (\text{snow blown off the ice sheet}) - (\text{total ablation}) - (\text{iceberg production}) - (\text{oceanic melting})$$

This can be simplified for practical purposes, since net accumulation is measured rather than precipitation

$$(\text{Gain or loss}) = (\text{net accumulation}) - (\text{net ablation}) - (\text{iceberg production}) - (\text{oceanic melting}).$$

It is now possible to estimate the net accumulation over the whole of Antarctica with some expectation of accuracy, but it is still difficult to assess the quantity of ice lost annually, as data are slight. Estimates of net ablation are probably adequate, since it is apparent that ablation plays only a minor role, but the rate of iceberg production is difficult to calculate from available data on flow velocities and ice thickness. Estimates of oceanic melting beneath ice shelves have only recently progressed from the realm of surmise, and are still undependable. With so much uncertainty, then, present outlines of the mass budget are only in the nature of experimental probings.

Nevertheless, it is interesting to see that the more credible estimates of recent years show a common trend, in that the ice losses are too small to achieve a balanced budget.^{15, 23, 59} This suggests that the Antarctic ice sheet, unlike most small glaciers of the earth, is actually gaining mass at the present time.

The outline of an Antarctic mass budget, which was drawn up at the end of the International Geophysical Year, is given below.²³ The comments in parentheses are based on a review of data which has appeared since the original estimate was made.

Annual gains and losses of ice:

Net accumulation	+17 x10 ¹⁷ g	(possibly rather high - but by a factor less than 2)
Iceberg production	-5.7 x10 ¹⁷ g	(may be too low - but by a factor less than 2)
Net ablation	-0.74x10 ¹⁷ g	(no grounds for significant revision)
Oceanic melting	-0.48x10 ¹⁷ g	(probably too low - by a factor greater than 2 but probably less than 10)

Accumulation surplus = +10¹⁸ g/yr (new data suggests that this could well be halved, but not entirely eliminated)

To obtain an estimate of average precipitation over the 14,000,000 km² ice sheet, losses by drifting snow and by evaporation in the accumulation zone were added to the net accumulation:

Net accumulation	17 x10 ¹⁷	(rather high, as stated above)
Drifting snow	1.9 x10 ¹⁷	(perhaps too high by a factor of 2)
Evaporation	0.63x10 ¹⁷	(probably should be neglected, since it may be balanced by direct crystallization)

Precipitation = 2 x 10¹⁸ g/yr, or an average of 14 cm of water per year (probably too high, but by a factor less than 2).

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THE ANTARCTIC ICE SHEET

Approaching the problem from a different angle, the ice margins of Antarctica have been studied for evidence of advance or retreat and changes of thickness in the ice sheet. It is apparent that the ice sheet was once of much greater areal extent and considerably thicker — 2000 ft thicker in places — than at the present time.^{25, 31, 32} The indications are that decline from this former glacial maximum was initiated roughly 10,000 years ago.^{25, 32, 41} In very recent times (the past century) it seems that there has been little change in the position of the ice margins. Cartographic, photographic, and botanical evidence shows that, in the last 50 years, the ice margins have been in a stationary position or, in a few places, in very slow retreat.^{1, 25, 31, 32, 41} This contrasts with the situation around Greenland and on most of the world's small glaciers, where retreat has been general and rapid in the past century.

At first sight, this seems to be a paradoxical situation, with mass balance studies showing an ice gain, and direct observations showing that the ice edges are stationary or in slow retreat. However, the edges of the ice sheet must be expected to respond slowly to any accumulation changes in the interior because of the great size of the ice sheet and the low flow velocities (unless accelerated surface "waves" transmit the effects of accumulation variations at an enhanced rate⁶⁵).

Some of the negative temperature gradients measured in boreholes have been explained in terms of secular climatic warming²⁴, although this conclusion is open to question. If the known recent rise of global air temperatures does extend to Antarctica, it would be unlikely to significantly increase the rate of ice wastage.

The observed rise of world sea level in recent times is apparently an argument for a decreasing Antarctic ice volume, although this deduction has been challenged on the grounds that rising temperatures would cause expansion of the ocean waters.

The only really safe statement which can be made about the regime of the Antarctic ice sheet is that the currently available data give insufficient basis for firm conclusions.

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APPENDIX 5.D

SELECTED CHAPTERS FROM INTRODUCTION TO ANTARCTICA

INTRODUCTION TO ANTARCTICA

Prepared as a public information service of the U.S. Naval Support Force, Antarctica to replace a publication formerly issued under the same title by the U.S. Antarctic Projects Officer. Washington: July 1969

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What is Antarctica?

Antarctica is the name of a great continent covered with snow and ice that surrounds the South Pole. In only a few places does this continent extend north of the Antarctic Circle, an imaginary line around the Earth at about 66°33' South Latitude. Including its permanently attached ice shelves, Antarctica covers about 5½ million square miles. This is an area about the size of the United States and Mexico combined. Over countless years, snow and ice have built up on the land, burying all but 4.5 percent of it, and nobody knows exactly what Antarctica would look like if all the ice were removed.

Antarctica has 18,500 miles of coastline; off the shores of this continent are many islands which are also ice-covered. They, too, are considered to be part of the south polar region usually called the Antarctic.

This glacier ends in one of few ice-free valleys in Antarctica. The frozen lake (foreground) is also a rarity. Bands of rock record part of continent's past.

Lands and Waters

The Antarctic, then, is composed of a continent and many small islands situated in the waters of three oceans: the Atlantic, Pacific, and Indian. It is quite different from the north polar region, the Arctic. The Arctic is an ice-filled ocean and the land around it, including parts of three continents—North America, Europe, and Asia—and a number of islands, of which Greenland is the largest. The boundary of the Arctic is defined in different ways by different experts, but many scientists regard the tree line as the margin. This line, north of which trees cannot grow, is easily recognizable. Differences in climate, animal life, and vegetation exist north and south of that line.

There is no tree line to mark the edge of the Antarctic—there are no trees. But a traveller going there by ship can feel, even if he cannot see, when he enters the Antarctic; he feels a rapid drop in the air temperature—about 5° to 10° Fahrenheit across a zone some 20 to 30 miles wide. This change in temperature takes place because water flowing north from Antarctica is cold. During the long antarctic winter, the surface of the seas around the continent freeze as far as several hundred miles from the coast. When summer comes, this ice breaks up and moves off northward, and the snow and ice of the continent melt around the edges. Huge pieces of ice break off to form giant icebergs that float majestically northward. Where the cold waters of the Antarctic meet the warmer waters of the Temperate Zone, the temperature of the air above the water changes. The antarctic waters and the temperate waters also differ in chemical composition and density, and they support different kinds of sea life. The 20- to 30-mile-wide zone all around Antarctica where these changes take place is known as the Antarctic Convergence.

5.D.2

A tabular iceberg is pushed to sea to clear channel to McMurdo Station. Icebreaker in foreground is 310 feet long.

As a boundary, the Antarctic Convergence is not completely satisfactory. It is not a precise line, and it moves constantly, especially from season to season. For that reason, the diplomats who negotiated the Antarctic Treaty in 1959 preferred to define the Antarctic as the land and water south of an imaginary but consistent circle, the sixtieth parallel south. To scientists, however, the Antarctic Convergence is useful as a boundary, even though its position changes. Because the Navy's role in the Antarctic is principally to support scientists, this pamphlet shall define the Antarctic as the region south of the Antarctic Convergence.

Seasons and Sunlight

The north and south polar regions do have things in common. Both are cold, and both have long days

in summer and long nights in winter. At the geographic poles there are six months of daylight followed by six months of darkness. (Daylight at the South Pole begins on September 21 and ends on March 21.) The periods of continuous daylight or darkness decrease as a person goes away from either pole until a line is reached, about $23\frac{1}{2}^{\circ}$ from the pole, where there is one summer day with no sunset and one winter day with no sunrise. In the Southern Hemisphere, this line is the Antarctic Circle. When it is summer in Antarctica, the South Pole is bathed in continuous daylight; at that time it is winter in the Arctic, and the North Pole is in continuous darkness. In the pages that follow, summer and winter will mean the seasons in the Southern Hemisphere.

While there are likenesses between the Arctic and Antarctic, there are also differences. Already mentioned is the fact that the Antarctic is a continent surrounded by oceans, while the Arctic is an ocean surrounded by land. From this important difference grow many others. The South Pole, for example, is on a high ice-covered plateau more than 9,000 feet above sea level, but at the North Pole there are only a few feet of ice drifting over some 10,000 feet of water.

Because Antarctica is a land mass, snow could pile up on it and compact into ice. As this ice layer increased in thickness—in some places to over 14,000 feet—its great weight caused it to push outward toward the oceans, grinding over the land beneath, pouring through mountain valleys in the form of glaciers, and often spreading out across the sea as ice shelves. Ice shelves are one of the distinctive features of the Antarctic, occupying over 540,000 square miles, and the largest of them—the Ross Ice Shelf—covers an area about the size of California. Ice shelves are attached to the land at the inside edge and float at the outside

Elevation of surface generally rises toward interior of continent.

Average temperatures in Antarctica show wide variation.

5.D.3

edge. As they push out to sea, great pieces break off and float away as flat-topped or tabular icebergs. Tabular bergs as big as Delaware have been sighted. The size of these icebergs so astonished early explorers that they called them ice islands.

Low Temperatures, High Winds

About 95 percent of the world's permanent ice is in the Antarctic: 7 million cubic miles of it. This great mass has made Antarctica the highest of all continents; its average elevation is about 7,500 feet. Antarctica is also the coldest and windiest continent. On August 24, 1960, the temperature at the Soviet Union's Vostok Station reached 126.9° below zero Fahrenheit, the lowest temperature recorded anywhere in the world. On July 20, 1968, scientists at Plateau Station recorded a low of -123.1° F., a record for United States stations.

Antarctic winds are famous in history. Early mariners soon learned that the oceans around the continent offer no obstacle to the storms that move from west to east. Indeed, the southern seas are the stormiest and windiest of the world. Accounts of land exploration are also filled with stories of great antarctic blizzards. The windiest area in Antarctica is the coast south of Australia; winds of over 100 miles an hour are frequent there. This happens because air above the high ice plateau of East Antarctica cools, and as it cools, it becomes heavier and flows down toward the sea, picking up speed as it goes. Such winds are called katabatic winds.

Three things stand out about the antarctic climate. First, a good deal of variation exists, as should be expected in an area of continental size. The average temperature at the South Pole is -60°F., while at the United States station on the Antarctic Peninsula it is a comparatively warm 26°F. Second, despite these rather wide differences, antarctic temperatures are all on the cold side as compared with those of the north polar area. The National Geographic Society reports that the average temperature in the Antarctic is 35°F. colder than in the Arctic. Third, there is extremely little precipitation. The high plateau that covers most of Antarctica is the world's largest and driest desert. The amount of water that falls as rain or snow varies from place to place: at the South Pole, on the central plateau, it amounts to less than 2 inches annually, while at coastal Palmer Station it measures about 23 inches. (By comparison, Phoenix, Arizona, in one of the driest parts of the United States, has an annual rainfall of 7.2 inches, and coastal New York City receives 42 inches.) In general, coastal areas receive slightly more precipitation, but even they are varied.

Although there is so much ice in Antarctica, there is almost no fresh water. Every other continent has at least one river over 2,000 miles long, but the closest thing to a river in Antarctica is a stream of meltwater from a glacier. Such a cold, dry area cannot support much life of any kind. On land, a few primitive plants exist, and there are bacteria and some insects and similar small animals. By contrast, the cold waters between the continent and the Antarctic Convergence abound in sea life ranging from microscopic plants to giant whales.

Edge of Ross Ice Shelf, seen from USS "Atka" in 1957, forms a cliff-like barrier at Little America V.

Antarctica Today

Even before the International Geophysical Year officially started, there had been talk of continuing the scientific program in Antarctica. The first proposal—to extend the IGY a year beyond the December 1958 closing date—was made in mid-June 1957 by United States scientists. Their colleagues in other countries reacted enthusiastically, and from that suggestion grew an expanded, long-range program which greatly influenced what Antarctica is today.

The decision to continue antarctic research had many consequences in many areas. Both the kind of scientific work done and the ways of planning and supporting it changed; the political status of Antarctica was discussed, and a treaty was signed; new logistic techniques were introduced; and, while some stations were closed at the end of the IGY, new and permanent ones were built, improving the way men live in the Antarctic.

A Committee and a Treaty

The first big step toward a long-range scientific effort was taken in September 1957. To continue the international scientific cooperation that was so important a feature of the IGY, the International Council of Scientific Unions established SCAR, the Special (since 1961, the Scientific) Committee on Antarctic Research. Members of SCAR represent either international scientific unions (which are organized according to fields of scientific study), or national academies of sciences. The committee develops broad programs in which it identifies subjects for investigation, establishes goals to be achieved, and describes uniform methods for collecting and presenting information.

LC-130s bring men, fuel, and supplies to the South Pole.

These programs differ in two significant ways from those of the IGY period. In the first place, they provide for work in biology, geology, and mapping. Second, they have no terminal date and are modified as knowledge increases and new scientific problems arise. The very existence of SCAR's long-range programs implies that an era of permanent occupation has arrived, not only along the Antarctic Peninsula, where Argentina, Chile, and the United Kingdom have been continuously active since the end of World War II, but also in many other parts of the continent.

Permanent occupation also made it desirable to regulate political relationships in the Antarctic. Prior to the International Geophysical Year, seven governments had laid claim to portions of Antarctica. They were Argentina, Australia, Chile, France, New Zealand, Norway, and the United Kingdom. Three of these claims—those of Argentina, Chile, and the United Kingdom—overlapped one another. The United States, which had explored more of Antarctica than any other country, had made no territorial claim of its own and did not recognize the claims of others, though it reserved the right to make a claim based on the activities of its citizens. The policies of the other nonclaimants, including the Soviet Union, were similar.

On May 2, 1958, the President of the United States sent a note to the 11 other governments supporting antarctic expeditions. In it he urged that a conference be held to arrange a political settlement. This invitation was accepted by all, and after a year of preliminary talks, a conference met at Washington, D. C., on October 15, 1959. Negotiations took about

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six weeks, and the Antarctic Treaty was signed on December 1, 1959. It became effective on June 23, 1961, when the last ratification was received. The Treaty remains in force indefinitely, and other nations may accede to it; since 1959, Czechoslovakia, Poland, Denmark, and the Netherlands have joined, raising to 16 the number of members.

Article I of the Treaty provides that the Antarctic "shall be used for peaceful purposes only." While it permits the use of military personnel and equipment for the support of peaceful activities, it prohibits military bases, military maneuvers, weapons testing, nuclear explosions, and the disposal of radioactive waste in the Antarctic. The Treaty does not affect the status of any existing claim to antarctic territory, but it does provide that no activity taking place while the Treaty is in force shall be used as the basis of a claim. In other words, the situation is frozen in the pattern that existed on June 23, 1961. The Treaty also endorses complete freedom of scientific investigation and encourages the full exchange of scientific information.

The Treaty requires a participating government to give advance notice to the others of expeditions going to the Antarctic, of all stations occupied by its nationals, and of any military equipment that it intends to introduce in support of peaceful purposes. To ensure observance of the Treaty's terms, all stations may be inspected at any time, as may ships and aircraft at points of loading and unloading in the Antarctic. The inspection provisions of the Treaty were

first applied in November 1963, when two New Zealand observers arrived at McMurdo Station. Many other inspections have been made since then, but no violations have been reported.

Because no document can possibly provide for all the problems that may arise, the Treaty states that representatives of the 12 signatory nations shall consult together from time to time. (Nations that have acceded may also attend if they are active in the Antarctic.) Such meetings have taken up a number of problems and have been notably successful in drawing up measures for the preservation of historic sites and the conservation of plants and animals. On the subject of conservation, the diplomats sought the aid of the scientists represented by SCAR. On their advice, the entire Antarctic—defined by the Treaty as the area south of 60°S.—was designated a special conservation area in 1964. In 1966, at the Fourth Consultative Meeting, certain localities of special biological interest were recommended for special protection, as were the rare Ross and fur seals. Except for whales, the catching of which is regulated by another international agreement, the wildlife of the Antarctic appears to be adequately protected against the depredations of man.

The Antarctic Treaty, which was largely made possible by the spirit of cooperation that developed during the IGY, has been a real landmark in a frequently troubled world. When a treaty regarding the future of outer space was negotiated at the United Nations in 1966, the Antarctic Treaty provided precedents for several of its provisions.

Shackleton's hut at Cape Royds (l.), built in 1908, and Scott's 1911 hut at Cape Evans (r.) are protected as historic sites under the Antarctic Treaty, as is Scott's 1902 hut near McMurdo Station. All three buildings are on Ross Island. The view at right shows how distances can be deceptive in the Antarctic: Mt. Erebus (in background) is over 13 miles distant from Scott's hut.

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clined from over 60 to about 40. Norway withdrew in 1960 and transferred its station to South Africa, which renamed it SANAE, for South African National Antarctic Expedition. The Belgians suspended operations at Roi Baudoin Base in 1961 but resumed them again in 1963 with the assistance of their neighbor, the Netherlands. At the end of the 1966-1967 season the base was closed for a second time. The Japanese closed down Showa in February 1962 because they lacked a suitable ship to penetrate the ice. They returned in 1965 with a newly built icebreaker, *Fuji*, thus becoming the third nation to operate this type of ship in antarctic waters (after the United States, in 1946, and Argentina, in 1954). In reducing its program, the Soviet Union arranged to transfer Oazis to Poland, but the Poles have occupied the base only briefly.

The United States withdrew from Ellsworth and Wilkes Stations and made them and their equipment available to other nations at the end of the IGY. Australia used Wilkes as long as the buildings remained habitable and then built a replacement station nearby. Argentina assumed custody of Ellsworth and operated it until 1962, when it was overwhelmed by snow and ice and closed down. The fate of Ellsworth Station typified the problem of using temporary stations for permanent occupation. Of the seven stations built by the United States for the International Geophysical Year, only Hallett and McMurdo were not threatened by snow. Both remain in use though Hallett was reduced to summer-only status at the end of *Deep Freeze 65* (1964-1965).

Station Construction

Through the time of the IGY, most expeditions planned to remain in Antarctica for only a year or two, and drifting snow was not a great concern in station construction. In fact, it could be turned to advantage. Admiral Byrd did this by placing his buildings on the surface and connecting them with enclosed passageways made of 2- by 4-inch boards over which he stretched chicken wire and burlap. The drifting snow soon turned these corridors into tunnels in which supplies could be stored and through which men could walk without exposure to the weather. But over the years, the snow builds up and gradually turns to ice. This accumulation not only crushes the roofs from the top but also moves against the sides and the floors—the effect is like the closing of a giant vise. Built in 1955-1956, Little America V had to be closed down in 1959 before it actually collapsed.

Most of the stations built on ice shelves or on the polar plateau for use during the IGY were constructed in this fashion, and many have had to be abandoned or replaced. To solve the problem of snow accumulation, several designs have been tried out, both in

Changes in National Programs

There were also some changes within national programs as the various governments adjusted to long-term research. In the United States, for example, the management of the scientific activity was shifted from the National Academy of Sciences to the National Science Foundation, which established an Office of Antarctic Programs. The National Academy, however, continued to participate in antarctic science through its membership in SCAR and its Committee on Polar Research. This committee, under the continued leadership of Dr. Gould, represents the United States scientific community and recommends programs for the consideration of the National Science Foundation.

Adjustment in the United States system was also evident in a new way of numbering the Navy's annual logistic operations. *Deep Freeze IV*, which was originally to have evacuated the IGY stations during the 1958-1959 summer, was the last support operation to bear a roman numeral. Starting with *Deep Freeze 60* in 1959-1960, United States logistic operations are numbered to correspond to the Federal Government's fiscal years, which—like the antarctic summer—start in one calendar year and end in the next.

The expense of antarctic operations caused the most obvious adjustment: many nations, including the United States and the Soviet Union, reduced their programs and the number of stations they operated. Although 10 of the 12 nations that had expeditions in the Antarctic during the IGY still supported antarctic operations in 1967, the number of stations de-

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AFTER AMERICAN GEOGRAPHICAL SOCIETY'S ANTARCTIC MAP FOLD SERIES

Stations occupied in winter of 1969 plus the two U.S. summer stations, Brockton and Hallett.

By November 1959, the relentless ice had bent the steel roof beams of Little America V and dripped through to form stalagmites.

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In building new Byrd Station, trenches cut by a Sno-Miller...

were covered with metal arches...

to form tunnels in which prefabricated buildings were placed.

Antarctica and in Greenland, where a similar condition prevails.

Some expeditions dug trenches in which buildings were placed. It was hoped that the snow would blow across the covered trench with minimum accumulation. The United States Army adopted an elaborate form of this technique in building Camp Century on the Greenland Ice Cap. When the original Byrd Station threatened to collapse after four years of use, the Navy copied this type of construction in building a new one. Trenches were first dug, then covered with metal arches, and finally the snow was blown back across the arches to create a level surface over the tunnels. Insulated buildings were erected in the tunnels with space left for walkways, thus creating a veritable village under the snow. Only exhaust stacks, radio antennas, and scientific observatories appear above the surface. A variation of this technique was used to prolong the life of Amundsen-Scott South Pole Station, which was also being threatened by accumulating snow.

Another approach developed for Greenland has had limited use in Antarctica. It involves elevating the building above the surface on columns. Even though most of the snow blows past beneath the building, some does gradually accumulate. When this happens, the building may be raised by extending the columns while jacking the building up. This type of construction is quite expensive and is worthwhile only where the accumulation problem is very severe. The rate of snow accumulation in Antarctica varies considerably from place to place. In 1929, Admiral Byrd installed a 75-foot radio tower at the Bay of Whales. Thirty years later to the month, only four feet remained above the surface. On the other hand, at the Soviets' Vostok Station on the plateau, there has been virtually no snow accumulation in 10 years.

Prefabricated buildings are commonly used in Antarctica; and for small stations, vans called wanigans have often been used. Looking like house trailers on skis, they are pulled into place by tracked vehicles. Vostok is an example of this construction, as is Little Rockford, a United States summer weather station established in 1958 and abandoned early in 1965. Because the wanigans can be moved, it is possible to relocate them on the surface as snow piles up.

Further development of the van concept came during *Deep Freeze 63* (1962-1963) when the United States built Eights Station, named for James Eights, the first American scientist in the Antarctic. Vans that could be joined together at the construction site were built to fit into an LC-130F cargo plane. Each unit was fully furnished for its intended use before it was flown from McMurdo Station to a site near the base of the Antarctic Peninsula. There, eight such units, mounted on skids, were pulled by a tractor into parallel rows of four each. Flooring was placed

A Station is Built

① A station van is unloaded from USNS "Towle" onto a tractor-drawn sled waiting on the bay ice of McMurdo Sound.

④ The vans are placed on the foundation leaving a "permawalk" area between that will later serve as a central room.

② At Williams Field, the "airport on ice" near McMurdo Station, the van is checked and outfitted with special equipment. When ready, each van is loaded into an LC-130. The vans' outside measurements were based on the dimensions of this aircraft's cargo compartment.

⑤ After the four vans are emplaced, a ceiling is constructed over the permawalk, and an observation tower is added. During the construction of this station, repeated LC-130 flights brought fuel to fill the two 25,000-gallon rubber storage bladders.

③ Delivered to the site on the polar plateau, the van is pulled from the airplane onto a specially designed platform. The ski-equipped platform and the van are then towed to a prepared foundation.

⑥ Once the building is completed, the scientific instruments are readied, the radio equipment is made operable, and the emergency camp (in the background) is checked out. Plateau Station is ready for the winter.

Annual snow accumulation is a major consideration in station construction. In general, accumulation decreases from the coast toward the interior.

between the rows and the whole complex was roofed over to form a large building of eight rooms around a central hallway.

Bases made of vans are easy to construct and can be disassembled and moved. This was not done at Eighties, but a similarly constructed summer weather station was brought back to McMurdo in 1966 and relocated the following season. Two other stations of this type were built in *Deep Freeze 66* (1965-1966). One was a small substation about 12 miles from Byrd Station. The other was built some 600 miles beyond the South Pole from McMurdo Station. Located on a featureless snow plain at 12,000 feet altitude, this most remote of United States stations was named Plateau Station.

In working out the design of Plateau Station, an effort was made to get away from the usual austerity of "frontier" buildings and furnishings in order to make the station as homelike as possible. Pleasant surroundings are important to men isolated far from their families for many months of the year. For this reason, comfortable design has been one of the features of United States station development, and it is not limited to newly constructed stations; conveniences have been added to the IGY stations that were renovated for permanent occupancy. In addition, station development plans have stressed greater logistic efficiency and more up-to-date scientific facilities. The expeditions of other countries have developed similar programs, and over the years, living and working conditions in the Antarctic have steadily grown better.

Nowhere is the contrast between past and present construction more evident than on Ross Island in McMurdo Sound. Here, only a short distance from McMurdo Station, stand the camps built by Scott in 1902 and Shackleton in 1908. They are little more

In October (Photo above), Scott's 1902 hut and McMurdo Station are separated by frozen anchorage. The PM-3A nuclear power plant is on side of Observation Hill, to right of pass leading to New Zealand's Scott Base. The 1969 aerial view at right shows extent of construction at McMurdo. The large building in the center is the new personnel building designed to house the winter-over group.

than wooden shacks, once briefly occupied and then abandoned. McMurdo, by contrast, has become a small city. Its original function as a logistic base has steadily increased, and it took over some of the scientific program from Little America V. Today, McMurdo has a church, a store, movies, and a gymnasium and is the biggest United States station: its summer population averages over 800 and about 200 people spend the winter there. As a result, it also has the sanitation and public health problems of community living—but aggravated by the peculiar conditions of the Antarctic, especially the scarcity of water.

Water, Fuel, and the Atom

In the past, no commodity was more precious in Antarctica than water. It is still difficult to obtain, even though 95 percent of the continent is covered with snow and ice. In the few areas where natural melting occurs in summer, it is possible to obtain

Hallett Station shares this lonely sand spit with an Adélie penguin rookery.

water from ponds, but in winter, other means must be used. The most common is to melt snow by heating it.

Often the snow melter is built around the exhaust pipes from the electric-generator engines, thus using heat that would otherwise be wasted. This method, however, is not sufficient for a station the size of McMurdo, and additional snow melters with their own oil-fired burners had to be used to supply the difference. As a rule, small stations can handle the problems of water supply and sanitation without elaborate equipment, but there are exceptions. Hallett Station, for example, is located on a sand spit that is also the site of an Adélie penguin rookery. The snow, therefore, is often contaminated. Since its construction in 1957, Hallett has had fuel-burning evaporators to desalt seawater, as well as conventional snow melters. The French at Dumont d'Urville Station had the same problem and in 1967 installed a distillation plant. On ice shelves and on the polar plateau, there is unlimited snow and no source of contamination, except the occupants of the station, who can be controlled.

Water from the snow melters is carefully rationed. Digging and carrying snow is arduous work, especially in nasty weather. Beyond that, all fuel to melt snow, heat buildings, generate electricity, and to power vehicles and aircraft must be imported into Antarctica over great distances and at considerable expense. In fact, fuel is the largest single item in the shipping of all expeditions. During *Deep Freeze 67*, for example, over 2 million gallons of diesel and automotive fuels were delivered to the United States stations; another 4 million gallons were brought in for aviation use.

To reduce the amount of fuel consumed in generating electricity, a nuclear reactor was installed at McMurdo Station in 1962, and this provided the opportunity for an improved water system. The nuclear power plant has not provided the economy hoped for, but after some initial difficulties, it has worked well. Heat from the reactor is used to desalt seawater pumped from McMurdo Sound. The distillation plant was tested successfully in February 1965 and became fully operational in December 1966. It furnishes a maximum of 110,000 gallons of fresh water weekly and is equipped with its own oil-fired burners so that operation will not cease when the nuclear power plant is shut down or when excess steam is not available.

Control console of PM-3A nuclear reactor.

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Installation of the distillation plant was accompanied by the construction of water-distribution and sewer systems. Some difficulties have been encountered in keeping the freshwater lines from freezing, even though they are protected with electrical heating tape. If the pipes freeze, water would be trucked from the distillation plant to the station buildings.

The scarcity of water helps make fire a great danger in Antarctica, perhaps the greatest single danger. Fire can destroy the buildings that shelter men and the food that sustains them. For that reason, an antarctic station usually consists of several separate buildings, and supplies are stored where they will not catch fire. Many bases have a refuge hut some distance from the main living quarters. If chemical fire extinguishers do not stop the fire and the base is destroyed, the men can retreat to the refuge, which is stocked with food and other supplies. They would be terribly crowded and they would have to ration their food carefully, but they could survive until a plane or ship came to their rescue.

Largest U.S. icebreaker, 8,775-ton USCGC "Glacier," in brash-filled channel to McMurdo. In 1965 and 1966, the Navy transferred all its icebreakers—including "Glacier"—to the Coast Guard.

Ships for Support

Fuel and most dry cargo are brought to Antarctica by ship. In recent years, the United States has had two tankers and several cargo ships plying the route to Winter Quarters Bay at the foot of McMurdo Station. Early in the season, a channel is cut for these ships by the icebreakers. Ideally, the V-shaped channel is several miles wide at its entrance and gradually narrows to several hundred yards at McMurdo's harbor, but varying conditions of ice and weather often change the plan.

To cut a channel, an icebreaker charges forward and rides part way up onto the ice so her weight can break it. The engines are quickly reversed to avoid getting stuck. This is repeated to left and right of the first cut. Often a second icebreaker weaves back and forth across the channel to keep the broken ice, called

brash, from refreezing—man may design ships to break the ice, but he must depend on nature to blow it out to sea. Cutting a channel to McMurdo may take three or more weeks. Over the past years, much has been done to increase the fuel storage capacity at McMurdo. This will allow the tankers to come later in the season, saving icebreaker effort. As summer advances, ice conditions grow less difficult and dangerous, and the Coast Guard icebreakers may be released from escort duties to perform other tasks, such as oceanographic surveys.

Tanker "Alatna" (right) is escorted to McMurdo with load of aviation fuel.

Aircraft are Invaluable

While ships still play an essential role, both logistics and research in Antarctica have been revolutionized by the airplane and the helicopter, especially the ski-equipped Hercules (LC-130) and the turbine-powered helicopter.

As we have seen, when the United States built the station at the South Pole during *Deep Freeze II* (1956-1957), it depended solely upon airdrops for the delivery of equipment and supplies. For the construction and support of Byrd Station, however, it relied mainly on tractor trains operating from Little America V. When Little America V was closed in 1959, aircraft took over the support of Byrd Station as well.

Parachuting and free-dropping cargo from the air was effective, but it had certain drawbacks. Most notably, it placed a heavy burden on the small complements of the inland stations who had to recover the scattered material, haul it to the station, and then store it; handling 55-gallon fuel drums is a back-breaking job. Also, the same lack of ski-equipped airplanes that forced the use of airdrops meant that expensive parachutes and other drop gear usually could not be recovered and reused.

In January 1960, the U. S. Air Force brought the first ski-equipped C-130 cargo planes to Antarctica and operated them out of McMurdo Station. These

aircraft, capable of landing on flat areas anywhere in the Antarctic, proved so useful and versatile that the Navy obtained four ski-equipped Hercules later that year. Brought into service during *Deep Freeze 61*, these LC-130s were at first used to resupply South Pole and Byrd Stations with dry cargo while Air Force C-124s went on air-dropping petroleum products to these inland stations. Such airdrops continued through *Deep Freeze 63* (1962-1963), after which there was no direct Air Force support to the inland stations. During *Deep Freeze 63*, a new system was successfully tested, and since *Deep Freeze 64*, Navy LC-130s have flown fuel inland in metal tanks of 3,600-gallon capacity. At the stations, the fuel can be pumped directly from these fuselage tanks to rubber storage bladders in a matter of minutes.

With special fuselage tank, LC-130 can carry fuel to stations or extend its own range.

The logistic usefulness of the Hercules was also demonstrated during the 1961-1962 season when five LC-130 flights carried all the building materials, equipment, and supplies needed to establish a summer scientific station, called Sky-Hi, more than 1,500 miles from McMurdo. It was this success which led to the development of air-transportable van-type stations such as Eights and Plateau.

Earlier, the LC-130 had revolutionized field-party support. On December 10, 1960, two of these aircraft placed in the field a party of nine men with 10 tons of equipment, including vehicles, at a distance of 1,300 miles from McMurdo. When recovered at the end of a season, such a party may either leave its vehicles where it plans to resume work the following year or have them flown back to a station for overhaul and repair.

Besides helping him in the field, the airplane makes the scientist's whole year more productive. Formerly, a scientist wishing to do field work arrived in Antarctica one season, spent the winter at a station, and took to the field the following spring. Now, he can leave the United States in October, reach the field

Artist's concept of June 1966 emergency flight to McMurdo Station.

early in November, conduct his studies, and return in February—accomplishing in 4 or 5 months what previously required 18. In 1967, the United States experimented with flying a small group of scientists to McMurdo Station in June, in the depth of the antarctic night, and bringing them back in August or early September, at the conclusion of the summer vacation of Northern Hemisphere colleges and universities. This permits antarctic work by scientists who could not otherwise journey to Antarctica.

Winter flights are not without precedent. On April 9, 1961, an LC-130 flew to Byrd Station to evacuate a Soviet exchange scientist who had become ill. Three years later, on June 26, 1964, another mercy mission brought out a severely injured sailor. In 1966, two similar flights were made, one to McMurdo on June 6, and the other to Byrd on September 13.

Helicopters were introduced into the Antarctic in 1947 on *Operation Highjump*. Based on ships, they were used for ice reconnaissance and as ship-to-shore transports. During the IGY and later years, additional helicopters—based on shore—were employed to place biologists and geologists in the ice-free areas around

Turbine-powered UH-1 helicopters allow geologist to do in hours what previously required days.

Photo-mapping

Tri-camera installation in C-121J Super Constellation took this panoramic photo in the Queen Alexandra Range. Turn page left and right to view side pictures. Note crevasses caused by ice flow.

The airplane has further enlarged man's picture of Antarctica by serving as a photomapping aircraft. Equipped with three precision cameras—one aimed straight down and one each at an angle to the left and right, a photo plane flies a carefully calculated path. The path is based on many factors, but the primary one is usually the position of the sun. Shadows hide details, so the more rugged the terrain, the more crit-

ical is the sun's position. Also, the plane must fly more or less toward or away from the sun to prevent it from shining directly into one of the cameras aimed to the side. Operating over West Antarctica during the 1966-1967 season, a Hercules and a C-121J Super Constellation obtained mapping-quality photographs of about 335,000 square miles, almost double the 1964-1965 amount, the previous record.

McMurdo Sound and to move them from one place of scientific interest to another. Piston-powered helicopters, however, could not fly far enough or high enough to support remote field investigations in mountainous areas or on the polar plateau.

During *Deep Freeze 62* (1961-1962), the United States Army sent two turbine-powered UH-1 helicopters to Antarctica. These machines could land at heights up to 13,000 feet, thus overcoming the altitude problem, and they could fit into an LC-130, thus overcoming their lack of range. They were first used in making topographic surveys and later adopted for geological investigation. From 1965 to 1969, the Army annually provided a detachment of three such helicopters to support field surveys by up to 20 scientists. In April 1969, the detachment's three UH-1s were transferred to the Navy for operation beginning in *Deep Freeze 70*.

Although airplanes and helicopters have opened vast areas of the Antarctic to man's curious eyes and mind, they do have their limitations. They must have good weather in a region notorious for bad weather. Even with skis, airplanes cannot land everywhere; helicopters, which might, lack the range. Compared with the size of Antarctica, even the range of the LC-130 is small—and in transporting fuel to extend its range, it consumes large amounts of this precious liquid. Finally, aircraft must have many facilities on the surface if they are to operate dependably and safely. Despite all this, aircraft have clearly established themselves as the most valuable resource of the United States antarctic program.

The United States has made the greatest use of aviation in the Antarctic, but it has not been alone. Many expeditions employ light planes and helicopters

Two U-6 Beavers wait at South Pole for companion Argentine C-47 to return from transcontinental flight to McMurdo in November 1965.

carried aboard ships, and some use larger airplanes. The Argentines, British, and Chileans have operated aircraft around the Antarctic Peninsula, and Argentine aircraft have twice visited the South Pole. On the second of these flights, one Argentine C-47 continued across the continent and landed at McMurdo. The Soviet Union supplements tractor-train support of its inland stations with aircraft, and on two occasions it has sent airplanes to coastal Mirny by way of McMurdo Station.

Surface Travel

The use of aircraft has not ended travel on the snow and ice. Some scientific work, such as taking closely spaced seismic soundings, is best done on a traverse with tracked vehicles pulling sleds across the great white wastes. Like the equipment used by Fuchs on his IGY traverse across the continent, present-day antarctic vehicles are virtually self-contained. They provide living quarters and working spaces for those doing research. Frequently, they are resupplied on the trail with fuel, food, and other necessities by aircraft. Even with all these improvements, some expeditions continue to use dog teams, particularly in mountainous areas, and some groups working near their camps manhaul their sleds as Scott and Shackleton did. Increasingly, however, dogs are being replaced by lightweight motor toboggans. These are easy to maintain—and, unlike dogs, they do not have to be fed when they are not working.

Antarctic travel remains difficult and dangerous. Great blizzards may start suddenly and last for days, bringing the mightiest vehicle to a halt. Even when the snow lies still, travel may be stopped by a white-out: under special conditions, light bounces back and forth between the snow and clouds until all shadows and the horizon disappear, confusing men's sense of direction and distance. There is also the danger of crevasses. These cracks in the ice may be only a few inches across—or they may be very wide and more than a 100 feet deep. They are not so dangerous when the traveller can see them, but snow often drifts over the top to form a bridge. If too much

Motor toboggan, the modern substitute for a dog team, can haul up to 1,000 pounds.

Sno-Cats are well equipped for traverse living.

Crevasse detector, mounted on Sno-Cat, uses radio signals to locate danger.

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weight is applied, the bridge gives way. Where it is impossible to detour around a crevasse, it is customary to blast it open and fill the abyss with enough snow to make a safe bridge.

Antarctic Clothing

On the trail or elsewhere, it is important for men in the Antarctic to dress for the occasion. On a calm day with the sun shining, men may be seen working outdoors in their shirt sleeves. Even a slight wind, however, will cause them to add outer garments—the wind literally blows away their body heat. The combined effect of wind and temperature is called the wind-chill equivalent. For example, when the thermometer reads 0° Fahrenheit and the wind is blowing 10 miles per hour, the effect on a man is the same as if the temperature were -21°F. without a wind.

Because of the effect of the wind, the outermost layer of clothing should be windproof. Under this outer garment, a man should wear only as many other layers of clothing as he needs to keep warm. Air trapped between the layers serves as insulation against the cold, but too many layers may be dangerous: perspiration diminishes the insulating quality of clothing. Hands, feet, nose, and ears are very susceptible to freezing and must be protected. Gloves are worn and, if it is really cold, thick mittens are drawn over them. Several types of cold-weather boots exist that will furnish adequate protection. Caps are usually equipped with earflaps, and coats and parkas have hoods which may be raised over the cap. Sometimes a face mask is needed to protect the nose and cheeks.

Properly dressed and with modern equipment, men can live in the Antarctic quite comfortably. Antarctica remains, however, a dangerous and unpredictable land, and a moment of carelessness can easily

cost a life. To survive there, men must never relax their guard. Yet men from many countries will continue to go to the Antarctic in pursuit of knowledge.

Cotton shirt and trousers may be adequate for a mild summer day at coastal locations, but windproof garments are usually needed. To counter bad weather, "bear paw" mittens and bulky thermal boots are added to outfit.

Most American personnel are transported between New Zealand and McMurdo by C-121J Super Constellation.

Antarctica Tomorrow

Even with the tremendous effort since 1955 to unlock its secrets, Antarctica remains the least known of continents. This fact alone should ensure that explorer-scientists will be going south for a long time, but still another factor is at work. In 1966, Peter Scott, son of the famous Captain Scott, visited the Antarctic. He pointed out that half the scientific research now drawing people to the area is on topics not even guessed at in his father's day, and he predicted that new fields requiring polar research will continue to appear. The future of the Antarctic is strongly linked to the future of science itself.

Even now, scientists are developing techniques which will broaden their horizons and suggest to their imaginations new subjects for antarctic research. There are, for example, data-recording machines powered by radioactive isotopes. Thus far, they have been used primarily as automatic weather stations, and some difficulties have been encountered in getting them to operate properly in the antarctic environment. These problems, however, can be solved, allowing expanded use of such devices. A network of automatic stations would offer the meteorologist a manyfold increase in the number of observations available for both forecasting and the study of climate. Similar data-recording machines can be used in other studies. They could, for example, make almost all the observations that have been taken at Plateau Station by upper-atmosphere physicists—without risking the lives of eight men in an isolated spot where accident or illness might have tragic consequences.

Satellites in polar orbit offer other possibilities. By radio, satellites could receive information from automatic observatories in Antarctica and retransmit it to laboratories and weather centers around the world. At least one experience indicates that satellites may also help to solve one of the great problems in antarctic operations: loss of communications. A magnetic storm that began in late January 1967 blocked most radio transmissions for almost a week,

Satellites in polar orbit promise a comprehensive view of the Antarctic. Here, subequatorial Africa is at top right, Australia at bottom right.

Atomic-powered weather station has been used in Antarctica since 1962.

but signals from a photographic weather satellite were regularly received at McMurdo Station throughout the blackout. Satellites already have their place in antarctic meteorology, and geophysical satellites passing over the area have obtained information unavailable to observers on the ground. Other uses will certainly arise. Already there are plans to use satellites in geodetic research, especially for pinpointing the location of geographic features. Satellites carrying different sensing equipment appear to have numberless uses in the Antarctic.

Very little is known about the ice pack, the floating belt of sea ice that surrounds the continent—perhaps less than about any other antarctic phenomenon. Although satellites orbiting a hundred or more miles up can play a part here, a closer look will also be necessary. Much can be done by icebreakers carrying helicopters, but scientists would like to look under the ice as well. Submarines have been used for research in the Arctic, and many small submersible research craft are under development. In the future, small submersibles, perhaps carried by an icebreaker, will undoubtedly be used in antarctic waters.

The future of the Antarctic as a scientific laboratory seems assured, but what of its natural resources? The most easily reached are those of the sea. Since the 1890s, the whales of the southern oceans have been hunted for their oil and meat. International agreement, however, has failed to adequately protect the stocks, and whaling is a declining industry—perhaps a dying one. While it might be possible under careful regulation to harvest seals and penguins, history discounts the promise. There are, though, the vast quantities of plankton on which most antarctic

life is based, and the Japanese and Soviets have been investigating whether plankton can be used for human nourishment. With the rapid growth of population in all parts of the world, every source of food will be needed, and the abundant life of the southern seas may contribute notably to the future of mankind.

Development of Antarctica's mineral resources is a remote event. At present, both the nature of these resources and their extent are imperfectly known; it will take time and much detailed geologic investigation to catalogue them. Even if the mineral resources prove to be valuable, the techniques for exploitation do not now exist. In a society characterized by rapid technological advance, it would be unwise to say that the necessary techniques cannot be developed, but it would be equally foolish to predict when this will occur.

Some prophets have imagined Antarctica crisscrossed by air routes connecting the nations of the Southern Hemisphere. That such flying can be done—with or without a stop in Antarctica—has been shown several times. Flights from New Zealand to Antarctica have been regularly conducted since 1955, and in September 1963, two United States Navy LC-130s flew from Capetown, South Africa, to McMurdo Station. The following year, an LC-130 made the flight from Punta Arenas, Chile, and another flew from Melbourne, Australia, to Byrd Station. In November 1966, a standard jet airliner made a nonstop flight from Buenos Aires, Argentina, to Christchurch, New Zealand. But to establish regular commercial air service across Antarctica, even though the flights were nonstop, would require alternate landing fields and better navigational aids and communications facilities

Sub-ice observation chamber (being readied for use at left) and scuba diving (right) allow only a peek beneath the sea. Scientists hope to probe wider area and greater depths with minisubs.

than now exist. Only a considerable quantity of air traffic could justify the expense, and the probability of this is slight. Examining a map of the world shows why. The principal land masses of the Earth, and hence the largest share of its population, are in the Northern Hemisphere. It is doubtful at present that the people living in the Southern Hemisphere can generate enough demand for air transportation between their continents to make transantarctic air routes profitable.

Tourism is one nonscientific activity that is already established and growing, though not sufficiently to pay for airfields, hotels, and other facilities. Tourist ships have visited the Antarctic Peninsula area since 1958. Travelling by ship has the advantage that tourists can live on board and do not require shore accommodations. Cruises to other areas seem quite possible. Historically, expeditions have been able to penetrate the Ross Sea, and visits to this area are certainly feasible with existing ships which, while they are not ice-breakers, have been strengthened to sail in the pack ice. Such ships under charter to Australian, Belgian, British, French, and South African expeditions have reached the coast at many points. So likely did an expansion of tourism appear to the delegates at the Fourth Consultative Meeting of the Antarctic Treaty powers—in Santiago, Chile, in 1966—that they adopted a recommendation to regulate it.

The Antarctic, then, has modest prospects for tourism, and its seas have real possibilities as a source of food, but the pursuit of scientific knowledge will long

be its main attraction. Scientific data will remain the chief export, and the men who obtain it will continue to be the principal inhabitants. No monetary value can be placed on scientific discoveries, but anything which expands man's understanding of his environment will help him improve his condition. If this should be the only value of Antarctica, it is value enough.

Successfully tested in a November 1966 flight to McMurdo, the giant pure-jet C141 Starlifter transport was put into regular use in "Deep freeze 69."

SUGGESTIONS FOR FURTHER READING

A few of the many books written about the Antarctic are listed below. This selection is limited to books which were published in the United States and enjoyed a fairly wide circulation. No attempt was made to survey periodicals, but the *National Geographic Magazine* and the *Geographical Review* have, over the years, printed many articles on the Antarctic.

What is Antarctica?

Hatherton, T., ed. *Antarctica*. New York, 1966. This book is a series of discussions on all aspects of antarctic scientific activity by authorities in the various fields.

Ley, Willy, and the Editors of *Life*. *The Poles*. New York, 1962. A popular account, lavishly illustrated, of what is known about the polar regions.

Scientific American, September, 1962. The entire issue is a summary of what scientists had learned about the Antarctic, including their discoveries during the International Geophysical Year.

Antarctic Animals and Plants

Billing, G. *Forbush and the Penguins*. New York, 1966. This novel contains much information on Adélie penguins.

Marret, M. *Seven Men Among the Penguins*. New York, 1955. Leader's story of a French expedition (1951-1953) to Adélie Land; contains interesting information on emperor penguins.

Robertson, R. B. *Of Whales and Men*. New York, 1954. An account of a British whaling voyage with much information on whales and whaling techniques.

What Men Do in Antarctica

Eklund, C. R., and J. Beckman. *Antarctica*. New York, 1963. A brief, simple explanation of science in the Antarctic.

Francis, H. S., Jr., and P. M. Smith. *Defrosting Antarctic Secrets*. New York, 1962. An explanation at the high-school level of scientific activities by two participants.

Lewis, R. S. *A Continent for Science*. New York, 1965. A clear, nontechnical account of scientific activities in Antarctica and the results.

The Age of Discovery

Amundsen, R. *The South Pole*. 2 vols. New York, 1913. About the Norwegian expedition (1910-1912) that discovered the South Pole.

Amundsen, R. *My Life as an Explorer*. New York, 1927. Autobiography by the great Norwegian explorer.

Andrist, R. K. *Heroes of Polar Exploration*. New York, 1962. A popular, profusely illustrated account of exploration in both polar regions.

Balchen, B. *Come North with Me*. New York, 1958. This polar aviator's autobiography includes his experiences as a pilot for Ellsworth and Byrd in Antarctica.

Berchervaise, J., and P. Law. *ANARE*. New York, 1957. A discussion of Australia's antarctic activities from 1947 to 1957.

Byrd, R. E. *Little America*. New York, 1930. Byrd's story of his 1928-1930 expedition.

Byrd, R. E. *Discovery*. New York, 1935. Admiral Byrd's account of his second antarctic expedition (1933-1935).

Byrd, R. E. *Alone*. New York, 1938.* Byrd's impressions of the months in 1934 that he passed alone in a weather station 123 miles from Little America.

Cherry-Garrard, A. *The Worst Journey in the World*. New York, 1930. A well written account of Scott's second expedition (1910-1913) by one of the survivors.

Ellsworth, L. *Beyond Horizons*. New York, 1937. This autobiography includes both his arctic and antarctic experiences.

Fisher, M. and J. *Shackleton and the Antarctic*. Boston, 1957. An excellent biography.

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- Giaever, J. *The White Desert*. New York, 1954. Official account of the Norwegian-British-Swedish Expedition (1949-1952) by its leader.
- Gould, L. M. *Cold*. New York, 1931. A description of Byrd's first expedition (1928-1930) by its chief scientist.
- Grierson, J. *Challenge to the Poles*. Hamden, Conn., 1964. A definitive history of aviation in both polar regions to 1954.
- Grierson, J. *Heroes of the Polar Skies*. New York 1967. This book for teenage boys contains good biographical sketches of Amundsen, Byrd, Ellsworth and Wilkins.
- Hoyt, E. P. *The Last Explorer: The Adventures of Admiral Byrd*. New York, 1968. A well-written fast-moving account of Byrd's life.
- Huxley, L., ed. *Scott's Last Expedition*. 2 vols. New York, 1923. About the 1910-1913 expedition on which Scott lost his life. Vol. I* is Scott's diary—a classic of antarctic literature. Vol. II contains first-hand accounts of other expedition activities.
- Kirwan, L. P. *A History of Polar Exploration*. New York, 1962. This is especially good in relating exploration to technical, social, and political developments.
- Lansing, A. *Endurance*. New York, 1958.* A stirring retelling of Shackleton's epic voyage of 1914-1916.
- Mawson, D. *The Home of the Blizzard*. 2 vols. Philadelphia, 1915. An account of the Australasian Antarctic Expedition of 1911-1914 by its leader. Well illustrated.
- Mitterling, P. I. *America in the Antarctic to 1840*. Urbana, Ill., 1959. Covers the early sealers and the Wilkes expedition (1838-1840).
- Mountevans, Admiral Lord. *The Antarctic Challenged*. New York, 1955. A history of the Antarctic up to the IGY by a veteran of Scott's second expedition (1910-1913).
- Nordenskjold, N. O. G., and J. G. Andersson. *Antarctica*. New York, 1905. An account by the leaders of the important Swedish expedition of 1901-1904.
- Quartermain, L. B. *South to the Pole*. New York, 1967. A definitive and very readable history of discovery and exploration in the Ross Sea sector of Antarctica.
- Ronne, F. *Antarctic Conquest*. New York, 1949. About Ronne's Antarctic Research Expedition (1947-1948), which included the first two women to spend a winter in Antarctica.
- Scott, R. F. *The Voyage of the "Discovery."* New York, 1907. About the British National Antarctic Expedition (1901-1904); Scott wrote extremely well.
- Scott, R. F. *Scott's Last Expedition*. New York, 1964. A reprint of Scott's diary with notes by his son and other material.
- Shackleton, E. H. *The Heart of the Antarctic*. 2 vols. Philadelphia, 1909. The story of the British expedition (1907-1909) that discovered the South Magnetic Pole and came within 113 miles of the South Pole.
- Shackleton, E. H. *South!* New York, reprinted 1962.* A fascinating narrative by the leader of the remarkable expedition of 1914-1917.
- Siple, P. A. *A Boy Scout with Byrd*. New York, 1931. Byrd's first expedition (1928-1930) as seen by its youngest member, who grew up to be one of the antarctic experts.
- Siple, P. A. *From Scout to Explorer*. New York, 1936. Byrd's second expedition (1933-1935) is described by the young scientist who had been on the previous Byrd expedition as a boy scout.
- Thomas, L. *Sir Hubert Wilkins*. New York, 1961. A biography of this great polar explorer.
- Walton, E. W. Kevin. *Two Years in the Antarctic*. New York, 1955. This review of British antarctic activity from 1946 to 1948 contains a good description of sledging with dogs.
- Wilson, E. *Diary of the "Discovery" Expedition*. New York, 1967. A personal record of Scott's first expedition (1901-1904) by a participant who was a very fine artist as well as a physician and a distinguished scientist.

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All-Out Assault: The IGY

Dufek, G. J. *Operation Deep Freeze*. New York, 1957. An account of *Deep Freeze I* (1955-1956) by the then commander of the U. S. Naval Support Force, Antarctica; it includes a description of the first aircraft landing at the South Pole.

Dufek, G. J. *Through the Frozen Frontier*. New York, 1959. An account, for older children, of *Deep Freeze I* (1955-1956) and *Deep Freeze II* (1956-1957) by the U. S. Navy admiral involved.

Fuchs, V., and E. Hillary. *The Crossing of Antarctica*. Boston, 1958. The story of the British Commonwealth Trans-Antarctic Expedition by its leaders.

Ronne, F. *Antarctic Command*. Indianapolis, 1961. An account of the first year (1956-1957) at Ellsworth Station by the officer-in-charge.

Siple, P. A. *90° South*. New York, 1959. A description by the station scientific leader of the first year at the South Pole. The author also reviews his experiences on earlier expeditions.

Sullivan, W. *Quest for a Continent*. New York, 1957.*

The best one-volume introduction to antarctic history from the early explorers through the preparations for the IGY. There is also a version for teenagers: *White Land of Adventure*.

Sullivan, W. *Assault on the Unknown*. New York, 1961. A good, nontechnical account of the International Geophysical Year.

Antarctica Today

Billing, G., and G. Mannering. *South: Man and Nature in the Antarctic*. Seattle, 1965. The Antarctic seen through New Zealand eyes; beautifully illustrated.

Dukert, J. M. *This is Antarctica*. New York, 1965. A short, general account for older children.

*Also available in paperback.

INFORMATION SOURCES

ON SCIENCE

Public Information Officer
National Science Foundation
Washington, D.C. 20550

American Geophysical Union
2100 Pennsylvania Ave., N.W.
Washington, D.C. 20037

Public Information Officer
National Academy of Sciences
Washington, D.C. 20418

ON LOGISTICS

Public Affairs Officer
U.S. Naval Support Force, Antarctica
Washington, D.C. 20390

FOR MAPS

Map Information Office
U.S. Geological Survey
Washington, D.C. 20242

American Geographical Society
Broadway at 156th Street
New York, N.Y. 10032

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SECTION 6: SEABED DISPOSAL

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6.0 SEABED WASTE MANAGEMENT SYSTEM

In the potential concepts shown in Figure 6.1 high-level radioactive wastes are managed by a system which features disposal in the seabed, generally in the deeper areas of the oceans. The various seabed areas studied were selected as representative of seabed areas which appear to have potential for long-term isolation of wastes. These areas include subduction zones--deep sea trenches, stable deep sea floor areas, and areas of relatively high sedimentation rates. In all cases, the waste is emplaced in the basement rock below the sediments to take advantage of remoteness from man, isolation from man's environment and high ion-exchange capacity of the sediments as backup protection. The management of the waste by these concepts shown in Figure 6.1, consists of collection of previously solidified and canned wastes at specialized embarkation ports, transport by suitable ships

to the seabed site and waste emplacement at the site from either a drilling ship or a semi-submersible drilling platform. Disposal is accomplished by the emplacement within the basement rock, and isolation is maintained by natural behavior within oceanic crustal layers after sealing of access/emplacement drill holes, or, in one concept, by further natural burial as a result of the geologic nature of the site.

The studies have evolved into consideration of the three concepts categorized according to the type of seabed area as discussed below, and shown in Figure 6.2.

6.1 CONCEPTS DESCRIPTION

6.1.1 Subduction Zones - Deep Sea Trenches

Deep sea trenches, most of which are now considered to be subduction zones, occur at the margins of

FIGURE 6.1. Schematic of Operations in Seabed Disposal System for High-Level Radioactive Waste

FIGURE 6.2. Concepts for Disposal of Radioactive Waste in the Seabed

certain oceanic plates.⁽¹⁾ Depths of water in these areas are 7 to 10 kilometers. In this concept, the waste canisters would be transported by ship and placed in previously drilled holes in the zones where seabed material is being subducted by the underthrusting or sinking of oceanic plates under continental plates. After a hole is filled to the desired level with waste canisters, the top of the hole would be sealed by cementing it closed. The hole in the sedimentary layer would be closed by backfilling with sediments or other sealants. The concept shown in Figure 6.2 could provide permanent disposal of waste by transport into the lower crustal zone of the earth. This concept would require canisters to remain intact during the extended time of movement of waste into the earth's mantle. Rates of movement of crustal plates toward and into these zones are estimated to be 1 to 10 km/10⁶ years.^(2,3) With a subduction zone 10 kilometers wide, 1 to 10 mil-

lion years could be required for enough earth plate movement to subduct the wastes into the earth's lower crust. In the meantime, isolation would depend largely on the sealant and the sediments above the waste canisters. Rates of sedimentation in these areas are generally very low, about a few centimeters per thousand years, with the exception of intermittent more rapid sedimentation due to current transport and slumping of material from the side walls of the trench.

6.1.2 Stable Deep Sea Floor

6.1.2.1 Abyssal Plains

The concept for disposal in stable deep sea floor areas is shown in Figure 6.2. In this concept, waste canisters would be transported by ship and emplaced in previously drilled holes in the seabed in abyssal plain areas as shown in Figure 6.2. Sealing would be done as described previously. Depths of

water are 4 to 6 kilometers; sediment thickness averages 1/2 kilometer in the Pacific Ocean and about 1/2 to 2 kilometers in the abyssal plains of the Atlantic Ocean.⁽⁴⁾ Sediments are generally more consolidated than in trench areas, and sedimentation rates may be as low as 1 to 3 cm/1,000 years. Abyssal plains are considered to be relatively stable areas in the framework of geologic time.

6.1.2.2 Deep Ocean Basins

Another important stable deep sea floor area is that of the geologically stable centers of the ocean basins. Depth of water is about 6 kilometers and the sedimentary cover is thin and firm. Currents are thought to be slow and biological activity is low.⁽⁵⁾ The deep ocean basins also offer the advantage of being generally far from land. Stable deep sea floor areas are considered to be some of the most geologically inactive areas in the world.

6.1.3 High Sedimentation Areas

The concept for disposal in high sedimentation rate areas is also shown in Figure 6.2. To take advantage of relatively rapid natural burial, the waste canisters would be transported by ship and emplaced in previously drilled holes in areas where natural sedimentation rates are high. The waste holes for this concept would be sealed as for the other concepts. These areas usually occur in deltaic settings at the mouths of major rivers such as the Mississippi, Amazon, Ganges and Indus.

Other potential sites for disposal, also connected with major rivers, are the fans or cones of sediments found farther off shore in deeper water. These cones of sediment are found at the foot of the continental slopes at depths of 2 to 4 kilometers and are generally believed to represent features built from material transported down the continental slope by turbidity currents.⁽⁶⁾ Details of this part of the seabed are unknown, but sediments are estimated to be 1 to 5 kilometers in thickness.

6.1.4 Nature of Disposal Medium and Area

The oceans of the world cover about 361 million square kilometers, or about 71 percent of the 510 million square kilometers of the earth's surface. The volume of water in the oceans, 1.37×10^9 cubic kilometers, accounts for approximately 97 percent of the earth's free water. The average depth is about 3,730 meters, and the greatest depth is about 11,000 meters. The Pacific Ocean is about 3,940 meters in average depth and, in the Mariannas Trench, contains the greatest water depth in the oceans. The Atlantic Ocean is 3,310 meters in average depth.⁽⁷⁾

The ocean is thought to be an old feature of the earth's surface but is geologically quite young. The oldest rocks recovered to date from the deep ocean floor are about 150 million years old. The continents are thought to be 3 to 4 billion years old.⁽⁸⁾ The boundaries between land and water, as shorelines,

have probably changed location many times.⁽⁶⁾ For example, 15,000 to 20,000 years ago during maximum development of the glaciers, sea level was about 130 meters below its present level. It has been estimated that if all the ice in the Greenland and Antarctic ice sheets melted, sea level would rise worldwide about 50 meters.⁽⁷⁾

6.1.4.1 The Sea Floor

The sea floor is considered here to be the interface between the ocean water and ocean bottom. Seabed is considered to mean the dense basement rock surface forming the ocean basin, usually overlain by unconsolidated sediments but may be directly in contact with the ocean water.

The sea floor, or ocean bottom, can be divided into three principal provinces, each consisting of dis-

tinct features and topographic forms, shown in Figure 6.3. These three provinces are the Continental Margins, the Ocean Basin Floor and the Mid-Oceanic Ridges.

The continental margins consist of the continental shelf, inland seas, margin plateaus, continental slope, landward slope of trenches, and the continental rise. These make up the most dynamic part of the ocean where seasonal water temperature changes are high, chemical and biological processes are most active and geology is complex. Surface material of the continental margins may vary from rock to gravel to clay within distances of a few miles.⁽⁸⁾

The continental shelf borders the continents to depths of 200 to 300 meters and is really the wetted perimeter of the continents.⁽⁹⁾ Margin plateaus, adjacent to the continents

FIGURE 6.3. Generalized Topography of the Ocean Bottom (Adapted from Heirtzler, 1968, and Heezen and Hollister, 1971)

and similar topographically to the continental shelves, occur at depths to 1000 meters. The continental shelf is a low relief, seaward sloping surface extending from the low water line to a region of steeper slopes which form the continental slope. The continental slope, at depths of 200 to 300 meters, and the continental rise, at depths of 3000 to 4500 meters, are often covered by deltas, aprons and cones of sediments off the mouths of major rivers. The foot of the continental slope, or of the continental rise in the Atlantic and Indian Oceans, marks the seaward edge of the continents.⁽⁹⁾

The continental margin can vary depending on its location relative to areas of crustal growth or destruction.⁽⁸⁾ If the margin is on a leading or destructive edge of a crustal plate, it may be characterized by narrow continental shelves that are steep, rocky, faulted and seismically active. If the margin is on a trailing or constructive edge, it may be broad, flat and seismically inactive. The characteristics of the two types of shelves are quite different and no one set of conditions can be described as typical of the two different margin types.⁽⁸⁾

The ocean basin floor province contains the abyssal plains, abyssal hills, oceanic rises and trenches. This province makes up nearly 30 percent of the earth's surface and contains the deepest parts of the ocean areas, from 4-1/2 to 11 kilometers in depth.

The abyssal plains are nearly featureless areas, built of con-

tinental margin sediments carried into the basin areas by turbidity currents, burying the pre-existing topography under large quantities of coarse material. The abyssal hills are generally found seaward of the abyssal plains and are believed to be oceanic crustal material originally extruded as basaltic material from a mid-oceanic spreading center. As the crust spreads away from the mid-oceanic ridge, it cools and sinks and begins to be covered with sedimentary material.

Mid-oceanic rises are broad, low swells of abyssal hills, 4 to 4-1/2 kilometers deep, although the term has also been used to describe isolated plateaus in the Pacific which are believed to be blocks of continent-like material, thus distinct from the basaltic abyssal hills.⁽⁸⁾

Deep trenches, 7 to 11 kilometers, occur in parts of the oceans, frequently forming the landward boundary of the abyssal hills or occurring seaward of some continental slopes. Most of these trenches are considered to be zones of subduction or destruction of oceanic crust, where oceanic crust is colliding with and being overridden by continental crust. Associated with the trenches, usually on the landward side, are arcuate groups of islands and volcanos, known as island arcs. Earthquakes occur frequently in these trench areas, triggering submarine slides and promoting volcanic activity.

The mid-oceanic ridge is a sea floor spreading center, about 40,000 kilometers long, that nearly circles the earth. A seismically active rift valley, 2 to 3 kilometers deep, is

located in the center of this ridge. From this rift valley new crustal material is constantly being extruded and moves symmetrically to both sides. This is the youngest part of the ocean.

Other features of the ocean are coral reefs built of corals (small colonial marine animals) and calcareous algae (tiny plants). Reefs are found most abundantly in the Indian and Pacific Oceans and may occur as fringing reefs, connected to land and paralleling the coast; barrier reefs, separated by shallow lagoons from the island or mainland and also parallel to the shore; and atolls, or coral reefs, surrounding a shallow lagoon.

Guyots, seamounts and tablemounts are submerged peaks that extend some distance above the sea floor.^(10,11,12) All are believed to be of volcanic origin,^(13,14) and the flat tops of some are considered to be wave cut surfaces, possibly formed when sea level was lower or the sea floor was higher. Sea floor spreading may also have contributed to the present depth below sea level of seamounts by moving those that formed on oceanic ridges into deeper water. Guyots, seamounts and tablemounts are found in most oceans of the world and frequently occur in lines or elongate groups of 10 to 100.⁽¹⁵⁾ The depth from the surface to the flat top may be on the order of hundreds to thousands of meters.

6.1.4.2 Sea Floor Spreading

The earth's crust is considered to consist of from 6 to 10 major plates or blocks "floating" on the mantle. The plates contain both parts of continents and parts of the ocean basins.

The boundaries of the plates may be the ridges or rises at which new crust is forming, the trenches at which older crust is being destroyed, or transform faults marking areas where the plates slide past each other. There is also evidence for crustal block convergence without transform faults or trenches in areas such as the Mediterranean Sea and Himalayan Mountains where plates may be colliding. The edges of the plates or blocks are usually associated with frequent earthquakes, volcanos or active mountain building.

New crustal material is apparently formed at mid-oceanic ridges by upwelling of molten rock through fissures. This crustal material moves away from the fissures at rates of 2 to 5 cm/yr. As the new material cools, the magnetic minerals align themselves with the earth's magnetic field, are preserved in the crustal material moving away from the ridges and, when correlated with dated magnetic events on land, provide an age scale for the sea floor. From studies of the magnetic patterns it is possible to show that much of the ocean bottom has formed in the past 100 million years and the oldest part is probably not older than 200 million years.⁽⁷⁾

As new crustal material is created at the ridges, it is apparently being destroyed at some of the trenches. The older crust at the edge of a moving plate moves under adjacent plates at trenches. These trench areas where the edge of one crustal plate is moving under another and apparently down into the mantle are the subduction zones associated with sea floor spreading.

Deep earthquakes, as deep as 700 kilometers within the earth, are typical of the continental side of the trench-island arc systems and are thought to be associated with the down-turned plate as it moves into the mantle. Shallower earthquakes at depths to 70 kilometers often occur under the island arcs and are also commonly found along the active faults separating segments of the mid-oceanic ridges and rises.

6.1.4.3 Deep Sea Sediments

Deep sea sediments can be divided into two major groups: pelagic sediments and terrigenous sediments.

Pelagic sediments are those found on the deep ocean bottom, usually far from land, that have settled down through the water where no strong currents exist. The sediments are usually the skeletal material of plants or animals or are fine-grained clays. Pelagic oozes contain more than 30 percent skeletal materials and are frequently named after the dominant organism in the sediment, as well as being further qualified as calcareous or siliceous, depending on the composition of the most prevalent part of the skeletal material. Rates of deposition are on the order of 1 to 5 cm/1000 years⁽⁶⁾ and vary depending upon such factors as biologic productivity of the surface waters and the depth of water. For example, most of the calcareous remains of organisms are dissolved before they sink much deeper than 4 to 5 kilometers (the carbonate compensation depth).

Pelagic inorganic deposits are the very fine-grained muds of the deep

ocean basins and contain less than 30 percent skeletal or biogenic material. Inorganic clays are usually reddish to brown, and their origin is not completely understood. Rates of deposition are very low, 0.1 to 0.2 cm/1000 years.

Authigenic deposits are precipitated directly from the sea water and may have undergone some physical and chemical alteration after accumulating on the sea floor. Phosphorite deposits and manganese nodules are examples of this type of deposit.

Accumulations of volcanic ash and dust in the deep sea are often classed as pelagic regardless of whether the volcanic source is submarine or on land.

Other types of sediments found in the pelagic realm are marls and cherts. Marls are soft sediments containing 35 to 65 percent calcium carbonate and a complementary content of clay.⁽¹⁶⁾ Chert is a dense, hard form of silica and occurs primarily as either nodular masses in carbonate rocks or in bedded deposits that may be quite extensive. Chert is usually found where siliceous skeletons or remains are abundant in sediments.⁽¹⁷⁾

Terrigenous sediments are derived from land, composed of various grain sizes and tend to be found near the margins of the ocean basins.

Terrigenous muds are found in the deep sea areas as a result of transport by ocean currents and wind. These muds may contain a variety of minerals typical of land rocks. The rate of deposit is variable but in general is several times higher than that of the pelagic sediments.

Slump deposits are sediments which have slid or slumped from a higher topographic position to a lower and generally farther from land position. Large blocks of terrigenous material may move in this way.

Turbidites are coarse-grained sand and silt layers found interbedded with fine-grained deep sea material.⁽¹⁸⁾ Wood fragments and shells of shallow water organisms are commonly found in turbidites and indicate a shallow water origin for the material. Turbidity currents (dense sediment-water mixtures) flow down the continental slope and onto the ocean floor, depositing sediment as the velocity of the current diminishes. It is also believed that turbidity currents may accomplish considerable erosion.

Deposits of glacially derived sediments occur on many parts of the continental shelf. The sediments consist of sand, silt and occasionally gravel which was originally carried by glaciers. The material was rafted over the ocean with the ice and eventually fell into the ocean as the ice melted.

Sedimentary particles have a substantial capacity to remove radionuclides of a variety of elements from the ocean.⁽¹⁹⁾ Radionuclide sorption seems to vary with the specific surface area, which is generally large for the fine-grained deep sea sediments, and with the specific minerals and radionuclide involved. In sediments with large cation-exchange capacities, radionuclides are somewhat more strongly sorbed than in those with low capacities. The details of the role of

marine sediments in these processes are not well known.

In addition to sediment-covered areas of the sea floor, there are areas of exposed rock, dominantly basalt, and areas where apparently little deposition is taking place. Ocean currents may keep areas swept clean of sediments and prevent accumulation for considerable periods of time.

6.1.4.4 Seawater

Seawater is a solution of salts of nearly constant composition dissolved in water. Seawater contains traces of most elements, but only six make up more than 99 percent of the sea salts. Salinity is calculated from chloride content and is usually expressed in parts per thousand. Salinity of seawater is normally close to 35 parts per thousand and varies between values of 33 to 37 for the open ocean.

Seawater can be described in terms of its salinity, temperature and density. The salinity of the surface waters depends primarily on the difference between evaporation and precipitation, and to a lesser extent on such factors as freezing of ice (which increases the salinity), runoff from land and melting of sea ice.

A general vertical distribution of salinity which approximates the temperature distribution can be expressed as follows:⁽⁶⁾

1. A well mixed surface zone, 50 to 100 meters thick, generally uniform salinity.
2. A zone of relatively large salinity change, or halocline.

3. A thick zone of relatively uniform salinity, extending to the ocean bottom.

4. A zone at a depth of 600 to 1000 meters in some areas, where a pronounced minimum salinity occurs.

The surface temperature of the ocean is related to latitude and the season of the year, while below the surface, currents can transfer heat from one area to another. The ocean surface is heated by radiation from the sun and sky, conduction of heat from the atmosphere and condensation of water vapor; it is cooled by radiation to the atmosphere from the water surface, conduction of heat to the atmosphere, and evaporation.

A typical distribution of temperature with depth is:⁽⁶⁾

1. A warm, well-mixed surface layer, 10 to 500 meters thick.

2. A transition layer below the surface layer, known as the main thermocline, where the temperature decreases rapidly and which may be 500 to 1000 meters thick.

3. A thick layer, up to several kilometers, which is cold and relatively homogeneous, in which the temperature decreases slowly toward the bottom.

The main thermocline is a layer of water with a steeper vertical temperature gradient than that of the water above or below it. This thermocline is essentially absent in the polar regions, and in areas such as the tropics it may occur near the surface. Below the thermocline, temperature and salinity show a close relationship, which can be used to define water masses or types.

The density of seawater is determined by complex interactions of salinity, temperature and pressure. Generally the density increases as salinity and pressure or depth increases, and as temperature decreases. Changes in density may result from such things as evaporation or heating at the ocean's surface.

Because of the tendency of denser water to sink, a stable density stratification is produced in seawater. Approximately the upper 100 meters of the ocean are well mixed by wind and wave action and are relatively uniform. Below this surface layer, large changes in temperature (the thermocline) and salinity (the halocline) produce a corresponding increase in density (the pycnocline).⁽⁶⁾ The deep, dense waters of the ocean are below the pycnocline.

The stable pycnocline effectively isolates the surface water from the deep water. In the polar regions the thermocline, halocline and pycnocline are absent and the density stratification does not exist. These polar areas are apparently the source of the deep ocean waters.⁽⁶⁾

6.1.4.5 Currents and Water Masses

Ocean circulation is primarily the result of wind and heating of the ocean. The interaction of these two atmospheric factors and the ocean produces two main types of circulations: a wind-driven circulation and a thermohaline or density circulation. The wind-driven circulation is stronger than the density circulation and is most effective in the upper 1000 meters of water.

The wind, generated by temperature and pressure differences, and deflected by the earth's rotation, exerts a stress on the ocean's surface and produces the wind-driven circulation of the ocean. The surface currents in the Atlantic and Pacific Oceans are deflected by land masses and forces due to the earth's rotation and form gyres, or closed circulatory cells. The action of nearshore wind on the ocean's surface can also cause upwelling (upward movement of water) or cause sinking of surface water.

The thermohaline circulation is caused primarily by density differences and is generally a deep water phenomenon. It is essentially a convection process, affected by tidal forces and rotational forces of the earth, in which cold dense water formed in the high latitudes sinks and flows slowly toward the equator. Most of the deep ocean water is believed to be formed in either the Norwegian Sea area or in the Antarctic.⁽⁶⁾

Direct observations of the deep ocean circulation are difficult to make because of great depths of water. Information on the thermohaline circulation is derived from measurements of temperature, salinity and dissolved oxygen. Photographs of the ocean floor have also yielded considerable evidence of deep current action and direction.⁽⁹⁾

The deep ocean circulation is not as well known as the shallow, wind-driven circulation. It is recognized that the deep currents are influenced by bottom topography and that water from the polar regions does cross the equator from both directions. The

cold (-0.4°C) Antarctic bottom water is recognized in all major ocean basins.

The deep ocean waters eventually mingle with other water and return to the surface. Residence time of the deep ocean water has been estimated to be from 100 to 1000 years.^(7,20)

6.1.5 Systems Requirements

Overall systems requirements for the potential concepts of seabed disposal are summarized in Figure 6.4. As shown in this figure, storage of unconditioned high-level liquid waste arising from the chemical reprocessing of irradiated nuclear fuels is expected to be followed by conditioning (specifically solidification and encapsulation), retrievable storage of the resulting canisters, transport of the canisters in casks to the disposal area, and finally by emplacement in the seabed. Details concerning requirements for waste treatment and handling prior to emplacement in the seabed, site preparation, transportation of the canisters to the site, and final disposal operation follow.

6.1.5.1 Prior Waste Treatment and Handling

The general system flow diagram, shown in Figure 6.4, starts with bulk high-level radioactive liquid waste from the nuclear fuel reprocessing plant. A number of potential options are shown. For seabed disposal, solidification of the bulk waste and disposal in the seabed are the basic steps required. The other options, while not needed for seabed

Only solidified high-level forms
are considered for seabed disposal.

If the stability of the seabed can be adequately verified, safe containment of waste forms for periods on the order of 1 million years or more is possible. Therefore, separation of actinides or long-lived fission products may not be required. However, difficulties and costs inherent in the system concerning the transportation, logistics and operations at the potential disposal site may suggest some separation of waste products. The actinides and long half-life fission products could be considered for disposal in the seabed areas and the remaining waste forms handled in other disposal systems that may not have the same potential for safe long-term containment.

On the other hand, if the seabed is found to lack sufficient stability for long-term disposal, separation would be required and the seabed considered for disposal of the higher heat-generating, short half-life radionuclides.

In this study, the anticipated path was assumed to be disposal of bulk solidified waste without chemical separation.

The reference concept as developed here considers the total high-level waste product 10 years after separation from the reactor fuel. Nominal canister dimensions are 30 centimeters in inside diameter by 3 meters long. Approximately 80% of canister volume is filled with about 170 liters of high-level waste. Radioactive material in each canister is approximately 1 megacurie with a heat generation rate of around 3 kilowatts. The canister is designed for emplacement through the drill pipe or conductor pipe at the site, to withstand or accommodate the hydrostatic pressure and to offer resistance to corrosion in a seawater environment.

6.1.5.2 Site Preparation

The first phase of site preparation would be to select and evaluate alternative potential disposal sites. After evaluation and final selection were accomplished, actual disposal site preparation would begin.

Site preparation would require detailed and precise positioning of the disposal site. Exact positioning and navigation could be accomplished by a satellite navigation system similar to that used in the Deep Sea Drilling Project.⁽²¹⁾ The site might

include a surrounding buffer area designated potentially hazardous and with restricted access. Appropriate navigational charts and marker sea buoys could mark the area to minimize shipping through the area.

The drilling ship or semi-submersible drilling platform would need to be on location for several months to perhaps 1 to 3 years before disposal operations could begin. The drilling platform would need to be positioned, supplied, equipped and rigged up to begin drilling. Markers or sonar beacons used on the sea floor would be put in place and tested. Holes would be drilled ahead of the disposal operations, and funnels would be installed above drill holes for re-entry as well as riser or conductor pipes through the unconsolidated sediments.

Embarkation ports would need to be established and functioning before the disposal site was fully prepared.

6.1.5.3 Transportation and Logistics

Transportation from the fuel reprocessing plant to the disposal site would be accomplished in two stages. The first stage would consist of transport by truck, rail or possibly barge to the port of embarkation. Waste canisters would be carried in specially constructed transport casks supplying the necessary radiation shielding and cooling. Temperature and radiation would be monitored continually during transport.

Upon arrival at the port of embarkation, the transport cask would

be off-loaded, the canisters removed, inspected and either stored temporarily before shipping to the disposal site or returned to the reprocessing plant if found unacceptable.

The second stage of transport would be by special ship from the embarkation port to the disposal site.

6.1.5.3.1 Overland Transport.

Transport to the embarkation ports would be accomplished by rail or truck or possibly barge if waterways were available. Before transport of the waste from processing plants to embarkation ports, the waste canisters would be enclosed in transport casks, weighing 50 to 100 tons. The transport cask would supply the necessary radiation shielding and cooling. An "average" cask could be considered to be one with a cavity diameter of about one meter, holding six waste canisters and weighing about 50 tons.

Existing special railroad cars can carry useful loads of up to 100 tons.⁽²²⁾ Trucks in general are limited by gross vehicle weight restrictions to loads of about 25 tons, but overweight permits can extend this to about 40 tons⁽²³⁾ and more in special cases.

6.1.5.3.2 Embarkation Facility.

The embarkation port facility would serve for examination and accumulation of the waste prior to shipment to the seabed disposal site. The transport casks containing the canisters would be unloaded in a dock-side shielded cell facility where the canisters would be removed and examined for leakage, contamination,

damage or other unsuitable conditions. Acceptable canisters would be either stored temporarily or transferred individually to specially designed shipping casks of about 20 to 25 tons, then loaded aboard transport ships. Any unacceptable canister would be placed back into the transport cask and returned to the reprocessing plant or to the nearest appropriate handling facility.

On-land handling by crane could be accomplished by existing cranes with loan capacities up to 300 tons.⁽²⁴⁾

6.1.5.3.3 Sea Transport. The second stage of transport would be by special ship from the embarkation port to the disposal site. The shipping casks would supply the radiation shielding, (although a system could be designed to use water for shielding) and artificial cooling would be supplied by the ship's facilities. Any additional shielding required would be an integral part of the ship construction. Cooling would be done by closed circulation water systems, filtered forced air systems, or heat exchangers cooled by sea water. The coolant would be continuously monitored for radiation and temperature changes.

The transport ship would be equipped with a handling device capable of removing the waste canisters and their casks to a shielded cell facility (the equivalent of a cube about 4.5 meters on a side) for examining the condition of the canisters, either enroute or at the disposal site. Any canister unacceptable for disposal could be repaired on-board ship if it were

a relatively simple job. Alternatively, the canister would be returned to the shipping cask and back to the embarkation port for return to the reprocessing plant or other handling facility if necessary. Each canister acceptable for disposal would be returned to the cask for transfer to the drilling or emplacement ship. Alternatively the canister could be transferred from dock to ship underwater, at a depth of 12 feet or greater, to provide sufficient protection to personnel during handling.

While aboard the transport ships, the casks or canisters could be fitted with locating devices and acoustically actuated flotation mechanisms. In the event the ship should sink, the shipping casks would be constructed so that a part of the cask could be released from the ship and a flotation system with a collar be activated to bring the canister and the recoverable part of the cask to the water surface. The release of part of the cask and the activation of the flotation device would be triggered by an acoustic signal from the surface. This operation is shown in Figure 6.5.

At the disposal site, transfer would be made to the drilling/emplacement ship or semi-submersible platform by positive handling after "firm" docking.

Transport ships capable of carrying 300 25-ton casks (total load weight 7500 tons) are well within the range of present day ships. For example, ships are currently being built in the 400,000 dead weight ton class (dwt) for ocean tankers.⁽²⁵⁾

The transport ship could travel a 6000 nautical mile (11,100 kilometer) round trip in about 25 days. With allowance for loading, unloading, fueling, bad weather, maintenance, etc., a net average trip requirement of 90 days is believed to be reasonable.

FIGURE 6.5. Potential Cask-Canister Recovery System

6.1.5.4 Operation of the Site

Operations at the disposal site would consist of positioning or docking the transport ship with respect to the drilling ship or semi-submersible platform, unloading the shipping cask, removing the canisters for inspection and emplacing the canisters into the drilled holes in the seabed through the drill pipe or conductor pipe.

Once the waste canister has been examined on the transport ship and it is cleared for emplacement, the emplacement operation would depend on which of several methods was used. The shipping cask could be designed so that it could be opened from the bottom as well as from the top.

For emplacement in drilled holes, which is used as the reference system in this study, the shipping cask would be off-loaded from the transport ship to the drilling or emplacement platform. The cask would then be positioned over the drill string at the drilling-floor platform. The cask would be opened at the bottom and the canister allowed to fall through the drill pipe to the bottom of the holes, or it could be pumped down by the drilling fluid. Alternatively, the canister could be lowered on a wire-line through the drill pipe. Appropriate instrumentation and equipment would indicate the exact position of the canisters within the hole.

The shipping cask would then be returned to the transport ship to return to the port of embarkation or to the fuel reprocessing plant.

In the example shown in Figure 6.1 emplacement is made from a semi-submersible platform. Several different emplacement methods are possible with this system. Alternative methods of emplacement, not involving drilled holes, are guided-fall along anchored cables, free-fall from a cable at a predetermined depth, and free-fall from the drilling or emplacement unit. These methods would all require a waste canister or containers for the canisters specifically designed to obtain maximum penetration of the sediments on the sea floor.

6.1.5.5 Final Sealing from Man's Environment

Final sealing from man's environment for methods using drilled holes

would be accomplished by pumping a high-density, chemically inert grout or cement of greater density than the seabed material down into the drilled hole. It is expected that this grout would displace any seawater in the annulus and between canisters and spacers if used. The upper empty portion of the hole above the canisters would be filled with the grout or cement as a sealing agent. The sealing agent would thus fill the space between the waste canisters and between the canisters and the upper empty part of the hole and might extend into the overlying unconsolidated sedimentary material. The grouting or cementing, aided by the accumulating sediments, would be relied upon to accomplish the isolation and sealing of the wastes from man's environment. In addition, back-filling of the hole through the sediments with sediments or with other sealants could be done.

Cement or grout would also prevent any convection current effects up the hole from heat generated by the canister. If desired, the casing could be located later by detailed survey with underwater magnetometers. For additional protection, a grout or cement cap could be considered for spreading over an area of seabed adjacent to and covering the hole. If casing above the seabed were used, the cement cap would also stabilize the soft surficial sediments around the area of the pipe as well as provide an aid in relocating the site.

In the guided-fall method of emplacement or free-fall from a predetermined height above the seabed, isolation of the waste canister from

man's environment is accomplished primarily by the natural covering.

Any telemetering and monitoring equipment would be installed and tested at this time, and surveillance would begin. Monitoring of the disposal sites would be difficult because of the remoteness of the disposal system. Radiation in the seabed and adjacent waters could be monitored by instrumentation placed or anchored on the seabed, and the resultant information could be telemetered to surface facilities such as ships. Alternatively, monitoring equipment could be suspended from the surface and transmit data back to the surface through conduit along the suspension cable. Ocean waters could be continuously monitored in the vicinity of the disposal site to record indication of canister leakage or failure. Monitoring would be difficult because of the great depths involved, the large area to be monitored, the deep sea tides and the presently unknown currents.

The concepts considered here for disposal are envisioned as potential means of permanent disposal. Retrieval would be most difficult. However, if retrieval were believed to be essential, considerations for this could be built into the system with additional effort and expense. For any of the disposal methods, a means of accurately locating the buried canisters must be built into the system. Once this was done, it is possible that the overlying material could be drilled out and attachment made to the canister for bringing it to the surface. Drilling grout or cement sealant would require more ef-

fort than would drilling natural covering to release the canisters from the sealing material. An integrated diving-bell recovery unit could be lowered from the surface for this task.

6.1.6 Heat Removal

At the time of canister loading, taken in this study to be about 10 years after fuel reprocessing, the high-level waste will contain about 1 megacurie of radioactive material, which will have a heat generation rate of approximately 3 kilowatts. This amount of heat generation is sufficient to raise the waste temperature to its melting point in a relatively short time if the canister is surrounded by a good insulator.

Present cask design includes provisions for adequate cooling during shipment from a retrievable storage location to the embarkation port. The marine transport ship used to move the waste canisters to the disposal area will be able to provide adequate cooling by the use of seawater. Upon arrival at the disposal site, further cooling will be provided at temporary storage facilities either on the drilling ship or on the semi-submersible drilling platform.

Heat removal from the canisters emplaced within the seabed will be primarily by conduction and will depend on the material at the specific site. Placing the waste canisters below the unconsolidated sedimentary material, with its higher water content, should prevent formation of convection currents. The drilled holes containing the waste canisters would probably be filled with cement

or other sealing agent, and heat would be conducted by the sealing agent to the material in which the hole is drilled.

If the material in the hole wall is basalt, as could be expected below the unconsolidated sediments in many places, thermal conductivities on the order of 5×10^{-3} cal/(cm)(C°)(sec) could be expected.⁽²⁶⁾ This is comparable to the thermal conductivity of many types of land-based geologic formations. If the hole wall material is sandstone or chalk, thermal conductivities of 5×10^{-3} and 2×10^{-3} cal/(cm)(C°)(sec) respectively would be typical.

In general, the thermal conductivities of the denser material is higher than that of the overlying unconsolidated sediments which have thermal conductivities on the order of 1.7 to 3.3×10^{-3} cal/(cm)(C°)(sec).^(27,28) Heat removal would thus be improved by having the wastes below the unconsolidated material.

6.2 TECHNICAL FEASIBILITY

Waste disposal in the seabed environment in general offers potentially favorable features such as:

1. Relative remoteness and isolation from man's environment,
2. High ion-exchange capacities of seabed sediments as backup protection, and
3. High heat-dissipation capability for shallow burial.

Unfavorable features of seabed disposal in general are:

1. Difficulty in monitoring and retrieval,
2. Extended sea transport,

3. Relative mobility of seawater, saturated sediments, and sediment porewater and uncertainty of sediment behavior around waste canister.

4. Possible concentration of waste by biological mechanisms, and

5. Relatively slow rates of sedimentation and movement of crustal plates.

Primary problem areas presently recognized in the feasibility of seabed disposal are stability and/or isolation with respect to man's environment, maximum drilling depth and means of emplacement, and rate of burial or disposal by natural sedimentation. Rates of burial or disposal by natural sedimentation are low enough to be considered unfavorable.⁽²⁷⁾ Some means of emplacement other than merely lowering the waste containers to the seabed seems desirable to assure isolation of the waste from man's environment. Drilled holes in the sea floor are the alternative selected here. Modern drilling technology has advanced to the point where drilling ships are able to return to the same hole after completely retracting the drill pipe at depths of about 4 kilometers.⁽²⁸⁾ Another possible emplacement alternative is free-fall penetration by specially designed waste containers which may be able to penetrate unconsolidated sediments as much as 35 meters. (See Appendix 6.B.)

Postulated disposal in subduction zones has been considered by several investigators.^(29,30) Again, crustal movement is slow, perhaps 5 to 10 cm/year, and emplacement in drilled holes would provide a better chance of getting the wastes into

the subducting material. The disposal of the waste theoretically would be completed in an estimated 6,000,000 years when depths of about 700 kilometers have been reached,⁽³¹⁾ but for practical purposes, could be considered complete when depths of 10 to 20 kilometers had been achieved. On the other hand, subduction zones and the geologic processes operating in them are not well understood or documented. It is possible that the activities associated with subducting material could destroy the waste canisters or the disposal site.

Stability of the disposal site and its effectiveness in isolating waste material must be considered from different approaches. Deep trenches and subduction zones are frequently associated with earthquake activity⁽²⁾ which could cause submarine landslides and slumping and conceivably destroy shallow emplacement sites. It has also been suggested that earthquake activity could loosen consolidated sediments enough that waste containers would sink through them.⁽²⁹⁾

Abyssal plain and deep basin areas are considered to be geologically stable,⁽⁴⁾ but are exposed to deep and poorly known ocean currents. Bottom currents are believed to be weak and variable with tidal velocities of 2 to 5 cm/sec.⁽⁸⁾ The estimated time for a parcel of deep ocean water to reach the surface is from 100 to 1000 years;⁽²⁰⁾ hence, unless buried below the unconsolidated sediments, waste container life would need to be on the order of thousands of years. (See Appendix 6.A

for data on canister longevity, materials, and corrosion rates.)

The disposal of radioactive waste in the seabed can be considered technically feasible, subject to certain limitations. The limitations are due mainly to lack of definite knowledge of the seabed and the geologic processes which operate in the oceans, particularly at great depths. Specifically for the three waste disposal concepts in the seabed, the existence of subduction zones has not been fully demonstrated; deep ocean trenches require more investigation on the nature and thickness of up to several hundred meters of sediments and are relatively unstable areas; and high-sedimentation rate deltaic areas are subject to various high-rate geologic processes which may make them unstable over relatively short geologic periods of time.

Sea floor materials of subduction zones and deep trenches are not well characterized but are thought to be usual oceanic sediments interbedded with turbidite sands and silts. Stable sea floor-abyssal plain sediments are relatively unconsolidated but contain cherts and lithified layers of ash and tuff in the Pacific Ocean. The deep ocean basin sediments typically consist of relatively thin firm clays overlying the consolidated bedrock. Deltaic areas contain considerable thicknesses of unconsolidated sands, silts and clays.

Natural sedimentation in much of the deep ocean areas could be expected to provide a cover for emplaced wastes of 1 to 35 meters in 1,000,000 years. Locally restricted deep sea areas such as some fracture

zones in the mid-Atlantic ridge have, or have had in the past, higher rates of sedimentation.

The feasibility of these disposal concepts considered depends to a large extent on knowledge of the geologic settings involved. The concepts for seabed disposal of radioactive wastes are considered for three different geological settings in the oceans. Two of the settings and part of the third are in the deeper parts of the oceans, which are not well known. Because of this lack of definite knowledge, a summary of existing knowledge and theory of the settings for the various disposal concepts is included here.

The concept of disposing of radioactive waste in subduction zones is dependent on the relative tectonic activity of these zones. The subduction zones are among the deepest parts of the ocean basins--a representative depth is 8 to 10 kilometers. Zones associated with crustal subduction are believed to occur around the margin of the Pacific Ocean and off the Antilles Islands in the Atlantic Ocean.

Rate of movement of the sea floor toward the subduction zones is considered to be on the order of 1 to 10 kilometers per million years.^(32,33,34) Seismic evidence and gravity anomalies in these zones indicate that seabed crustal material is moving downward, either by subsidence or by being thrust under the margins of the plates involved.^(2,3,35)

The subducting plates are considered to be 80 to 100 kilometers thick.^(3,31) These plates may remain

quite rigid to depths of about 700 kilometers. Seismic evidence indicates that below this depth the plates may be assimilated into the mantle.⁽³¹⁾ The areas where oceanic plates appear to be thrusting under continental plates are characterized by shallow earthquakes, 30 to 70 kilometers deep, and also by deeper earthquakes from 100 to 700 kilometers in depth. The deeper quakes originate more on the landward side than the shallow quakes and presumably trace the inclined, descending plate.^(36,37)

The behavior of the accumulated sediments in the trenches associated with subduction zones is not well understood. The sediments may be carried into the upper mantle with the subducting plate;⁽²⁷⁾ they may be fluidized by seismic activity and remain in place;⁽²⁹⁾ they may be "piled" against the trench wall before being subducted;⁽³⁰⁾ or they may act in combination of the above. The crustal material is undoubtedly subjected to deformation, possibly extreme, and eventually to melting and assimilation into the mantle material.

Knowledge of the deep trenches of the oceans is largely inferred. Samples are difficult to obtain, the position of the sample location is difficult to determine, and the actual depths and configurations of the trenches are currently subject to various interpretations.⁽³⁸⁾ Deep ocean trenches occur in both major oceans but are far more numerous in the Pacific. The Pacific Ocean is surrounded by a nearly continuous series of trenches along its margin.

No trenches are known to occur between Mexico and southern Alaska or between New Zealand and South America.⁽³⁸⁾ Most of the trenches are bounded on the continental side by folded mountain ranges or an arcuate series of islands. The deep trenches are seismically active, and many earthquakes occur along or near the trench axes.⁽⁶⁾ Most of the deep trenches are considered to be subduction zones in the theory of plate tectonics.⁽⁶⁾

The trenches tend to be narrow with a nearly flat floor. The width of the floor is generally not more than a few kilometers.⁽³⁸⁾

The sediments of the deep trenches have not been studied in detail because of difficulties in obtaining undisturbed samples. Surface deposits on the trench floors are generally dark clays, silts, sand, and often volcanic pumice and glass. Below the surface these sediments are interbedded with coarser graded material deposited by turbidity currents and slumping from the trench walls.⁽³⁸⁾ The bottom currents are essentially unknown.

The abyssal plain areas are the smooth, almost featureless areas of the sea floor found in general between the continental rise and the more irregular relief of the abyssal-hills province.⁽⁶⁾ Deposition of material by turbidity currents, covering the previous topography, is generally considered to be the method by which abyssal plains are formed.^(6,39) Abyssal plains are found in oceans throughout the world but cover a lesser proportion of the Pacific Ocean than the Atlantic.

This is because of the sediment-trapping trenches surrounding the Pacific and because few large rivers flow into the Pacific to provide sediments.⁽⁶⁾

Abyssal plain sediments are generally deep-sea clays and oozes interbedded with silts, sands, gravels, and often sediments from more shallow environments. In some areas in the Pacific, tuffs and other volcanic materials are part of the sedimentary sequence.⁽⁴⁰⁾

In general, the abyssal plain sediments are unconsolidated and soft for tens to hundreds of meters below the sea bottom. For example, the GLOMAR CHALLENGER drilled through 600 meters of silts, clays, oozes, sands, and marls of the Ceara Abyssal Plain off the eastern coast of South America at rates averaging about 120 m/hr for the first 120 meters, about 60 m/hr for the next 280 meters, and less than 40 m/hr for the last 200 meters.⁽⁴¹⁾ These high drilling rates can be done only in soft or unconsolidated material. However, five attempts to drill into abyssal sediments in the western Pacific were stopped by lithified ashes, tuffs and/or cherts. The first hard layers were found as shallow as 1.5 meters below the sea floor and as deep as 124 meters.⁽⁴⁰⁾ Drilling trouble on some of these locations occurred due to insufficient thickness of soft sediments to bury the bottom assembly of the drill string. Thus unsupported, the sides of the assembly apparently buckled and twisted off when the hard layers were encountered.⁽⁴⁰⁾

The abyssal-hill region lies generally seaward of the abyssal plains

and covers a large part of the deep ocean basins. Relief is low, consisting of hills which may be only a few tens of meters high, but several kilometers in diameter.⁽⁸⁾ The hills are mostly basalt and overlain in places by several meters of limestone. The surface covering is generally 50 to 100 meters of firm, brown clay.

The deep ocean basins are considered geologically quite stable. They are in regions of very few reported earthquakes and beyond the reach of turbidity currents. The centers of the deep basins are generally far from the continents and are within the range (about 6000 meters) of existing drilling equipment.

The center of a basin in the North Central Pacific Ocean is being considered by Sandia Laboratories as a possible waste disposal area.⁽⁵⁾ This particular basin is located near the center of a tectonic plate and is considered to have very low biological activity.

High sedimentation rates occur in deltaic areas of rivers that drain the continents. The Fraser River of British Columbia, for example, deposits sediments in a restricted area at a rate up to 6 kilometers of depth per million years.⁽²⁷⁾ Offshore deltas are usually formed by a complex of sub-deltas, which have been built up and abandoned as the flow channels shift their courses. The shifting of the course into successive distributaries is typical of delta evolution; the Mississippi River has built five large sub-deltas in the last 5000 years.⁽⁴²⁾

Delta sediments are typically composed of sand, silt, and clay in an

interbedded and alternating sequence. The sediments in general are relatively unconsolidated and poorly cemented and often reworked by wave action.

Deltaic areas are geologically unstable. They are subject to such actions as subsidence, slumping, shifts in sea level, wave action, and long-shore currents⁽⁴²⁾ as well as possible transport of material internally by diapiric action of clays.⁽⁴³⁾

Another area of high sedimentation rates is found where turbidity currents emerge from channels or canyons onto the relatively flat areas of the lower continental rise or an abyssal plain. As the velocity of the current is reduced in these areas, sediment is deposited and in time may build up a deep sea fan or cone of sediment. Well developed fans are found along the west coast of North America, and abyssal cones occur off the Mississippi, Congo, Ganges, and Indus Rivers.⁽¹³⁾ Distributary channels form as the currents abandon channels across the cones and form new ones. The materials of these fans and cones are probably turbidite silts, sands, and possibly gravels; but the actual nature and thickness are not well known. The sediments that accumulate at the heads of submarine canyons are known to be subject to slides and flows.⁽⁴⁴⁾

The sediments of the oceans are not uniformly distributed and the rates of sedimentation vary widely depending on the location. In general the rate of deposition of material consisting mainly of calcareous ooze averages about 10 meters per

million years, and the rate of deposition of red clay averages less than one meter per million years.^(3,45)

Higher rates of accumulation exist in deltaic areas connected with rivers draining the continents, in some areas, associated with the oceanic ridges and in areas at the foot of the continental slope. There are also areas where the seabed is essentially free of sediment, due either to action of bottom currents⁽⁴⁶⁾ or possibly to nondeposition.

The rates of sediment accumulation in the oceans, with locally restricted exceptions, would provide burial on the order of 1 to 35 meters in one million years for material placed on the floor of the oceans. Turbidity currents of sediment-laden seawater may actively increase the rate of sedimentary accumulation, particularly in areas where there are no deep trenches off the continental shelf and slope areas. These currents are difficult to predict, sporadic in nature, and act as erosional agents as well as depositional agents.

Thermal conductivities of sea floor sediments have been measured by various means.^(47,48) In general the values vary with type of material and consolidation. Typical values for relatively unconsolidated oozes are on the order of 1.75 to 3.3×10^{-3} cal/(°C) (cm) (sec), which is intermediate between the values for concrete (2.1) and salt (4.1).

6.2.1 Containment Assurance

Assurance that the disposal media associated with the seabed concepts will contain the waste for the time period required is speculative at

this point. However, the potential for long-term containment assurance, especially in the stable deep sea areas, is highly promising. The containment is essentially a problem of the stability and properties of the disposal medium once the canister's life has been exceeded.

Some failure modes for the seabed disposal concepts are listed in Section 3.1.1 of this report. Detailed failure mode analysis has not been done for seabed disposal.

In all the seabed disposal concepts it is considered that the waste canisters must be emplaced at depths on the order of 100 meters or more into the bedrock below the unconsolidated material, thus putting the waste canisters in relatively dense and impermeable material below the reach of sea currents and below the more easily erodable material. The holes for emplacement would be sealed with an impermeable and dense material, isolating the waste canisters in the seabed for containment, thus accomplishing disposal.

The duration of containment after canister failure will depend upon the longevity and stability of the solidified waste form, the longevity and effectiveness of the seal above the canisters and upon the properties of the containment material and geologic stability of the particular seabed area. The properties of the containment material would be determined when site evaluations are made for specific locations. The effectiveness of the seal will depend somewhat upon the nature of the containment material and upon the design specifications of the material used.

Geologic events may affect the seabed in which the wastes are emplaced. Earthquakes, volcanos, faulting or uplift could over a long time period open channels for seawater to circulate through the disposal site or possibly bring the waste canisters to the surface of the seabed. Such events are difficult to predict and would have to be based on a geologic evaluation of the specific sites. Certain proposed disposal areas, however, could be considered relatively safe from disruptive geologic events. The stable deep sea floor areas, for example, are considered to have been tectonically quiet for tens of millions of years. On the other hand, subduction zones and deep ocean trenches depend partly on geologic activity for their effectiveness as disposal sites. Their activity or changes in rate of activity are difficult to predict.

6.2.2 Siting Limitations

Siting limitations will depend on the disposal concept selected. All the concepts are directed toward certain geologic settings and are thus site specific. Siting limitations other than technological are determined by the availability of the specific geologic setting for each concept.

The surface trace of subduction zones forms less than 1 percent of the earth's surface,⁽⁷⁾ and thus possible disposal sites are limited to a small part of the oceans. The area taken up by trenches is only about 1.2 percent of the total area of the earth's surface.⁽⁷⁾

The stable deep sea floor areas are less limited by available sites. Abyssal plains are widespread, particularly in the Atlantic Ocean, and in general the depths of water associated with these areas are not beyond the reach of existing equipment. The ocean basins occupy about 30 percent of the earth's surface.⁽⁷⁾

The disposal concept directed toward high sedimentation rate areas would also be limited to the occurrence of geological features such as large river deltas and sedimentary fans or cones of suitable thickness, depth of water and location with respect to man's activities.

6.2.3 Prior Waste Conditioning

Radioactive waste is considered to be in solid form, such as borosilicate glass, and encapsulated in metal canisters for all the seabed disposal concepts. The canister may be pressure-resistant, requiring extra-thick, high-strength walls, or pressure-compensated requiring a leak-proof compensation system. Physical characteristics of the waste and the canisters are discussed in Section 6.1.5. Interim storage time for thermal decay is an optional waste conditioning step.

6.2.4 Energy Requirements

Preliminary calculations indicate that the energy required for transport and emplacement in the seabed of the waste canisters is about five orders of magnitude lower than the electrical energy generated by the nuclear power plants that supply the fuel.

The energy requirement in all seabed disposal concepts are largely committed to the transport and logistics associated with moving the waste from the reprocessing plant to the embarkation port and from the embarkation port to the disposal site. A smaller part of the energy requirements, as fuel, is associated with drilling and emplacement operations.

The major fuel requirements of the transport systems associated with seabed disposal are shown in Table 6.1

6.2.5 Status of Technology

Technology for placing waste containers on or in the sea floor exists today. Present deep sea drilling

technology under good conditions can drill several hundreds of meters into the sea floor in about 6,000 meters of water and could probably drill farther in deeper water if proper incentive were provided. A typical drilling rate into the seabed, based on the GLOMAR CHALLENGER's records, is 2 to 4 meters per hour.

Transport and handling facilities exist at present to handle loads of 25 to 100 tons on land and up to several hundred tons at sea. These are suitable for transport of canisters of waste for seabed disposal. All the seabed disposal concepts are considered to require controlled emplacement of the waste in the seabed and below the unconsolidated sediments. This requirement is part of

TABLE 6.1. Fuel and Energy Requirements for Transport of High-Level Radioactive Waste to Seabed Disposal Areas(a)

System	Liters Fuel	Equivalent Electrical Energy (kW)(b)
50 ton cask transport from Reprocessing Plant to Port Facility (1500 km round trip; 2 km/liter; 2500 trips)	1.9×10^6	2.1×10^7
Marine transport (60 day round trip; 1.9×10^4 liters/day; 25 trips)	2.8×10^7	3.1×10^8
Operation of Drilling Ship or Semi-Submersible Platform (1.9×10^4 liters/day; 365 days)	6.9×10^6	7.6×10^7
Total	3.5×10^7	4.1×10^8

- a. The basis is one plant reprocessing 5 MT/day of fuel with an average output of 600 waste canisters/year for 25 years. Electrical energy for the associated nuclear fuel is 10^{13} kW-hour.
- b. Electrical energy calculated by assuming 3.7×10^4 Btu/liter fuel converted in a power plant at 35 percent efficiency as 3.4×10^3 Btu/kW-hour or 11 kW-hour/liter.

the concepts because of a lack of definite knowledge of the properties and nature of the sediments in some of the concept areas and lack of design criteria on the amount of sediment cover considered adequate. New knowledge of marine sediments and their properties may make the use of sediments for disposal possible in the future. Controlled emplacement below the unconsolidated sediments, in previously drilled holes, followed by sealing would provide the best assurance of isolating the waste for the longest time.

Conclusions from a feasibility study of subsea floor emplacement methods by the Civil Engineering Laboratory, U.S. Naval Construction Battalion Center, Port Hueneme, California, (Appendix 6.B), indicate that free-fall penetration of the sea floor and forced emplacement by being driven at the end of a drill pipe, give penetrations of one to two orders of magnitude smaller than those achieved by drilling. The drilled holes would give greater security and isolation by placing the waste canisters farther below the bottom of the free seawater and by placing the waste in material of greater resistance to erosion, transport, or other processes that might expose it.

In evaluation of the status of technology concerned with this waste management system, the following overall conclusions can be drawn:

1. Existing means of land transportation are adequate for transport to embarkation ports. Appropriate monitoring devices can be installed.

2. Existing port and handling facilities could be adapted to the needs of the system for off-loading, monitoring, checking of waste canisters and on-loading to transport ships. Present ships are capable of carrying large numbers of shipping casks and could be adapted to provide necessary radiation handling facilities on board.

3. Handling and emplacement equipment at the disposal site depends upon the site selected and the method of emplacement chosen. Present drilling ships such as the GLOMAR CHALLENGER, capable of drilling in approximately 6,800 meters of water^(49,50) would not reach the deeper areas considered for disposal sites such as subduction zones and deep trenches. Semi-submersible drilling craft are more stable than hull designed ships and could be dynamically positioned. But because of pipe design limitations they have the same limitations as conventional drilling ships for drilling depth of water. Drill strings could be designed with tapered pipes and should increase effective depths to 9,000 to 10,000 meters, which is satisfactory for these concepts. Semi-submersible craft, because of their greater stability, could simplify handling due to the possibility of firm docking of the transport ship.

4. Guided-fall or free-fall penetration of the sea floor material is limited only to shallow emplacement (about 35 meters) in the unconsolidated sediment layers of the deep seabed.

6.2.5.1 Emplacement

The best example of the state of technology in deep-sea drilling is the current work of the GLOMAR CHALLENGER on the Deep Sea Drilling Project.⁽²¹⁾ The GLOMAR CHALLENGER, 122 meters long and 20 meters wide at the beam, has a draft of 6 meters. The ship can remain at sea for 90 days. On site, it can handle drill string lengths up to 6,860 meters (22,500 feet) with performance generally limited to 6,100 meters (20,000 feet) of water and to date has attained a maximum penetration into the seabed of 1,300 meters (4,300 feet).

The GLOMAR CHALLENGER drills a 23.5 centimeter (9 1/4-inch) hole and takes a 6.4 centimeter (2 1/2-inch) core. Larger holes, up to 20.5 centimeter (2 feet) in diameter or larger, are possible by using larger bits. The GLOMAR CHALLENGER is equipped with a 43 meter (142 foot) derrick with a hook load capacity of 454,000 kilograms (1,000,000 pounds). An automatic pipe rack in front of the derrick can carry 7,000 meters (23,000 feet) of drill pipe, with below deck space for additional storage.

Drilling and coring rates of the Deep Sea Drilling Project varied within wide limits, depending on the depth of water, sea conditions, and the nature of the material being drilled or cored.

Emplacement of waste material within the sediments should be readily accomplished in places where sediments have accumulated to significant depth on the seabed. Areas containing layers of chert and/or highly

siliceous material are exceptions. In general, the material accumulating on the sea floor is low strength, soft, porous, and requires relatively little effort to penetrate. In several instances, the GLOMAR CHALLENGER was able to penetrate tens of meters without rotating the bit.⁽⁵¹⁾ When rotation is necessary, a typical drilling rate for the softer material is 15 to 35 meters per hour,⁽⁵²⁾ and may be considerably higher.

Holes 9 and 9A, Site 9, were drilled on the northeastern flank of the Bermuda Rise east of Bermuda Island in 4,974 meters of water. Total depth of penetration was 834.5 meters below the sea floor. Average coring rate for the first 203 meters was about 91 meters/hour, coring soft oozes. For the next 630 meters, average coring rate varied from 9 to 45 meters/hour, coring clay, and for the last approximately 1/2 meter the rate was less than 0.1 meter/hour, coring igneous basement rock.⁽⁵³⁾ When encountering chert layers or when drilling "hard layers," drilling and coring occasionally were reduced to rates so low as to make progress almost negligible^(54,55,56) and at times stopped completely.^(57,58,59)

In 1970 the GLOMAR CHALLENGER developed the capability to return to the same drill hole after completely retracting the drill string. The system uses a funnel-shaped structure placed over the drill hole and equipped with acoustic reflectors to aid in positioning the drill string over the funnel. Re-entry has been accomplished in 3,962 meters of water.⁽²⁸⁾

The GLOMAR CHALLENGER maintains its position on site by means of a dynamic positioning system. The system uses a sonar beacon implanted on the sea floor to transmit signals to hydrophones extended below the ship's hull. The signals are fed to a shipboard computer which controls four tunnel thrusters and the ship's main screws to control the ship's heading and position over the hole. Under normal operating conditions, it is possible to maintain the ship within 24 meters (80 feet) of the desired location for periods as long as 6 days which is the battery life of the sonic reference on the sea floor.

Precise navigation is accomplished by means of a satellite navigation system. The system utilized four satellites of the U.S. Navy Navigation Satellite System (NNSS) in polar orbit to provide all-weather, worldwide, precise navigational information. Geographical position can be fixed with an accuracy of one-tenth of a nautical mile (185 meters) anywhere in the world, day or night, regardless of local weather conditions.

Semi-submerged drilling platforms with flotation units below the depth of wave action offer possibility of deep sea work but so far have operated only in depths of water where bottom mooring was possible.

6.2.5.2 Transportation and Handling

Depending on the size and weight of waste canister/cask units, transportation and handling could be accomplished with or developed from existing facilities. Certain features

for shielding, temperature control, and monitoring would probably require modification of existing railroad cars, trucks, or barges. Equipment for transporting material by truck is presently limited by gross vehicle weight to loads of about 25 tons, but overweight permits can extend this to about 40 tons.⁽²³⁾ Railroad cars capable of carrying useful loads of 50 to 100 tons have been in service since 1969.⁽²²⁾ Cranes are available for land use with capacities of up to 300 tons.⁽²⁴⁾

Ships are currently being built in the range of 400,000 dead weight tons for ocean tankers.⁽²⁵⁾ The only limitations on these ships is the availability of port or loading facilities. A load of three hundred 25-ton casks (total load weight 7,500 tons) should be carried without difficulty.

Aircraft have not been considered at present for transporting loads of tens of tons, but may be of possible use as intermodal transfer vehicles.

6.3 ESTIMATED RESEARCH AND DEVELOPMENT REQUIREMENTS

Research and development needs are associated with emplacement of waste and with the relationship of the waste canisters to their surroundings after emplacement. Modern drilling equipment would need some additional development, design, and modification to be capable of the emplacement operations as visualized here, but these should not present insurmountable problems. Early primary effort would be design and testing of drill pipe with sufficient strength to drill as an unsupported string in

deep sea locations and sufficient diameter to be used as a conductor for emplacement operations.

The interaction between the radioactive waste and its surroundings is the key to the successful isolation of the waste from man's environment. This interaction would be dependent upon physical characteristics of the seabed material, the sea currents, and the stability of the sea floor with respect to the time required for waste containment. The present state of knowledge of seabed conditions and materials is inadequate and would need considerable research of the type being done by the Deep Sea Drilling Project.⁽⁶⁰⁾ and Sandia Laboratories.⁽⁵⁾

In summary, the Research and Development needs are primarily those of a basic nature concerning the properties of the sea and seabed and those concerning drilling and emplacement equipment. Overall time requirements are estimated to be 25 to 30 years. A more detailed presentation of the scope of the Research and Development needs is presented below.

6.3.1 Geological/Geophysical/ Oceanographic Studies

Research and Development efforts in this area would be directed first toward determining the nature of the sea floor environment and second toward determining the effects of the heat and radiation and possible leakage of material from the waste canisters.

Research of the deep sea floor is difficult due to the extreme depths and current lack of means for sampling the bottom material in the

deeper parts of the oceans. Research would be needed to investigate the following areas:

- The nature of the unconsolidated sedimentary material of the disposal site must be known. This would include particle size, mineral composition, water content, porosity, permeability, geologic age, thermal conductivity and other physical properties.
- The nature of the consolidated bedrock material beneath the sediment needs to be identified. Because waste would probably be placed in the consolidated material, its physical and chemical properties would have to be known. A means of sampling this material would have to be developed but could be done by coring once the drilling equipment problems discussed previously were solved.
- Accurate and detailed mapping of the sea floor would have to be done in the disposal areas. This could probably be done with continuous depth profiling aided by satellite navigation systems.
- The geologic stability of the disposal area must be determined with respect to the time period necessary for the waste containment. This cannot be done directly but would come from other geologic evidence such as paleontology, age-dating of material, and paleomagnetism. These methods require samples of the material for laboratory analysis. Geophysical evidence of faulting and folding would help determine the geologic history and thus aid in determining the stability, but a detailed local study of the disposal area would also be required. Data such as those

being collected by the GLOMAR CHALLENGER in the Deep Sea Drilling Project are supplying useful information on many of these questions, but the deep ocean trenches and subduction zones are beyond the reach of its drill.

- The deep ocean currents are poorly known, particularly in the deeper trenches. Knowledge of the direction, intensity, and distribution of the bottom currents at the disposal area must be acquired because of the effect of the currents in possibly uncovering buried waste; aiding heat dissipation; and transport of material in case of leakage from the canisters. Possible future changes in ocean currents should be considered.
- The effects of heat and radiation on the material in which the waste would be placed should be studied. Once the materials were known and samples obtained, conditions could be simulated to study the effects of heat and radiation. Ideally experiments would be designed to monitor the effects of heat and radiation on the sea floor material in place, under the actual pressure conditions and in the seawater.
- The effects of corrosion by actual seawater on the surface of the waste canisters at the real temperatures involved should be studied.

6.3.1.1 Seabed Studies

The objective of the geologic/geophysical evaluation is to determine the effectiveness of the material to act as a containment medium and to assess and predict, as much as

possible, the tectonic stability of the disposal area. Samples of the bottom material are necessary to determine many of the physical characteristics. This phase of the program would begin when equipment capable of reaching and sampling the deeper parts of the ocean had been developed. The investigation of deep ocean currents would involve establishing monitoring equipment and an extended program of data collection and analysis, not only of the local area, but also regionally. The time required is estimated to be 15 years and would require a coordinated effort by a large number of scientific personnel at considerable expense. Attempts to emplace a package suitable for instrument housing are planned for the GLOMAR CHALLENGER and could be regarded as preliminary experimentation.⁽⁶¹⁾

6.3.1.2 Site Evaluation

The objective of site evaluation would be to assess the suitability of the specific site for waste disposal. The evaluation would consider the geological, geophysical, and chemical properties of the material in particular as well as the character and thickness of the unconsolidated material. Also considered in the site evaluation would be such factors as meteorological patterns and currents that might affect surface operations, relative position with respect to shipping lanes, and distance from inhabited islands and mainland. Site evaluation is estimated to take 5 to 8 years.

6.3.1.3 Laboratory Studies

The study of the effects of heat and radiation on the containment medium would also require samples or cores of the seabed material. A large portion of this study could be done in laboratories, but, to obtain the degree of safety necessary, actual in situ tests should be conducted to observe the effects under actual operating conditions of temperature, pressure, and currents at the disposal site. Corrosion effects of seawater under actual conditions would be investigated under the same program. The time required is estimated to be 5 to 10 years.

6.3.2 Transportation Systems

The transportation system as discussed in Section 6.1.5.3 is considered adequate in its essential features. Modification of existing means of transport would be needed to provide the necessary shielding and cooling capacity onboard ship. Load carrying capabilities and handling facilities are adequate for the transport and shipping casks presently considered.

Installation of specialized equipment, such as shielded cells, would be required at designated embarkation ports. This modification would not involve developing new equipment but would consist primarily of incorporating available equipment into a port facility design for optimum safety and efficiency in handling.

6.3.2.1 Transportation Vehicles

Once adequate shipping casks are constructed, the railroad cars and

truck trailers can be fitted with the necessary auxiliary equipment.

Present ships possess the cargo carrying capacity for transporting three hundred 25-ton casks. Installation of radiation shielding and cooling facilities for a concentration of shipping casks within a confined area would require considerable modification of existing ships. However, the alterations would be in the cargo or hold areas and would not affect the basic structure of the ship.

Primary research needs for transportation equipment would be investigation of adequate cooling and radiation shielding equipment to be installed for the most part on existing types of vehicles. It is estimated that 5 years would be adequate once the requirements were specified. If further analysis indicated complete redesign of ships to be more economical, an additional 5 years could be necessary.

6.3.2.2 Embarkation Ports

Certain ports would be designated as embarkation ports, chosen on the basis of their proximity to such things as the disposal area, waste processing centers, and transportation routes and distance from centers of population. The selection as embarkation ports would require considerable investigation and evaluation of candidate ports. Once they were selected, the installation of the port facilities would be undertaken. The installation would include the means for receiving the waste, off-loading, inspection, handling, and either loading on the transport ship

or storing temporarily for return to the processing plant if necessary. Investigations in this area would consist of design of the embarkation port complex as a unit to be placed within the port.

Five years time is assigned to the task of selecting ports to be the embarkation ports for the collection of waste canisters and the shipping to the disposal area. The selection would be based on the most safe and efficient relationship of all factors involved, including relative geographical location of the disposal site and embarkation port; location of waste processing plants; available transportation networks; separation from shipping lanes; adequate harbor facilities; public acceptance, and any other factors that might enter into the total concept.

The design, construction, and installation of the port facilities are estimated to require 5 years after the selection of the port is made. However, if major modification of the harbor is required, the time involved might need to be extended to ten or more years.

6.3.3 Containerization, Placement, and Operating Systems

Containerization of the wastes is assumed to be in metal canisters approximately 0.305 meter (1 foot) in diameter and 3.05 meters (10 feet) in length. A discussion of the corrosion resistance of the various metals is presented in Appendix 6.A.

Casks for transporting and shipping the waste canisters are considered to weigh from 20 to 100 tons and are described in Section 6.1.5.3.

Placement for all the concepts would probably be through the drill pipe or through a conductor pipe into the drilled hole. At present one of the main limitations in drilling in seawater of greater than 6 kilometers (20,000 feet) is the strength of the drilling pipe. For example, it is not generally accepted that drilling pipe of 66 centimeters (26 inches) diameter could be used in 7.5 kilometers (25,000 feet) without danger of failing (see Appendix 6.B). In addition, drilling ships should be able to limit horizontal motion to about 5 percent of the water depth to prevent drill string fatigue damage and to prevent permanent bending of the pipe at the sea floor surface (see Appendix 6.B).

A pilot-scale demonstration would provide an operating test for the disposal concept selected.

6.3.3.1 Containerization

Research needs on containerization are those associated primarily with the longevity of the waste canister.

Canister material must be resistant to seawater corrosion during emplacement. It may be of further value to be corrosion-resistant for a reasonably long time period while it is buried in the seabed. Further research would determine the optimum combination of design for withstanding or accommodating hydrostatic pressure and material for longevity in the disposal site environment.

6.3.3.2 Drilling Equipment

The purpose of this program would be the development of drilling equipment capable of performing the operations necessary for seabed disposal

of the waste canisters. The objective is to develop drilling pipe, hoisting equipment, drilling bits and drilling vessels with capabilities beyond those presently available. Because the development of drilling equipment would be essentially extending the capabilities of existing equipment, it is felt that 5 years would be sufficient for this task. The semi-submersible drilling vessel would probably require an additional 5 to 10 years for construction and testing.

At present there exist land-based drilling rigs with derrick capacities of 907 metric tons (2,000,000 pounds) and hook-load capacities of 454 metric tons (1,000,000 pounds).^(62,63) One of these rigs⁽⁶²⁾ is designed to lift the pipe and tools for a design depth of 12.1 kilometers (40,000 feet). Hoisting capacity is adequate for a string of pipe of this length and a 12.7 centimeter (5 inches) outside diameter; but for this length of larger diameter pipe, additional design work would be needed.

A string of drill pipe, unsupported laterally in seawater, can transmit no compressive stresses. Any extra weight for drilling purposes must be added to the bottom assembly and adds to the tensile stresses on the drill pipe and joints when lowering or raising it. The long drill string, with only the buoyant forces from the seawater instead of from a dense "weighted" drilling mud, would require very heavy duty equipment at the surface for handling it.

To obtain the strength required for drilling in water depths of

greater than 6 kilometers (20,000 feet), the pipe diameter and wall thickness could be increased. Using larger diameter drill pipe would increase the shipboard requirements for storage and considerably increase the total weight of the pipe to be transported and stored.

Aluminum drill pipe would weigh less for a given length and diameter but would lack both the needed tensile and torsional strength (see Appendix 6.B). It is possible that turbo-drills (down-hole motor drills) could be combined with steel and aluminum drill pipe in such a way that would avoid rotating a lighter, but stronger, drill string.

Considerable drilling in oil fields is being done with turbo-drills (see Appendix 6.B). Results in other areas have varied, depending on the particular location and conditions. To design a turbo-drill for hole diameters larger than 30.5 centimeters (12 inches) would require considerable extension of current drill technology, particularly if part of the center were removable by wireline to allow waste emplacement through the opening.

Semi-submersible drilling platforms, similar to those in use by the petroleum industry, offer advantages of stability for loading-unloading and drilling operations and a large area for equipment, storage and personnel quarters. At present semi-submersibles are limited to operation in water depths of about 620 meters (2000 feet).⁽⁶⁴⁾ These units are self-propelled but are designed to be moored or anchored when in position.

or storing temporarily for return to the processing plant if necessary. Investigations in this area would consist of design of the embarkation port complex as a unit to be placed within the port.

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Containerization of the wastes is assumed to be in metal canisters approximately 0.305 meter (1 foot) in diameter and 3.05 meters (10 feet) in length. A discussion of the corrosion resistance of the various metals is presented in Appendix 6.A.

Casks for transporting and shipping the waste canisters are considered to weigh from 20 to 100 tons and are described in Section 6.1.5.3.

Placement for all the concepts would probably be through the drill pipe or through a conductor pipe into the drilled hole. At present one of the main limitations in drilling in seawater of greater than 6 kilometers (20,000 feet) is the strength of the drilling pipe. For example, it is not generally accepted that drilling pipe of 66 centimeters (26 inches) diameter could be used in 7.5 kilometers (25,000 feet) without danger of failing (see Appendix 6.B). In addition, drilling ships should be able to limit horizontal motion to about 5 percent of the water depth to prevent drill string fatigue damage and to prevent permanent bending of the pipe at the sea floor surface (see Appendix 6.B).

A pilot-scale demonstration would provide an operating test for the disposal concept selected.

6.3.3.1 Containerization

Research needs on containerization are those associated primarily with the longevity of the waste canister.

Canister material must be resistant to seawater corrosion during emplacement. It may be of further value to be corrosion-resistant for a reasonably long time period while it is buried in the seabed. Further research would determine the optimum combination of design for withstanding or accommodating hydrostatic pressure and material for longevity in the disposal site environment.

6.3.3.2 Drilling Equipment

The purpose of this program would be the development of drilling equipment capable of performing the operations necessary for seabed disposal

of the waste canisters. The objective is to develop drilling pipe, hoisting equipment, drilling bits and drilling vessels with capabilities beyond those presently available. Because the development of drilling equipment would be essentially extending the capabilities of existing equipment, it is felt that 5 years would be sufficient for this task. The semi-submersible drilling vessel would probably require an additional 5 to 10 years for construction and testing.

At present there exist land-based drilling rigs with derrick capacities of 907 metric tons (2,000,000 pounds) and hook-load capacities of 454 metric tons (1,000,000 pounds).^(62,63) One of these rigs⁽⁶²⁾ is designed to lift the pipe and tools for a design depth of 12.1 kilometers (40,000 feet). Hoisting capacity is adequate for a string of pipe of this length and a 12.7 centimeter (5 inches) outside diameter; but for this length of larger diameter pipe, additional design work would be needed.

A string of drill pipe, unsupported laterally in seawater, can transmit no compressive stresses. Any extra weight for drilling purposes must be added to the bottom assembly and adds to the tensile stresses on the drill pipe and joints when lowering or raising it. The long drill string, with only the buoyant forces from the seawater instead of from a dense "weighted" drilling mud, would require very heavy duty equipment at the surface for handling it.

To obtain the strength required for drilling in water depths of

greater than 6 kilometers (20,000 feet), the pipe diameter and wall thickness could be increased. Using larger diameter drill pipe would increase the shipboard requirements for storage and considerably increase the total weight of the pipe to be transported and stored.

Aluminum drill pipe would weigh less for a given length and diameter but would lack both the needed tensile and torsional strength (see Appendix 6.B). It is possible that turbo-drills (down-hole motor drills) could be combined with steel and aluminum drill pipe in such a way that would avoid rotating a lighter, but stronger, drill string.

Considerable drilling in oil fields is being done with turbo-drills (see Appendix 6.B). Results in other areas have varied, depending on the particular location and conditions. To design a turbo-drill for hole diameters larger than 30.5 centimeters (12 inches) would require considerable extension of current drill technology, particularly if part of the center were removable by wireline to allow waste emplacement through the opening.

Semi-submersible drilling platforms, similar to those in use by the petroleum industry, offer advantages of stability for loading-unloading and drilling operations and a large area for equipment, storage and personnel quarters. At present semi-submersibles are limited to operation in water depths of about 620 meters (2000 feet).⁽⁶⁴⁾ These units are self-propelled but are designed to be moored or anchored when in position.

of the final seal would be checked at this time. The entire operation would demonstrate disposal, and it is assumed that recovery of the canisters would not be attempted.

Time required for the pilot-scale demonstration, once the equipment is developed, is estimated to be about 2 to 5 years. A separation of the various tasks and the associated estimated time required is shown in Table 6.2.

The geological/geophysical/oceanographic studies and the site evaluation will probably require the most time. The large area of the world involved, the great distances to some of the remote parts and the great depths to the seabed all contribute to the time needed for this task. The time estimate is flexible because data of the type useful to this task are presently being collected by a number of organizations. Assuming that current programs such as the Deep Sea Drilling Project, funded by

A site would be chosen for the demonstration, preferably in a locality geologically similar to one of the concept settings. The pilot-scale demonstration would utilize the actual equipment and systems to be used for disposal. The demonstration would be completed by the sealing of the canisters in the drilled hole, and the properties and effectiveness

Task	Years After Beginning						
	0	5	10	15	20	25	30
Geological/Geophysical/Oceanographic Studies	————— 1 ——— 2 ———						
Site Evaluation				————— 2 ——— ——— 3			
Laboratory Studies			————— 1 ———				
Transport Design and Construction					————— 3		
Embarkation Port Design and Construction					2 ————— 3		
Drilling Equipment						————— 3	
Semi-Submersible Platform						————— 3	
Pilot-Scale Demonstration						————— 3	
<u>Key Milestones</u>							
1	Data Collected, Tentative Site Selections						
2	Decision on Disposal Concept, Final Site Selection						
3	Begin Routine Waste Disposal						

the National Science Foundation, and ocean research vessels from various universities continue operating, the time estimate for the task could be shortened. The time required for site evaluation could also be shortened for similar reasons.

Laboratory studies would begin only after some part of the geological/geophysical/oceanographic task had been accomplished, thus supplying seabed material for use. A part of this task might include testing of waste canister material in the seabed, and observation would continue for possibly the entire period of the program.

The time required for the tasks associated with transportation, embarkation ports and drilling equipment would be somewhat dependent upon the disposal site selected. For example, some of the potential disposal sites are within reach of present drilling equipment, thus shortening the time required for further developing this equipment.

It is assumed that a number of these tasks could be conducted concurrently.

6.3.4 Research and Development Costs

Research and Development cost estimates are based on the disparity between the information currently available and that needed for evaluating the seabed disposal concepts plus the level of effort believed necessary to obtain this information. It is recognized that during the estimated 25 to 30-year program significant accomplishments by any of the groups engaged in ocean research might drastically reduce the time and cost requirements.

The Deep Sea Drilling Project, funded since 1966 by the National Science Foundation, is currently conducting research of the type to supply part of the needed information. The yearly funding rate, 8 to 10 million dollars⁽⁶⁵⁾ is therefore used as a basis for the estimated research cost. It is also estimated that universities, government agencies, and other research groups bring the level of ocean research to approximately 40 million dollars. It is felt that this effort would need to be increased to a level of about 200 million dollars per year to obtain the necessary data in the estimated time period, considering the area, personnel and equipment involved.

The spending level is estimated to reach 200 million dollars per year by the fourth year. The spending level would remain at 200 million dollars per year until near the end of the program, when it would decrease.

Total program costs are very difficult to estimate. However, it is believed that the costs would be in the range of 2 to 5 billion dollars. Of this cost, an estimated 75 percent would be applied to obtaining basic information on the sea and seabed, and, while this is necessary information, it is not directly a cost of the seabed waste disposal concepts. The remaining approximately 25 percent of the total program is considered to be the cost directly related to seabed disposal and would include the costs associated with laboratory studies, transportation systems, embarkation ports, containerization, placement and operating systems. These costs are estimated to be on the order of 400 to 1000 million dollars.

6.4 ESTIMATED TIME REQUIREMENTS FOR OPERATION

The estimated time requirement for operation is 25 to 30 years, as controlled primarily by Research and Development time needs. It is believed that once the Research and Development has been successfully carried out through the demonstration phase, routine operations could begin almost immediately.

6.5 ESTIMATED CAPITAL AND OPERATING COSTS

6.5.1 System Description for Cost Bases

To provide a basis for preliminary capital and operating cost estimates, a reference system description was selected. It is obvious that a number of variations of this reference system could be used, but that chosen is believed to be cost-representative of most variations. This section describes the reference system used for development of cost estimates.

Cost estimates are based on a 7-kilometer depth of water, which is an average depth for the deeper seabed disposal concepts. The depth of each hole drilled into the basement rock below the unconsolidated sediments is assumed to be 800 meters. One hundred canisters would be placed in each hole, thereby filling 300 meters of the hole. The top 500 meters of basement rock would be backfilled with a sealant. The total number of waste canisters is assumed to be 14,522 or the amount of waste from one reference plant reprocessing 5 MT/day of fuel over a 25-year period. This amount of waste was then

normalized to that from the estimated U.S. nuclear fuel economy through the year 2000 (with the waste disposed of in the year 2010). The canisters are considered to be 30 centimeters in diameter and 3.05 meters in length and to generate about 3 kilowatts of heat per canister. The drilled holes are considered to be on 1.6 kilometer centers. This use of drilled holes and spacing would require about 145 holes in an area of about 400 square kilometers, or an area about 20 kilometers on a side for the waste from the reference reprocessing plant.

6.5.1.1 Embarkation Facility

The embarkation facility includes a shielded cell and concrete block/steel roof buildings for the receiving facility; water cooled storage basins for about 600 canisters; office buildings; laboratories; and maintenance facilities. The receiving facility would be equipped with a 100-ton bridge crane for handling the casks. An in-cell 15-ton crane would manipulate the waste canisters and cell cover blocks. An electric/hydraulic remotely-controlled transfer cart is used in the shielded cell to transfer canisters to the load-in, load-out area below the cover block of the transfer cell. The shielded cell is equipped with six viewing windows and six pairs of slave manipulators. Fans and filters would control about 300,000 liters per minute of ventilation air.

The embarkation port would also include the pier and docking facilities, as well as a 50-ton movable crane.

6.5.1.2 Transport Ship

The transport ship's construction or modification will be directed toward its primary purpose: Transporting the waste canisters in their shipping casks from the embarkation port to the disposal site. Each cask, containing two waste canisters, is considered to weigh 20 to 25 tons.

The transport ship's capacity and dimensions would be determined by the final design size of the shipping cask, the docking facilities at the emplacement ship or platform, and the number of trips required per year. At present, a ship of 125-meter length, 25-meter beam and approximately 10,000 to 12,000 metric tons displacement is considered an adequate size for about 300 25-ton shipping casks, each containing two waste canisters. The waste from one reference reprocessing plant would require about 600 waste canisters transported per year (see Section 6.5.1). This quantity could be transported in one ship load/year if desired. However, further study may show the most efficient and economical marine transportation scheme to be that of several trips per year, carrying fewer waste canisters each trip.

The ship would be equipped with a small shielded cell. The shielded cell would be similar to (but smaller than) that previously described for the embarkation facility. However, the ship's receiving facility would be modified to permit entry and removal of the casks by shipboard crane. Cooling, as needed, and monitoring equipment would be part of the ship's systems.

6.5.1.3 Drilling Platform

For the seabed disposal concepts, a semi-submersible drilling platform is assumed for the emplacement vessel because of the larger working area available, greater stability at sea and better handling facilities for the transport ships. The platform would be constructed with a bay for firm docking of the transport ship.

The platform will be essentially self-supporting and will contain all the repair, maintenance and living facilities for an extended time on site, requiring only fuel and operating supplies on a scheduled basis.

Equipment would include a derrick with a 900-metric ton capacity and a complete drilling rig, 50- and 100-ton cranes for handling the casks and canisters, and a small water-cooled temporary storage basin for the waste canisters. It is assumed that the canisters have been inspected during transport and are accepted for disposal before transfer to the emplacement platform.

It is possible that for emplacement hundreds of meters into the seabed one drilling unit might be unable to keep ahead of the emplacement load and another rig would be required.

6.5.1.4 Operations Staff

The operations staff for the waste disposal systems as visualized is estimated to be 100 to 120 persons. These personnel are those actually associated with the handling and management of the waste and not with auxiliary systems. The operating staff can be divided approximately as shown below.

Embarkation Port

8 supervisory, 26 nonsupervisory

Administration: 4 supervisory,

10 nonsupervisory (including 5 security guards)

Engineering/Operation: 4 supervisory, 16 nonsupervisory

Operation: 7-day week, 3 shifts

Transport Waste Management Operations

(Incremental to normal ship's complement)

3 supervisory, 12 nonsupervisory

Operation (during time of actual transport): 7-day week, 3 shifts

Emplacement Operations at DisposalSite

(Incremental to transport waste management staff)

1 supervisory, 12 nonsupervisory

Operation: 7-day week, 3 shifts

Drilling Platform

5 supervisory, 35 nonsupervisory

Operation: 7-day week, 3 shifts

6.5.2 Capital and Operating Costs

Capital and operating costs for the seabed disposal concepts are divided into two groups. The concept for potential disposal sites associated with subduction zones - deep ocean trenches and for stable deep sea floor areas are assigned the same capital and operating costs because of the similarity of water depths and equipment needs. The disposal concept associated with high sedimentation rate areas is treated separately because the relatively shallower water depths would require different drilling and emplacement equipment.

The estimated capital and operating costs are summarized below in Table 6.3. See Section 3 of this re-

TABLE 6.3. Estimated Capital and Operating Costs for Seabed Disposal

BASIS: To handle the waste from one reference-sized plant reprocessing 5 MT/day of fuel for 25 years

CONCEPTS: Subduction Zones-Deep Sea Trenches and Stable Deep Sea Floor

Capital Costs, in million dollars:

1. Construction of Embarkation Port Facility	20.0
2. Sea Transport Vessel, including fully equipped Shielded Cell, 40-ton Bridge Crane, etc.	100.0
3. Deep Sea Drilling Platform (152m x 152m x 65m)	300.0
4. Drill Pipe and Casing	5.0
5. Monitoring Equipment	2.9
6. Shipping Casks (300)	45.0
Total Capital Costs	472.9

Operating Costs Per Year, in million dollars:

1. Operation of Embarkation Port Facility	1.0
2. Operation of Surface Vessel	8.1
3. Platform Operations	8.0
4. Cost of Drilling Operations	6.8
Total Operating Costs Per Year	23.9

CONCEPT: High Sedimentation Rate Areas

Capital Costs, in million dollars:

1. Construction of Embarkation Port Facility	20.0
2. Sea Transport Vessel, including fully equipped Shielded Cell, 40-ton Bridge Crane, etc.	50.0
3. Shallow Water Drilling Platform	50.0
4. Drill Pipe and Casing	5.0
5. Monitoring Equipment	2.9
6. Shipping Casks (300)	45.0
Total Capital Costs	172.9

Operating Costs Per Year, in million dollars:

1. Operation of Embarkation Port Facility	1.0
2. Operation of Surface Vessel	2.0
3. Platform Operations	8.0
4. Cost of Drilling Operations	6.8
Total Operating Costs Per Year	17.8

port for further discussion of costs.

Total costs converted to levelized charges assessed at the time of reprocessing are estimated to be \$17,000/MT or $60. \times 10^{-3}$ mills/kW-hr for the deep sea concepts. Total system unit charge for the high sedimentation rate concept is estimated to be \$14,000/MT or $50. \times 10^{-3}$ mills/kW-hr. These costs are for total waste management system costs, including reprocessing, 5-year interim liquid storage, solidification, and 5-year interim solid storage, transport to the disposal site and final emplacement. More information on the cost model is given in Section 3.

6.6 PUBLIC RESPONSE, POLICY, ENVIRONMENTAL IMPACT

6.6.1 Public Response

The overall question of public response and the public's perception of risk is discussed in Section 3.0. In that section, key elements of perceived risk are defined and the results from answers to a preliminary study questionnaire are presented. Because of the highly preliminary nature of the public response study, only tentative and qualitative indications can be derived. Some of the indications from that study are presented below.

After a brief introduction to the disposal schemes, a small group of in-house study participants perceived seabed disposal as having the highest risk level in overall ratings of risk for the five generic disposal concepts studied. After a presentation of descriptive information on the disposal schemes, seabed disposal was ranked next to the highest in perceived risk level. In general, seabed disposal was perceived as having unfavorable characteristics regarding protective measures believed achievable in event of leakage; similar reactions were recorded for retrievability, detectability and overall safety once the waste was in place. It was rated relatively safe with respect to distance and population density.

6.6.2 Policy

A number of existing treaties and agreements impose restrictions on

the use of the oceans for dumping and disposal of radioactive material. Such policies would require revisions before seabed disposal could be used. These factors are important not only because use of the seabed for disposal would require international agreement but also because once agreed to and demonstrated as feasible, the seabed could become an international repository. Policy, restrictions and international treaty agreements to seabed and other disposal concepts were considered in more detail in Section 3 of this report.

6.6.3 Environmental Considerations

The seabed disposal concepts and waste management system, if properly equipped and functioning as visualized, should have relatively little significant nonradiological effect on the environment.

Once the waste canisters were emplaced and sealed from man's environment, the effects of heat and radiation should be very small, if any. The canisters will be well down into the dense consolidated seabed material, below the circulating water level, and will be sealed from the overlying unconsolidated sediments and water by the grout or cement seal. As long as the sealing agent and disposal medium remain intact, the waste should remain isolated from the seawater, marine life and man's environment. The nonradiological environmental considerations for seabed and other disposal concepts are discussed in more detail in Section 3.

6.6.3.1 Land

The sea floor disposal area can be considered land. In these concepts, an area of about 400 square kilometers is required, or an area approximately 20 kilometers on a side for the waste from each reference reprocessing plant. This area is a result of placing 100 canisters per hole in holes drilled on a 1.6-kilometer spacing of centers and assumed here to be in a square array pattern.

Another land-use environmental effect from the seabed disposal concepts would be that for the embarkation port facility. The port facility would be a shielded cell and, including dock and loading facilities, would require an area of about 1 square kilometer. For safety assurance, the port facility would be equipped with its own separate water, power and sewer systems. Noise and atmospheric emissions should be minimal.

6.6.3.2 Water

The use of seawater for cooling the canisters would include a closed circulating system for fresh water and thus would have no effect on the sea except for a nearly undetectable temperature rise. Seawater might also be the drilling fluid. During drilling, some material from the hole would be disturbed and transported away from the hole. This material would be the naturally occurring sea bottom material and would be disturbed only locally. It is unlikely that any of it would reach the surface when drilling in water 4 to 8 kilometers deep. Heat developed

during drilling would be dissipated in the sea, and its effect would not be detectable.

6.6.3.3 Air

Essentially no impacts on the air are expected. Some exhaust gases from possibly three 1050-kilowatt (1400 hp) diesel drilling engines would present, but at an open sea location would dissipate rapidly.

The conditions under which it would be reasonably possible to find oil or gas are almost exclusively in the high sedimentation areas. If drilling into high pressured gas reservoirs were done accidentally, it is possible some gas would escape to the atmosphere before control was established. Site evaluation and test holes at a proposed disposal site would greatly reduce the probability of selecting a disposal area where gas might be encountered. At present there are no known or producing gas fields in the deeper parts of the ocean basin.

6.6.3.4 Ecologic Impact

The ecologic impact should be small. Even though the aquatic ecology of the deep sea bottom is not well known, the effect of drilling operations on it should be minimal. The disturbance of the sea floor by drilling will only be local. If seawater were used as the drilling fluid, essentially no foreign material would be introduced at the sea floor. However, future drilling may show the need for a drilling mud which would introduce other material. Although the deeper parts of the oceans are known to contain some organisms, they

are probably not abundant. The ecology of the near surface zone should be essentially undisturbed.

Gas or oil could cause some damage to the marine environment if accidentally drilled into during operations. However, prior site investigation and evaluation should essentially eliminate proposed disposal areas if any indication of hydrocarbons were found or anticipated.

If a transport ship or the drilling platform should sink, there would be a possible loss of oil and fuel that would affect marine life. The amount lost would be small in comparison to the volume of water available for dilution and dispersion. Unless the accident happened near land or in shallow water, the effect is not expected to be significant.

6.6.3.5 Aesthetic Impact

The aesthetic impact will be small. The embarkation port buildings will be of modest size, and most of the operations will be conducted within the buildings. There should be no unsightly storage yards or piles of material. The drilling and emplacement operations will be at sea where their effects will be negligible.

6.6.3.6 Transportation Impact

Overland transportation will probably be by truck or rail and would require about 100 trips per year for each reference reprocessing plant. For the total U.S. nuclear economy the number of trips could increase to about 800/year for 10-year-old waste by the year 2010. Each trip is considered as a round trip from the reprocessing plant to the embarkation

port and back to the reprocessing plant.

Marine transportation by ship from the embarkation port to the disposal site will require from one to four trips per year for each reference reprocessing plant, depending on distances involved, capacity of the transport ship and the rate at which the canisters are emplaced. This phase of transportation would be on the open seas and would have little impact on the environment.

The waste canisters could be equipped with flotation and other devices for recovering them if a transport ship should sink. Thus essentially all waste canisters from such an incident should be recoverable. During transport the canisters will be shielded and cooled to prevent radiation and high temperature effects on the environment.

Emplacement operations may make it desirable to restrict certain areas of the ocean surface to transportation by ships not involved in the disposal operation. The area would be small relative to the total ocean area available. For example, if the restricted area were twice the area of the seabed disposal area for the waste from one reference reprocessing plant, the 800 square kilometers would represent a small part of the 180,000,000 square kilometers of surface water area of Pacific Ocean alone.

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APPENDIX

SECTION 6: SEABED DISPOSAL

APPENDIX 6.A

Waste Canister Material for Seabed and Ice Sheet Environments

6.A.1

WASTE CANISTER LONGEVITY IN SEABED AND ICE SHEET ENVIRONMENTS

J. R. Divine

A survey was done of the potential suitability of materials for canisters of radioactive waste to maintain their integrity for periods of 1,000 and 1,000,000 years. In this study, there were no restrictions on materials of construction so long as the material has the potential to survive the times studied.

ENVIRONMENTS

The environments being considered are:

- Sea floor - above the mud line
- Sea floor - below the mud line
- Ice sheet - above the soil surface

In an oversimplified sense, seawater is approximately equivalent to a 3.3 to 3.7 wt% aqueous solution of NaCl. In the real sense, seawater is a complex mixture containing a myriad of constituents. The temperature of seawater at the sea bottom (excluding very shallow regions) is normally around 1°C with a range of less than $\pm 2^\circ\text{C}$. In the higher shelves and shallows it can reach 10 to 20°C. The oxygen content in the free ocean ranges from about 7 ppm (approximately saturated) at the surface to about 4 ± 1 ppm at the floor in deep ocean areas. The oxygen level reaches a minimum of 0.5 to 4 ppm at approximately 1000 meters below sea level. The oxygen concentration at the sea floor is expected to be about that of the surrounding water.

Little information has been found to date about conditions in the mud at the sea floor, particularly at depths of several feet below the mud line. It is assumed that for several feet, the temperature is similar to that of the surrounding water. Generally the mud is anaerobic with, in some cases, some hydrogen sulfide present.

The composition of the bulk of the ice cap is relatively pure water. However, at the ice-rock interface the ice could have been derived from freezing of seawater. This study will review both compositions. Information in this report is for the case where the ice has the same salinity or greater salinity than seawater. In this case the temperatures would be expected to be between 0 and -5°C . No information has been obtained on oxygen levels in this environment.

The actual temperature of the environment at the canister wall would be controlled largely by the heat in the waste. In the case of canisters buried in sea mud, as little as 0.2 kW/m of capsule length can cause cylinder surface temperatures as high as 260°C (500°F), depending on soil conductivity. With power loadings of 10 to 100 M/liter [0.16 to 30 kW/ft (or 120 to 4800 Btu/hour ft²) for 6 to 24 inch diameter, 10 foot long cylinders] there is the possibility of reaching surface temperatures of several thousands of degrees Fahrenheit.

6.A.2

When the cylinders are placed in water with only natural convection cooling, it is estimated that the surface temperature will be about 40°C (104°F).

CORROSION

The role of oxygen in corrosion processes has many aspects. Normally, higher oxygen levels are expected to accelerate the corrosion rate of metals. On the other hand, with some materials, predominantly the stainless steels or related alloys, the presence of oxygen is necessary to maintain a passive (non-corroding) state. Another variable is the water flow rate past the surface of the material. The higher the flow rate, the better the oxygen supply and therefore the greater or lesser the amount of corrosion, depending on the material.

A common form of corrosion in seawater applications is crevice corrosion. Crevices can be formed, for example, between the metal and the material on which it rests or between the metal and biologic fouling deposits. When this occurs, there is a possibility of forming an oxygen concentration cell. As a result, the metal in the crevice or immediately adjacent undergoes rapid dissolution, often leading to perforation of the metal.

Like oxygen, the effect of temperature on the canister durability is variable. It is generally assumed that a reaction rate, and therefore corrosion rate, doubles for each 10°C temperature rise in chemical processes. No work has yet been located which studies this variable in the deep ocean. Other studies in hot brine from desalination plants indicate that in the range of 80 to 187°F (27 to 86°C) there may be little temperature dependence. More information is being sought on this subject.

Stress corrosion cracking may occur in the presence of some specific ion when a metal is stressed. Practically all metals or alloys are found susceptible to stress corrosion in one environment or another. Generally chloride is the prime factor although other ions are important for various systems. High heat fluxes can effect conditions suitable for stress corrosion.

If water flows past the containers, it may entrain solids which can erode the surface. The basic methods for combating erosion-corrosion are to use extra thick pads of metal, to use a very hard metal to resist abrasion, or to use a soft coating such as gum rubber which yields to the particles but is not eroded.

PRELIMINARY RESULTS

The preliminary results are discussed in terms of aqueous environments--combining both seawater and saline polar ice conditions and hypomud line conditions.

Aqueous Environment

If only uniform corrosion is considered, many metallic claddings may be usable. These include the iron, nickel and chromium alloys, titanium,

6.A.3

zirconium and the precious metals. These have corrosion rates of less than 0.0001 mil/year, which for 1,000 years amounts to 0.1 inch (0.25 centimeter). Insufficient data are available to indicate whether the precious metals--platinum, gold, and silver--as well as zirconium and titanium are suitable for the 1,000,000-year period.

Unless special arrangements are made to prevent the waste containers from contacting other objects, crevices of some nature will be formed. In this case all of the stainless steels, the nickel base alloys (with exceptions), the copper base alloys and the aluminum alloys are eliminated, since the crevice attack can cause rapid penetration of the cladding. Materials which appear to be immune to crevice attack include the precious metals, zirconium (unless boiling occurs), titanium [if the water is less than 250°F (120°C)] and possibly Hastelloy C-276.

Other possible cladding are ceramics, glasses, ceramic-glasses, graphite and plastics. Of these, the plastics (as well as other organic coatings) would be expected to be rapidly destroyed by the radiation field. No data have yet been located to describe the effects of hot seawater (at about pH 8) on the dissolution of glass. As long as temperatures remain less than about 100°F (38°C) it is possible that glass would be suitable. Graphite and various ceramic compositions are reportedly immune to dissolution, radiation and heat. Their mechanical properties are not so good as metals, however.

Burial Below the Mud Line in Seabeds

In this situation two extremes are possible. In one case the waste loading of the containers is restricted to keep the temperature low--say, well below boiling. On the other hand, the container can be heavily loaded, which could raise the temperature significantly.

For the low temperature case, it appears that the same materials used in the open water under crevice producing conditions can be used. With the exception of silver, none of the other metals or alloys is subject to attack by sulfides commonly present in anaerobic conditions. Similarly, the glasses, ceramics, and graphite presently appear chemically reliable.

If the temperatures are expected to reach several thousand degrees, ceramics are the only containment material available since even the refractory metals lose strength and corrode rapidly. Graphite would be suitable if water/water vapor were kept away. At these temperatures, however, the attack on the interior of the container by the waste material must be considered.

GENERAL DISCUSSION

For the short term, gamma and beta radiation appear to lack a noticeable effect on corrosion rates. It is known, however, that gamma radiation will enhance the reaction of oxygen at an electrode. Additionally, radiation generates free radicals and ions which might cause some corrosive effect.

6.A.4

Reportedly, gamma radiation has no effect on graphite. In summary, no conclusions can be drawn yet regarding the effects of radiation on the long-term durability of candidate canister materials.

With a large number of waste canisters located in seawater, a thermal plume would be expected to be generated in the water. Should the plume be of sufficient magnitude, substantial water velocities might exist at the outer perimeter of the depository. This condition would provide for enhanced corrosion because of the higher flow and also because of a greater opportunity to entrain sand for erosion.

APPENDIX 6.B

Feasibility Study:

Sub-Seafloor Emplacement of Nuclear Waste

6.B.

Feasibility Study:
Sub-Seafloor Emplacement of Nuclear Waste

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Feasibility Study
Sub-Seafloor Emplacement of Nuclear Waste

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INTRODUCTION

This report evaluates the technical feasibility of embedding nuclear waste containers in the seafloor for the purpose of "permanent" disposal (i.e., possibly as long as 1,000,000 years duration). This report does not consider disposal techniques which require the waste container to rest unattended on the seafloor in direct contact with the water column, regardless of the exposure time. Three concepts to achieve embedment have been evaluated:

1. Free-fall penetration or dynamic penetration.
2. Static penetration or constant force penetration.
3. Insertion into a drilled hole.

In addition to the determination of initial embedment depths, consideration has been given to predicting the positioning accuracy of the waste containers, to identifying mechanisms which might expose the package to the water column during the required burial period, and to estimating the dollar cost of achieving seafloor embedment disposal.

This report does not consider the effects of a nuclear waste container as a heat source on the surrounding soil and soil porewater, on the overlying water column, or on animal and plant life; nor does this report consider the influence of the seabed environment on waste container deterioration.

BACKGROUND

Mankind is faced with a growing nuclear waste disposal problem, and the Atomic Energy Commission has embarked on an examination of possible disposal techniques. One possible technique is to bury or otherwise embed the waste beneath the seafloor sediment surface in a position where the wastes will be secure. Burial by this technique might be accomplished satisfactorily in most seafloor areas where no possibility of upheaval, fouling, slumping, and erosion is anticipated.

Deep-sea trenches have been specifically called out as ideal oceanic disposal sites for radioactive wastes,¹ because the trenches may be areas of occasional sediment liquefaction causing heavy containers to sink possibly 70 feet per year. Trenches have been suggested as disposal sites for low toxicity wastes; by selecting an active trench site having a high sedimentation rate, the sediment liquefaction hypothesis need not be invoked.² Then the wastes would be rapidly covered to separate them from direct contact with the water column, and they might ultimately be subducted. Certain evidence used in support of the liquefaction hypothesis are disputed,³ and the entire concept of waste disposal in trenches is objected to because of the difficulty of properly positioning the waste parcels.³

This report considers the feasibility of going one step further -- of forcing or placing the waste container far beneath the seafloor, rather than waiting for natural processes to accomplish the feat.

EMPLACEMENT CONCEPTS

Various techniques for achieving embedment beneath the seafloor surface have been evaluated primarily in terms of technical feasibility and secondarily in terms of economics and ecological effects. This section deals exclusively with the technical feasibility of the embedment concepts.

In all three concepts, the waste canisters were assumed incompressible, a cylindrical steel shell filled completely by ceramic material. These canisters would be fitted into a pipe section and the intermediate void filled with an incompressible material or filled with a fluid and pressure compensated. This exterior pipe section would serve only to transmit driving forces to the tip end of the assembly. It would not serve as a pressure vessel to maintain an internal void space at atmospheric pressure. Hereafter, this exterior pipe section and its enclosed canister will be referred to as a waste container. Container dimensions selected were outside diameters of 7, 13½, and 26 in., and wall thicknesses of ¼, 3/8, and ½ in., respectively, to enclose canisters of 6, 12, and 24 in. diameter, respectively.

The wall thicknesses required for cylindrical pressure vessel type containers were analytically estimated for the 6 and 24 in. canisters as 2.2 and 8.3 in., respectively⁴ (50,000 psi yield strength steel at 36,000 ft. of water hydrostatic pressure), compared with the ¼ and ½ in. wall thicknesses for the non-pressure resisting containers. The great wall thicknesses required for the pressure vessel type containers would present many fabrication problems and would cost a great deal, rendering the use of pressure vessels for waste containment unattractive. Alternate solutions appear technologically feasible at lower cost: for instance, the voids between canister and container could be filled with lead, grout, etc., or the voids could be filled with distilled water and pressure compensated. This approach to the containerization problem probably precludes the deep-sea disposal of canisters filled with nuclear waste of the flake or powder form because this material, with its high void space, would be highly compressible compared to the denser, solid, ceramic form and the flake form would probably require a pressure vessel container.

Briefly, the three seafloor embedment concepts are described as follows:

1. Concept 1 suggests free-falling the nuclear waste containers into the seafloor. Long waste canisters would be fitted within a pipe section, and the pipe section fitted with a streamlined nose and tail. These waste containers could be released at the water surface, or could be lowered via wire or synthetic line and released remotely while some distance above the seafloor.

2. Concept 2 considers the possibility of pushing the waste containers into the seafloor sediments using a dead weight as the driving force. This concept would likely utilize a self-propelled drill-platform/ship such as the DV GLOMAR CHALLENGER. The waste container would be attached to the end of the drill-string, looking much like an extension of it. Next would come several feet of lead-filled pipe to serve as the dead weight, then a bumper sub assembly to eliminate compressive loads in the drill-string. Such compressive loads at the drill pipe end could cause the package direction to deviate from vertical and could result in failure of the string. This

problem is easily realized by visualizing a scale model of a 22,500-foot drill-string: a 1/16-inch diameter wire hanging from a 22nd floor window to the ground.

3. Concept 3 involves first drilling a hole in the seafloor and then inserting a package or packages into the hole. This concept would also utilize a self-propelled mobile drilling platform. This concept and the previous two are illustrated in Figure 1,

Soil Profiles

The first two embedment concepts require a reliable estimate of soil engineering properties, especially the shearing strength, for use in calculating the resistance to penetration. Three idealized profiles were developed for the analytical examination. (See Figure 2.) Profiles 1 and 2 are based on extensive reliable data in the 0 to 10-foot depth interval⁵, extrapolated to greater depths via knowledge gained from Deep Sea Drilling Project findings.⁶ The strengths of relatively disturbed DSDP samples were measured and corrected for disturbance. The corrected strengths appear to be accurate to within about plus or minus 50 percent. Profiles 1 and 2 are suggested as being typical of deep ocean cohesive soils. Profile 3 is based for the entire depth on measured data obtained from the birdfoot delta of the Mississippi River.⁷ This represents perhaps the weakest soil to be found anywhere in the oceans.

A plot of an average strength profile for the California continental borderland is also provided (Profile 4). These soils are approximately twice as strong as the deep ocean soils represented by Profiles 1 and 2. This profile is a generalization of data generously supplied by oil companies; specific data and sources are proprietary. As of this writing, no conclusions have been drawn regarding the shear strength profiles to be expected from trench soils. The strengths are probably comparable to Profiles 1 and 2, however.

The strength Profiles 1 and 2, while suggested as being typical of deep ocean cohesive soils, may be considerably in error for certain environments. For instance, an erosion or slump surface near the existing sediment surface in an abyssal hill province has been found.⁸ Soil strengths above the unconformity were negligible while those in the apparently overconsolidated material beneath reached 8 psi. Reasonable penetrations in such an environment by either free-fall or static embedment concepts are impossible. However, such high penetration resistance environments can be identified by preliminary installation of a test or dummy container.

Free-Fall Penetration

The free-fall penetration concept (Concept 1 in Figure 1) involves the dropping of a long, cylindrical container with streamlined nose and finned tail from some point in the water column. This container would attain a terminal velocity, strike the seafloor surface at that velocity, and penetrate some distance into the sediment before dissipating its kinetic energy. It is a purpose of this study to predict the penetration depth.

FIGURE 1. Embedment concepts.

FIGURE 2. Soil shearing strength versus soil depth.

6.B.6

Penetration predictions were made for two waste container sizes in two soil profiles. Both containers were steel pipe sections fitted with a streamlined nose and finned tail to attain an assumed drag coefficient of 0.2 in water and 0.5 in sediment. The smaller container is 7-in. outside diameter by 17 1/3-ft. long enclosing a 6-in. diameter waste parcel of specific gravity 3.0. The larger container is 26-in. outside diameter by 38 2/3-ft. long enclosing a 24-in. diameter waste parcel. Some void space was allowed between the container wall and the waste material cylinder to facilitate loading of the containers. Calculations were made with this space or void in two conditions: filled with seawater or filled with lead. Other container characteristics are given in Figure 3.

A terminal velocity, v_0 , for the container in seawater was estimated. Then this terminal velocity and soil strength data from the desired profile were entered into the Poncelet penetration equation, which for soils takes the form⁹

$$m \frac{dv}{dt} = -s N_c A_F - \delta_a s A_s - \frac{1}{2} \rho C_D A_F v^2$$

where

m = mass of projectile (FT^2L^{-1})*

s = dynamic soil shear strength (FL^{-2}) (may vary with depth)

t = time (T)

v = velocity of projectile (LT^{-1})

N_c = bearing capacity factor (known function of soil friction angle)

δ_a = adhesion reduction factor

A_s = side area of projectile (L^2)

A_F = frontal area of projectile (L^2)

ρ = mass bulk density of soil (FT^2L^{-4}) (may vary with depth)

C_D = drag coefficient of soil (essentially constant for turbulent flow)

in which penetration resistance is expressed as a combination of static shear and inertial drag resistance.

This equation may be integrated incrementally starting from the conditions $t = 0$, $v = v_0$, and sub-bottom depth, $x = 0$, and progressing until the velocity is reduced to zero. The dynamic shear strength, s , is allowed to vary with x .

In using this procedure, the dynamic shear strength, s , in the frontal resistance term, $s N_c A_F$, was taken as twice the static shear strength given

* F, L, and T represent generalized units of force, length, and time, respectively.

<i>small</i>	<i>Size</i>	<i>large</i>
	<i>Submerged weight, lbs.</i>	
649	<i>Water filled voids</i>	17,630
979	<i>Lead filled voids</i>	22,800
	<i>Payload (waste)</i>	
2.95	<i>Volume, ft.³</i>	94.3
552	<i>Air weight, lbs.</i>	17,650
	<i>Penetration depth-nose, ft.</i>	
32	<i>Profile 1 (water filler)</i>	81
47	<i>Profile 1 (lead filler)</i>	102
181	<i>Profile 3 (lead filler)</i>	363

FIGURE 3. Free-fall container characteristics

on strength-depth profiles. This approximation corresponds roughly with average values of dynamic strength increase factor observed in recent experimental investigations.^{10,11} In the side resistance term, $\delta_a s A_s$, the dynamic strength was reduced by a factor of five,¹² corresponding to an average sensitivity of about five for typical seafloor soils, to account for the strength reduction which results from disturbance as the soil is forced out and around the advancing projectile.

Predicted penetration depths are given in Figure 3. Note that the depths listed are measured to the tip of the container nose; the tail of the container is nearer the sediment surface, i.e., for the small container with lead filler, in Profile 1, the tail is 47 ft, minus 17 ft. equals 30 ft. beneath the sediment surface.

As a rough approximation, for continental shelf sediments (e.g., California Borderlands) having twice the strength of the deep seafloor sediments the penetration depths would be about one-half of the above estimated values, for the same impact energy (energy = distance x resistance).

Static Penetration

The static penetration concept (Concept 2 in Figure 1) involves the controlled lowering of a large soil penetration assembly to the seafloor via a ship's drill-string. The assembly consists of a waste container at the bottom end, a weighted pipe section called the drive pipe, and a lead mass topping the drive pipe (See Figure 4). The waste material has a diameter, d_w , and is fitted inside a pipe section of outside diameter, d_c . Length of the container section is variable and could range up to 100-ft. A disconnect assembly is located between the waste container and several lengths of lead weighted drive pipe having the same outside diameter as the container (similar to conventional drill collar sections). A bumper sub assembly is located above the weight section providing a connection to the pipe string proper. It is envisioned that a drill ship of near conventional design would lower this total assembly to the seafloor. The waste container would be permitted to enter the seafloor under the influence of the weighted pipe section. As penetration progressed the assembly would encounter increasing resistance until eventually the weight of the weighted pipe sections would be balanced. At this point the disconnect would be effected leaving the container as the drive pipe is withdrawn from the sediment.

Two elements are to be examined. First, the load-penetration relationship for three container diameters and three soil profiles; and, second, the buckling load-length relationship for the length of drive pipe above the seafloor surface.

Load-Soil Penetration. Static penetration analysis assumes that the waste container enters the seafloor at near zero velocity. No engineering assumptions are required for a dynamic soil shearing strength or for drag coefficients. The analysis follows that used in a conventional pile foundation behavior prediction where

$$Q_d = Q_p + Q_s - Q_b$$

FIGURE 4. Static penetration concept.

$$= q_p A_p + 2\pi r f_s D_f - A_p D_f \gamma_s$$

where

Q_d = bearing capacity (F)

Q_p = point resistance (F)

Q_s = side resistance (F)

Q_b = soil bouyancy effect (F)

q_p = point pressure (FL^{-2})

A_p = cross-sectional area of pipe (L^2)

r = pipe radius (L)

D_f = depth of embedment (L)

f_s = average side resistance pressure (FL^{-2})(skin friction)

γ_s = unit weight of the soil (FL^{-3})

In the above relationship, the point pressure, q_p , is equal to $9 \times c$, where c is the soil shearing strength, and the skin friction, f_s , is equal to c . The point resistance is the same as that used in predicting the ultimate capacity of piles used in foundations;¹³ the skin friction differs in that pile design assumes a reduced available skin friction due to different soil strains along the pile.¹⁴ The assumption of $f_s = c$ for this waste container penetration analysis may therefore be somewhat conservative.

Container outside diameters of 7-, 13½-, and 26-in. were selected with waste package diameters of 6-, 12-, and 24-in. (similar to those used in the free-fall analysis). Figures 5 and 6 illustrate the effect on penetration of varying the soil strength profile, and Figure 7 illustrates the effect of varying the container diameter. The difference between Profiles 1 and 2, in terms of penetration performance, is negligible. Figures 5, 6, and 7 depict only the relationship of static penetration depth versus load on a weightless tube.

Loads required for the 7-in. diameter concept are quite reasonable even with today's state-of-the-art, for instance, 100 kips are required to push the container to 90 ft. (with the tail of the container 72 ft. beneath the sediment surface). If it is assumed that, when the container is disconnected, a force of 100 kips will be required to extract the weighted pipe section from the sediments, then the drill-string tip will be required to exert a pull of 200 kips.

The ALCOA SEAPROBE is a specially designed deep-ocean search and recovery vessel built along drill ship lines. This ship, if it were equipped with a special, high-strength steel drill-string, is expected to handle this load of 200 kips in 18,000 to 20,000 ft. of water.¹⁵

FIGURE 5. Load required versus penetration depth for the 7-inch diameter pipe in three profiles. - static penetration

FIGURE 6. Load required versus penetration depth for the $13\frac{1}{2}$ -inch diameter pipe in three profiles — static penetration

Drive Pipe Buckling Load. Further concept examination reveals that the container penetration is not so easily obtained. If the weighted pipe sections are made the same outside diameter as the container, and then the interior of the pipe filled with lead, the weight of a one-foot length is not sufficient to drive the assembly one foot deeper. Additional force must be applied at the top of the assembly; and since the drill-string can transmit no compressive forces, this force must come from an added mass at the top of the penetrating assembly. The volume of this added mass will probably prevent further penetration much like the head of a thumb tack. Moreover, during intermediate stages of penetration, while a laterally unsupported length of weighted pipe remains above the seafloor, this length of pipe will be in danger of buckling. The effect of this failure mode on the static or forced penetration concept was briefly examined analytically.

The laterally unsupported length of the lead-filled pipe was treated as a pin-ended column (see Figure 8). For simplification, the column was treated as weightless. The Euler buckling load of such a column is

$$P_c = \frac{\pi^2 EI}{L^2} \quad (\text{derived for example in reference 16})$$

where

E = modulus of elasticity

I = moment of inertia of the section

L = unsupported length

Critical loads, at which column buckling is incipient, were calculated for a range of lengths, L, and are plotted in the top half of Figure 9. This curve represents the Euler buckling load versus length for a 7-in. outside diameter pipe with wall thickness of 7/8-in. In the bottom half of Figure 9, the penetration resistance versus embedment relationship is plotted, to the same scale. This embedment relationship is modified somewhat, by calculating the weight of the assembly in the sediment to arrive at the load required at the sediment surface. This modification yields Curve A of Figure 9. Figure 9 connects the two thoughts of assembly length embedded in the soil and remaining assembly length standing above the seafloor. For instance, a 70-kip load applied to the assembly will cause it to penetrate 80 ft. in a material having the shear strength of Profile 2. At this axial compressive load, the maximum possible length of remaining assembly above the sediment surface, to avoid buckling, would be about 48 ft.

The form of Figure 9 was altered in Figure 10: specifically, the length-depth scale (ordinate) has been re-arranged. In Figure 9, length is measured from the seafloor surface; but, in Figure 10, length is measured from the tip end of the penetration assembly. Thus, in Figure 10, the vertical scale now shows the maximum possible assembly length for a given axial load. The maximum length function dips to a minimum at 124 ft. corresponding to 40 kips load -- the 7 in. O. D. assembly cannot exceed 124 ft. in length. Further, assuming the large mass at the head end of the assembly does not penetrate the soil, the maximum tip embedment for the 7 in. O. D. container is 124 ft. A similar analysis of the 26 in. O. D. container

FIGURE 8. Analytical model of drive pipe in the static or constant force penetration concept.

indicates that the maximum assembly length is 300 ft., or that the maximum tip penetration is 300 ft. (see Figure 11). Next, of course, comes the question of whether the required loads could be handled by a surface vessel.

Handling Feasibility. The 7 in. assembly, 124 ft. long, would weigh 190 kips submerged and extraction from the sediments would require twice that or 380 kips capacity at the tip of the drill-string. The ALCOA SEAPROBE can accomplish this task in 6,000 ft. water depth but not in 20,000 ft. This limit is due mainly to the strength of the drill pipe and the drill pipe steel. In order to obtain 380 kips capacity at 20,000 ft., a much larger diameter drill pipe would be required compared to the 4½ in. O. D. pipe presently on the ALCOA SEAPROBE. The change is possible. A recent study has shown that 10 ¾ in. O. D. pipe of high grade steel will satisfactorily support a load of up to 1200 kips to a depth of 7,500 ft.¹⁷ Combining this size and quality of pipe near the surface with a tapered pipe could possibly provide 380 kips uplift at 20,000 ft. Derrick, sheaves and hoisting equipments, and working platform would require limited extensions of current technologies.

The 26 in. O. D. assembly, 300 ft. long, would weigh 2530 kips submerged and would require 5060 kips for extraction; this 25-fold required increase in lift capability, while not impossible, does seem too great a hurdle to consider.

In conclusion, it appears feasible to embed a waste container of 7 in. O. D. in water depths to 20,000 ft. by a forced or static penetration concept to a soil depth of 124 ft. (106 ft. tail to soil surface). The embedment of containers of greater diameter, or the embedment of the 7 in. container to greater depth, are problems of much greater difficulty.

Insertion in Drilled Hole

In the concepts reviewed previously, the waste container has been utilized to form its own hole. Now the possibility of first forming the hole and then inserting the container into that hole will be considered.

Drilling Background. The technology of offshore oil well drilling has taken great strides in recent years. Most drilling from floating rigs has been done with the vessel moored in position with, say eight drag anchors positioned around the ship. Deeper water depths cause the moored system to be overly expensive because of the large capital outlay for mooring lines and because of the significant time cost involved in establishing and recovering each mooring. Drill ships must limit horizontal vessel motion to about 5 percent of water depth to prevent drill-string fatigue damage and to prevent permanent bending at the seafloor.^{18,19} Where moorings cannot be established, dynamic positioning has been used with success.^{20,21,22}

The drilling of an offshore well requires the use of a riser pipe to the surface. This riser pipe serves mainly to conduct drilling mud used to support the hole walls, it also serves to guide the drill bit back into the hole on the seafloor. Riser pipes have been used in water depths to 1700 feet, incorporating special buoyancy material,²³ but their use in greater water depths is uncertain. Non-petroleum production drilling, such as the present GLOMAR CHALLENGER (Deep Sea Drilling Project) operations for

scientific purposes, are able to drill in deeper water by eliminating the riser pipe. Because drilling mud cannot be returned to the surface, seawater is used as the drilling fluid to cool the bit and to remove cuttings from the hole. Seawater is an excellent drilling fluid, apparently increasing the cutting rate of the bit, but it does not assist in supporting the walls of the hole.²⁴ Because the riser pipe is eliminated, the drill bit cannot easily re-enter the drill hole. Presently, the Deep Sea Drilling Project (DSDP) has developed bits of sufficient quality to permit reaching seafloor penetrations of interest ¹⁹ (to 4300 ft. beneath the seafloor).²⁵ A technique has been developed to effect re-entry into an established drill hole using a landing base cone on the seafloor and a sonar transducer at the tip of the drill-string.²¹ (See Figure 12.) To effect re-entry the sonar transducer in the drill-string locates the landing cone and the ship is maneuvered to bring the bit over the 14 ft. diameter cone.

In regions having turbidites (deep sea sands) a drill-string can jam very quickly due to hole collapse when supporting drilling mud or casing is absent. Occasionally the drill-string and bit are freed, but often a portion of the assembly is broken off or explosively cut off.²⁶

Deep-sea drilling has been done primarily from conventional ship configured vessels. A new breed of deep ocean work platform has evolved, however, partly due to work done for the Project Mohole, sponsored by the National Science Foundation, and carried out by Brown and Root, Inc. This new breed is generally referred to as a semi-submersible. Although some semi-submersibles to date have been self-propelled in transit, they have all been operated as moored platforms during drilling, most likely because operating water depths have not been sufficiently great to render moored systems uneconomical.

The ideal drilling platform is fast moving, semi-submersible for high stability, dynamically positioned, and capable of operating at any water depth. Unfortunately, existing platforms do not incorporate all of these characteristics in one vessel type: the ship configured vessel is faster (10 knots versus $1\frac{1}{2}$ - 2 knots for the semi-submersible) and safer in transit than the semi-submersible, but the semi-submersible has better on station stability and can thus operate in worse weather and for longer periods compared to the ship configuration.²⁷

Feasibility. Given this very brief and necessarily incomplete introduction to state-of-the-art ocean drilling from a floating platform, the problem of placing a container beneath the seafloor was then approached. The GLOMAR CHALLENGER has demonstrated a capability to drill a hole of 9.875-in. diameter to a depth beneath the seafloor on the order of 4,300 ft. in non-turbidite materials. The maximum water depth in which the ship is capable of working is 20,000 ft., which encompasses more than 98 percent of the seafloor but excludes many seafloor trench areas. The ship can presently handle 22,500 ft. of drill-string for a 2,500 ft. bottom penetration at the deepest water depth. By changing a portion of this drill-string to aluminum (from the existing steel) additional aluminum pipe can be added to attain a 25,000 to 30,000 ft. long drill-string.²⁸ A new vessel, now under construction, is believed to have a design pipe string length of

FIGURE 12. Dynamic positioning and hole re-entry acoustic systems.

30,000 to 35,000 ft.²⁹ (but this string may be non-rotating). The drill-string of the drill ship GLOMAR CHALLENGER is 5 in. O. D. and 3 15/16 in. I. D. Further, the technology exists today to return the entire drill-string to the surface and then lower it to the seafloor a second time and re-enter the same drill hole.

This state-of-the-art, i.e., 3 15/16 in. I. D. pipe, offers two waste disposal techniques. First, the drilled hole can be extended to desired depth, the drill bit can be disconnected remotely, and very slender containers of about 3 in. diameter could then be run down the inside of the pipe and out the open drill pipe end as the drill pipe is raised a few feet to accommodate. The overall volume of waste is small with such a small diameter, but the accompanying low heat content requiring dissipation may be desirable. Second, the drilled hole can be extended to depth and then the drill-string tripped to the surface. Here the bit would be replaced by the first waste container of 8 to 9 in. diameter and the string tripped back to the seafloor where the container would be guided into the hole by available acoustic re-entry techniques. The container would be lowered to the bottom of the hole and released hydraulically. In both of these techniques, it is possible to place more than one container in the same hole, one on top of the other, possibly with grout plugs between, and in any case with a grout seal for some distance over the last container.

The possibility of passing larger diameter waste containers through a drill pipe was considered. First, in order to pass larger size containers through a drill pipe, the drill pipe diameter would have to be increased and would probably become prohibitively heavy and would consume far too much ship space. (For instance, 26-in. O. D. casing demands at least a ten-fold increase in weight and a 25-fold increase in volume.) It is possible that the pipe string could be made of aluminum to alleviate the weight problem, but aluminum does not have high strength in torsion, and thus would not long endure. These torsional stresses can be greatly reduced by switching to a large turbo-drill, where the rotary motor is located immediately above the bit and the drill-string does not rotate. The Western Europeans and Russians use turbo-drills on about 90 percent of their oil wells.²⁴ However, the design of a turbo-drill to drill a large diameter hole, and to pass a container of say 26-in. diameter through the bit, would require considerable development -- possibly a large portion of the turbo-drill would have to be removable by wire-line to provide the necessary opening. But, given all this conjecture, it is not yet generally accepted that such a large diameter pipe can be made to reach 25,000 feet in length in the ocean without danger of failing.

For larger diameter containers, it appears a great deal more practical to utilize the acoustic hole re-entry technique. Thus, the landing base cone and its attached 160-ft. length of casing would be enlarged to accommodate a larger bit. The AEC is responsible for much large diameter rock bit design through its Nevada Mercury project and Amchitka Island test. In shallow seafloors, holes to 42 in. diameter have been drilled.³⁰ Sufficient energy should be available to turn the larger drill bit because wall friction losses would be reduced by the larger hole diameter to pipe diameter ratio. However, pipe whip in the hole may be aggravated, and the whip may in turn reduce the stability of the drill hole walls. However,

since 9 7/8 in. holes have maintained their integrity, the problem does not appear insurmountable.

In summary, then, it appears that waste containers of up to 9-in. diameter and variable length could be deposited up to 4,300 ft. beneath the sediment surface and 25,000 to 30,000 ft. beneath the water surface with only minor hardware development. In addition, it appears likely that limited development could make possible the depositing of much larger diameter containers.

Other Concepts

During the course of this evaluation, two other embedment concepts were suggested: (1) use of a submarine to act as the drilling platform to minimize the drill-string length, and (2) development of a seafloor mole (probably expendable) to push or pull containers into the soil. The use of a manned submersible combined with a drilling platform appears very unlikely because man would be required to remain inside a small steel sphere, while the drilling rig operated automatically outside at ambient pressure -- under these conditions man might just as well monitor the operation from the sea surface via television and other electronic aids. Thus, man was removed from the seafloor platform, and Concepts 1 and 2 were considered together.

First a semi-automatic, remote controlled drilling platform is possible, especially for shallow penetrations of say 100 ft. An incremental seafloor corer has been built to obtain continuous soil cores to 50 ft. below the seafloor in water depths to 6,000 ft.³¹ Although considerable system modification would be necessary to reach a water depth of 20,000 ft., including probably a seafloor power supply and buoyancy units, the drilling unit itself would not be more complicated except for devices to increase reliability. Other possibilities arise such as placing the containers at the tip ends of jacked-in or screwed-in piles installed from a seafloor platform, probably bottom powered; such a platform to function in 6,000 ft. of water has been discussed.³² The screw augers could operate from a much smaller frame, drive themselves in, and tow a small waste package. A prototype auger mole system has been considered as a propulsion unit for a sediment in-situ property measurement device.³³

These seafloor based embedment techniques have not been evaluated in this report; however, it is probably true that they will be limited to a soil penetration of 50 to 300 feet. Proper evaluation will require a preliminary hardware design for each including power supply and transit technique from sea surface to the floor and from site to site. For such an evaluation, definitive guidelines will be required on the required soil cover over the container, on the allowable exposure time to the water column, etc.

PERIPHERAL CONSIDERATIONS

Proposed radioactive waste disposal via embedment in the deep-seafloor requires examination of a great many factors other than the problem of accomplishing embedment described earlier. A few of these problems are reviewed here. First, radioactive waste containers require accurate positioning with respect to (hereafter abbreviated wrt.) seafloor topography

and a global coordinate system. Second, some seafloor soil types may undergo considerable reductions in shear strength when subjected to earthquake forces, at which time waste containers of high density would sink deeper in the weakened soil mass to supposedly safer positions; the validity of both hypotheses, that liquefaction of deep-sea soils can occur and that a deeper position attained through liquefaction is safer, must be established. Thirdly, certain environmental factors may result in the soil cover over a waste container being reduced in depth; areas where such uncovering can occur should be established. Fourth, although cost has been largely ignored earlier, it is an important determinant, after safety and environmental factors; therefore, a short cost analysis is presented.

Other equally serious problems, such as the influence of waste container heat on the sediment strength and on the soil porewater flow, are not treated herein.

Positioning and Position Determination

Accurate container positioning and position determination is a necessity to prevent containers from being placed too close together, to avoid subsequent drilling into contaminated zones, and to make possible meaningful environmental monitoring. In this section, various pieces of data are assembled and combined to give resultant position determination and positioning accuracies. The accuracies quoted are statistical quantities and are selected such that waste container emplacement operations will be within these limits 99.7 percent of the time. It was assumed that the entire family of data from any one operation could be represented by a normal distribution; therefore, the accuracies quoted represent three standard deviations, 3σ .³⁴ The predicted position accuracies for various waste container disposal operations are presented in Table I and Figures 13 and 14, and their origin explained below.

Ship Position wrt. Global Coordinates, 1 Sighting, Table I-A1. At sea, a good satellite positioning system, incorporating pitch and roll sensors and a ship velocity sensor, is reported capable of a ± 250 ft. rms (root mean square) position determination accuracy wrt. global coordinates.³⁵ This statistical description means that, given a collection of measured positions, 68 percent of these measured positions will be within 250 ft. of the respective real global coordinate positions.³⁴ This ± 250 ft. accuracy represents one standard deviation, σ , of a normal distribution, which can be tripled to obtain three standard deviations, 3σ , equal to ± 750 ft. This 3σ statistical description means that, given a collection of measured positions, 99.7 percent of these measured positions will be within 750 ft. of the respective real global coordinate positions.³⁴

Ship Position wrt. Global Coordinates, 15 Sightings, Table I-A2. If the vessel were to be maintained perfectly on station while repeated satellite sightings were made (approximately once every 90 minutes),³⁵ then increasing accuracy in establishing the ship's position would be achieved according to:

$$3\sigma_N = 3\sigma_1 / \sqrt{N} \quad \text{Reference 34}$$

Table I. Position Determination and Positioning Accuracies

		Accuracy expected 99.7% of the time (to nearest 10 ft.)
A. Ship Position Determination wrt. Global Coordinates		
1. Given 1 satellite sighting ³⁶		±750 ft.
2. Given 15 satellite sightings while being dynamically positioned wrt. seafloor acoustic beacon		±250 ft.
B. Seafloor Acoustic Beacon Position Determination wrt. Global Coordinates		
1. Given 1 satellite sighting		±750 ft.
2. Given 15 satellite sightings while being dynamically positioned wrt. seafloor acoustic beacon(s)		
a. Short baseline system		±250 ft.
b. Long baseline system		±250 ft.
C. Waste Container Excursion Circle wrt. 1 Seafloor Acoustic Beacon		
1. Container on drill-string above seafloor		±60 ft.
2. Container free-fallen from 500 ft. above seafloor		±70 ft.
D. Waste Container Excursion Circle wrt. 3 Seafloor Acoustic Targets or 3 Seafloor Acoustic Beacons, 1500 ft. long baseline.		
1. Container on drill-string at seafloor		±30 ft.
2. Container free-fallen from 500 ft. above seafloor		±40 ft.

FIGURE 13. Mapping accuracies of emplaced container position with respect to global coordinates.

FIGURE 14. Emplacement accuracies with respect to bottom acoustic beacons for static embedment and drilled hole concepts. (See Table I for free-fall embedment concept accuracies.)

where $3\sigma_1$ = accuracy of position determination based on one sighting

N = number of sightings

$3\sigma_N$ = accuracy of position determination based on the average of N sightings

Thus, if the position determination accuracy of one sighting, $3\sigma_1$, is taken as ± 750 ft., then the average result of 9 sightings will be:

$$3\sigma_N = \pm 750 / \sqrt{9} = \pm 250 \text{ ft.}$$

This number is theoretically correct for 9 sightings, but not realistic because the ship cannot maintain a strictly fixed position. It has been assumed here, with the support of references 35 and 36, that the achievement of a position determination accuracy on the order of ± 250 ft. would require about 15 satellite sightings while being dynamically positioned with respect to a seafloor acoustic beacon.

Seafloor Acoustic Beacon Position wrt. Global Coordinates, Table I-B. An appropriately equipped vessel is capable of determining its position wrt. a seafloor acoustic beacon with an error of 0.1 percent (rms) of the water depth, or about ± 20 ft. rms accuracy in 20,000 ft. of water.^{20,37} If these data are treated similar to the data of the previous sections, the result indicates that a ship can determine its position with respect to the position of one seafloor acoustic beacon with an accuracy of ± 20 ft. about 99.7 percent of the time in 20,000 ft. of water. This estimate assumes about 15 observations of the beacon within a few minutes time interval.

The combination of the above statistical accuracies, for the object of beacon position accuracy determination, is accomplished via the relationship:

$$3\sigma_R = \sqrt{\Sigma (3\sigma_N)^2} \quad \text{Reference 37}$$

where $3\sigma_R$ is a resultant accuracy arising from the combination of two or more component accuracies, $3\sigma_N$. For instance, the position determination accuracy for a seafloor beacon wrt. global coordinates, based on 1 satellite sighting and 15 acoustic beacon sightings, is obtained as follows:

$$3\sigma_R = \sqrt{(\pm 750)^2 + (\pm 20)^2} \approx \pm 750 \text{ ft.}$$

Figure 13 illustrates the position determination accuracies that are obtainable with present commercial systems.

Waste Container Emplacement Accuracy wrt. 1 Seafloor Beacon-Static and Drilled Hole Concepts, Table I-C1. Determining the position of an established container is only half the problem -- placing the container at a preselected point is the other half. In order to place a container at a given point, it is necessary to determine its present location wrt. to that point and then move the container. Individual accuracies are involved with each step

in the positioning process; these individual accuracies have been combined and the resultant accuracies for various emplacement procedures presented in Table I.

To emplace a container with reference to one seafloor acoustic beacon, the ship must maintain position above the beacon; must determine the location of the container wrt. the ship; and then must maneuver the waste container, on the end of 20,000 ft. of drill pipe, over the desired point. The position of the seafloor beacon and the position of the container wrt. the surface can be determined to ± 60 ft. accuracy for each measurement, individually (where 60 ft. is assumed to be 3σ in 20,000 ft. of water, based on reference 20). However, because a portion of this error arises due to attitude changes of the surface ship, and because this portion of the error in simultaneous position determinations is cancelled, the ability to measure container position wrt. the seafloor beacon is improved over the sum of the component errors, being about ± 60 ft. for 3σ ,^{38,39} i.e., the sum-of-squares formula does not apply. Thus, the position of the container wrt. one seafloor acoustic beacon can be determined with an accuracy of ± 60 ft.

The container, at the end of a drillstring (and presumably also at the end of a wire or synthetic rope), can be maneuvered over a 7 ft. radius landing base cone.²¹ This ± 7 ft. maneuvering capability of the drillstring end is not a statistical accuracy, but it has been incorporated into the analysis as if it were a 3σ accuracy. Thus, combined "accuracy", wrt. the seafloor reference, would be

$$3\sigma_R = \sqrt{(\pm 60)^2 + (\pm 7)^2} = \pm 60.4 \text{ ft.} \approx \pm 60 \text{ ft.}$$

This is the positioning accuracy wrt. the seafloor beacon, not the global coordinate system; this accuracy applies to the static embedment concept and the drilled hole concept.

Waste Container Emplacement Accuracy wrt. 1 Seafloor Beacon--Free-Fall Concept, Table I-C2. The positioning accuracy of a free fallen waste container wrt. 1 seafloor beacon will depend on the positioning technique employed, the container velocity, the current velocity distribution and its variation with time, and the stability of the container. A free falling waste container of specific gravity about 3 may not be perfectly stable, even though it will be streamlined and finned.⁴⁰ It is possible, at the high velocities required for seafloor embedment, to develop a significant imbalance of the pressure field acting laterally on the container, exceeding the mass-buoyancy righting moment, and causing the container to glide away from its design trajectory.³⁸ Reliable quantitative answers as to the probability of gliding away may be available elsewhere, but are considered beyond the scope of this report.

However, it is still possible to achieve free-fall embedment with reasonable accuracy by lowering the waste container via synthetic line to about 500 ft.⁴⁰ above the seafloor and then releasing the container via an acoustic release device. The distance above the seafloor at the time of release would be selected such that the container would be moving at or near terminal velocity at the instant of seafloor impact, but yet would

not have appreciable time during which to glide away from the desired trajectory.

It is assumed that the currents in the last 500 ft. above the seafloor can be pre-measured and that they will remain constant over the time interval of interest; thus the current influence on positioning accuracy during free-fall can be pre-calculated, and the current will have no influence on overall accuracy. In the 500 ft. drop the container will still deviate somewhat from the pre-calculated path due to turbulence about the container and minor, temporary changes in attitude. The accuracy of the predicted free-fall path is estimated to be ± 25 ft. at impact $(3\sigma)^{40}$ based on engineering experience with little supporting data. Combined accuracy for the 500 ft. drop, free-fall embedment concept, wrt. one seafloor reference, would therefore be

$$3\sigma_R = \sqrt{(\pm 60)^2 + (\pm 7)^2 + (\pm 25)^2} = 65.4 \text{ ft.} \approx \pm 70 \text{ ft.}$$

Waste Container Emplacement Accuracy wrt. 3 Seafloor Beacons, Table I-D.

Should it be necessary, the positioning accuracy of containers about to be embedded may be significantly improved by employing three or more established seafloor reference points. The seafloor points may be either acoustic reflectors or acoustic beacons. Three such points established about 1500 ft. apart will permit position determination accuracies of ± 30 ft. (3σ) , assuming the three seafloor beacons were surveyed in with a towed fish.^{38,39} (If the seafloor beacons were surveyed in by the survey vessel in 20,000 ft. of water, then position determination of the container wrt. the beacons would deteriorate to about ± 60 ft., 3σ .^{38,39}) Combining this accuracy with the ± 7 ft. maneuvering accuracy and the ± 25 ft. free-fall drop accuracy yields an accuracy of ± 30 ft. (± 30.8) for the static embedment and drilled hole concepts and ± 40 ft. (± 39.7) for the 500 ft. drop, free-fall embedded concept, wrt. the three seafloor references.

Figure 14 summarizes some container emplacement accuracies considered attainable 99.7% of the time.

Deep Ocean Trench Characteristics

As discussed previously, deep ocean trenches have been suggested as possible waste disposal sites. Advantages of some trench locations are their susceptibility to earthquakes and the possibility, held by some, that material present on a trench bottom may eventually be subducted into the interior of the earth. Frequent earthquake occurrence is being regarded as a beneficial factor to the waste disposal problem since earthquakes may produce liquefaction of coarse grained sediments which would in turn cause progressively greater penetration of high density waste parcels.

Trenches also have serious disadvantages: material in trenches may be more heterogeneous and since the topography is more rugged than most deep ocean locations, accurate positioning is more important. Even if subduction is accepted, the trench sediments may be scraped off by the landward wall instead of progressing more deeply into the earth.⁴¹ Furthermore, the subduction process may be episodic having long inactive periods.⁴²

A brief investigation was made of the sediment types to be found in trenches and their susceptibility to liquefaction during earthquakes.

Trenches are very difficult to explore acoustically because they tend to produce a weak and scrambled echo. An extremely narrow beam sounder is needed. The trenches which have been explored, even those which are very deep and V-shaped, have a narrow band of nearly flat bottom, 1600 to 10,000 ft. in width, which is usually attributable to sedimentary fill. The trench bottoms may often be made up of a series of basins or terraces separated by sills tens to hundreds of feet wide. Pinnacles or ridges may often project from the trench flanks.⁴³

The sedimentary contents of the trenches are probably quite varied, perhaps more so than other portions of the deep ocean. Since many trenches lie directly off continents, they serve as traps for sediments being eroded from the land. These sediments may often be deposited in the form of turbidites, or graded sand and silt beds. For instance, all level areas of the Aleutian Trench are believed to contain turbidites.⁴⁴ If it can be presumed that the turbidites of trenches do not differ significantly from similar deposits in other elongate disposition basins,⁴⁵ then the data from non-trench turbidites may be used to analyze the behavior of trench turbidites.

In terms of liquefaction potential it is possible to rapidly evaluate a sediment for a particular magnitude earthquake.⁴⁶ The technique requires a mean sediment grain size, sediment buoyant and total unit weight, and earthquake magnitude. The mean grain sizes for a graded turbidite in the Hudson sub-sea fan fall between .087 and .177 mm;⁴⁷ this size range is very susceptible to liquefaction.⁴⁶ Typical values of the ratio of total to buoyant unit weights is probably two to three. Finally, a reasonable design earthquake magnitude for the active trenches in the western Pacific would be 8.0. Given these values, the analysis technique of reference 46 indicates that liquefaction could occur to sub-bottom depths in excess of 100 ft. Thus, it is not certain that liquefaction would occur, but a strong possibility does exist.

In regions where numerous small, shallow focus earthquakes occur (e.g., the Aleutian trench) the probability of liquefaction is reduced outside of the immediate epicentral area. However, since liquefaction has occurred during earthquakes with magnitudes as low as 5.5 (1957, San Francisco),⁴⁶ the potential for liquefaction under the adverse conditions of the seafloor is still significant.

It is likely that it will be more difficult to embed containers via the free-fall mode in trench turbidites than in deep ocean clays and oozes. An example of this is provided by the core length data of reference 44. Core lengths from the Aleutian Trench are found to be the shortest of many throughout the North Pacific, probably as a result of high soil strength although conceivably as a result of sediment washing out of the core liner. To progress beyond more than a qualitative evaluation of trench sediment penetrability is not possible at present.

Mud Lumps, Slumping, and Erosion

In general, a relatively dense object that has been sequestered into the sediments of the seafloor will remain buried. Events disruptive to the depositional process include piercement forces (forces responsible for instance for salt dome formation), sediment slumps, submarine landslides,

and erosion. These events are almost exclusively restricted to continental margins and concentrate in areas of rapid sedimentation where these phenomena have been observed or inferred from the seafloor's topography and sub-bottom structure.

Of the various materials that are known to have formed piercement structures (mud, salt, shale, igneous intrusions) only soft sediment intrusions (mud lumps) can form and move rapidly enough to expose a sequestered waste container within several thousand years. Mud lumps have formed off the mouth of the Mississippi River with such rapidity that transient islands are formed which are eroded over a few seasons by surface waves.⁴⁸ Mud lumps have also been reported on the deltas of the Magdalena,⁴⁹ the Niger,⁵⁰ the Orinoco,⁵¹ and the Fraser⁵² Rivers. No mud lump structures have been reported from abyssal plains provinces.

Slumping of overlying sediment could conceivably expose a waste container to the seawater column, or could significantly decrease the thickness of overlying sediment. Unstable slopes have been noted only in specialized areas of relatively rapid accumulation, such as river deltas and submarine canyons.^{53,54} Fortunately, most sediments in the deep sea are deposited at such a rate that consolidation is complete and quite steep slopes will be stable, hence, slumping does not appear to be a mechanism in the deep-sea^{53,54,55} (assuming no local tectonics).

Hagerty⁸ has reported direct evidence of sediment overburden removal in an abyssal hills province in the North Pacific. Box cores obtained contained an erosion or possible slump surface. Combining the 8 psi vane shear strength of the clay beneath the unconformity with the idealized Profiles 1 and 2 (Figure 2) suggests that 100 ft. of overburden may have been removed in this area. This unconformity occurs in a faulted region containing submarine basalt outcroppings.

Other evidence, indirect evidence, of deep-sea erosion has been reported by others. This evidence consists of seismic reflection records of sediment distribution about topographic anomalies; the distribution patterns are suggestive of post-depositional redistribution by bottom currents, but may be better explained as resulting from non-deposition. Hamilton⁵⁶ has shown that the depressions which encircle many seamounts in the northeast Pacific are caused by non-deposition, as the subsurface strata of the seamounts' "rim-synclines" conform to the topography of the seafloor. Hollister and Heezen⁵¹ discuss various forms of sediment redistribution on the continental margins and adjacent abyssal plains of the western North Atlantic. They report no evidence for erosion on abyssal plains that is not associated with topographic features such as turbidity current conduits.

The difference between erosion and non-deposition is a fine distinction energy wise, but is important and relevant to this discussion as erosion can uncover sequestered waste, but non-deposition cannot. Fortunately, non-deposition and erosion are readily recognized for what they are with seismic reflection profiles. Basically, if strata underlying a depression conform to the seafloor slopes then non-deposition is indicated. Erosion is indicated when strata intersect the seafloor slope at some recognizable angle.

A waste package that has been sequestered into the sediments of an uncomplicated abyssal plain should be expected to remain buried long enough to satisfy the requirements for long-term nuclear waste burial, that is, up to one million years.

Costs

The cost of only one concept, insertion in a drilled hole, has been estimated. Two emplacement vessels were considered.

First, a drill ship of the GLOMAR CHALLENGER's capability was considered, emplacing ten containers 9 in. in diameter by 12 ft. long (waste size 8 in. in diameter by 10 ft. long) in 20,000 ft. of water at a sediment depth of 3,000 ft.

A detailed estimate of time was made, then the time required was converted to dollar cost today. The disposal site was assumed to be 3,000 nautical miles from the port of loading. Round trip time for a drilling vessel at 10 knots would be 25 days.

From this point the time breakdown, where possible, was based on experience of the Deep Sea Drilling Project.²⁶ Upon arriving at a site, the first operation would involve lowering the landing base, a short length of casing, and the drill-string to the seafloor -- estimated duration 24 hours. Installation of the short casing and continuous drilling of the hole in sedimentary material to a depth of 3,000 ft. would require 120 hours, assuming the drill bit does not wear out and require replacement. Upon completion of the hole, the drill-string would be tripped up, the drill bit removed, a waste container attached, and the drill string tripped back to the seafloor, the total operation requiring 25 hours. At the seafloor, the sonar transducer would locate the landing base; the waste container would be guided into the drill hole; the waste would be lowered to the bottom of the hole and disconnected from the drill-string; and a grout plug placed above, all in an estimated 12 hours. For each additional container, this operation must be repeated, requiring 36 hours per container. After the final container was set in place, a substantial grout plug would be placed followed by mud filling the hole to the surface, requiring 12 hours. Return of the drill pipe to the surface would take 15 hours. Table II summarizes the time requirement.

If three days are allowed for replenishment of ship's stores, loading of waste containers, and rotation of the ship's crew and orientation of new personnel, a total time duration of 50 days is obtained for ten waste parcels in one drilled hole.

Daily cost of the required drill ship, including Government supervisory personnel and depreciation of the vessel, is predicted to be \$30,000 per day in 1973 dollars. Thus, a one-hole, ten-container trip would cost \$1.5 million. This total cost breaks down to \$150,000 per container, or to about \$230 per pound of fused radioactive waste of specific gravity 3.0.

A second cost estimate was prepared assuming that the emplacement vessel was a large, self-propelled, semi-submersible vessel, built much along the lines of the once proposed MOHOLE vessel. The drilling vessel was assumed to have a 2,000 nautical mile round trip at 2 knots; a stay on station of 6 months, during which time 8 waste holes would be completed embedding a total of 80 waste containers; and a daily cost of \$40,000 for the semi-submersible plus \$5,000 for a supply vessel. Given these assumptions, the estimated cost of nuclear waste disposal is about \$195 per pound of fused material. Considering the uncertainty of the assumptions made in

Table II. Time Required per One-Site Trip, Drilled Hole Concept

Item	(hours)	Duration (days)
Loading supplies, waste containers		3
Transit time to site		12½
On site		
Lowering string, base, & casing	24	
Drilling	120	
Ten container emplacements	360	
Sealing hole	12	
Retrieving string	15	
Subtotal	531	22
Return transit time		12½
Total		50

developing these cost estimates, the authors suggest that the cost difference of \$195 to \$230 per pound is not significant. In other words, a study of much broader scope will be required before a conclusion can be drawn regarding the best-suited type of emplacement vessel and best emplacement technique.

Obviously, this cost figure can be decreased by increasing the container diameter and length; however, heat dissipation of these larger waste volumes may not be adequate.

The above cost figures do not include canister and container fabrication, waste loading, sealing, and land transport costs.

RESULTS AND CONCLUSIONS

1. Embedment of nuclear waste containers in the deep seafloor is technically feasible. The evaluation considered three container diameters -- 7, 13½, and 26 inches -- emplaced in a typical normally consolidated deep-sea sediment. A comparison of results is given in Figure 15, a summarization of which follows:

TABLE III

Concept	Embedment Depth (ft)	
	Present	Projected
Free-fall penetration	100	100
Static penetration	124	300
Insertion in drilled hole	4300	5000+

2. Greater static and free-fall penetrations are possible in active river deltas. However, environmental factors such as the development of mud lumps and the occurrence of slumping render such sites potentially unsafe.

3. Free-fall penetration is the sole present technique for accomplishing embedment in most deep-sea trenches. Deep-sea trenches do not offer significant established advantages, compared to other deep-seafloor environments, for the sequestering of nuclear waste containers.

4. Emplacement accuracies of all concepts in 20,000 feet of water, with respect to one seafloor reference point, are about the same, ± 60 or ± 70 ft. The use of a long baseline position measuring system, employing three or more seafloor reference points at a 1500 ft. spacing, will improve this accuracy reducing the potential error to ± 30 ft. These emplacement accuracies noted are with respect to existing seafloor markers, not global coordinates. Global coordinates can be established for a waste container with an accuracy of ± 250 ft. using a good, commercially-available satellite navigation system. True errors will be within the accuracy limits specified 99.7% of the time.

5. Of the three concepts examined, insertion of waste containers into a drilled hole appears to be the best because of the far greater embedments possible.

concept 1
free-fall

concept 2
static

concept 3
drilled

FIGURE 15. Concept capability comparison.

6. The static and free-fall embedment concepts appear near equal from an engineering point of view. The free-fall penetration concept is capable of embedding the greatest quantity of waste per unit time (for all three concepts). The static penetration concept achieves slightly greater penetrations than the free-fall concept, with increased positioning control and with an option to recover the container after full embedment but prior to release. A determination of maximum allowable canister diameter and volume, from a heat dissipation standpoint, will be required in order to effect a comparison between concepts 1 and 2.

7. A remotely operating seafloor system for the embedment of waste containers appears technically feasible. Its capabilities are thought similar to those of the free-fall and static penetration concepts, i.e., about 300 ft. sediment embedment maximum. A cost comparison requires some preliminary system design.

8. An analysis using a drill ship/platform installation model indicates that seafloor disposal of nuclear waste by embedment will cost about \$195 to \$230 per pound.

RECOMMENDATIONS

1. If seafloor embedment of high-level radioactive wastes is considered further, then the effect of the container, as a heat source, on the surrounding sediments should be established. Guidelines are required on the maximum allowable waste package diameter, on the maximum waste volume per unit depth, and on the minimum depth of overburden.

2. If overburden depths to 300 ft. are found sufficient, and if substantial volumes of waste material are involved justifying a significant development investment, then remote seafloor embedment systems should be evaluated and designed in sufficient detail to permit a cost comparison with embedment concepts operating from the sea surface.

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Cleveland, OH 44114

Cincinnati Public Library
Cincinnati, OH 45202

Toledo Public Library
Toledo, OH 43624

University of Tulsa Library
Tulsa, OK 74104

Reed College Library
Portland, OR 97202

Carnegie Library of Pittsburgh
Pittsburgh, PA 15213

Providence Public Library
Providence, RI 02903

Charleston College Library
Charleston, SC 29401

Carnegie Free Public Library
Sioux Falls, SD 57101

Public Library of Nashville &
Davidson County
222 Eighth Avenue North
Nashville, TN 37203

Dallas Public Library
Dallas, TX 75201

Houston Public Library
Houston, TX 77002

Brigham Young University Library
Provo, Utah 84601

Virginia Polytechnic Institute
Carol Newman Library
Blacksburg, VA 24061

Seattle Public Library
Seattle, WA 98104

Spokane Public Library
Spokane, WA 99201

Marshall University Library
Huntington, WV 25701

Milwaukee Public Library,
Regional
Milwaukee, WI 53233

Natrona County Public Library
Casper, WY 82601