*Journal of Hazardous Materials*, 10 (1985) 205—226
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

# A SURVEY OF MONITORING TECHNOLOGY FOR SUBSEABED DISPOSAL OF RADIOACTIVE WASTE*

KENNETH A. SOLOMON and MARK TRIPLETT**

*The Rand Corporation, 1700 Main Street, Santa Monica, CA 90406 (U.S.A.)*

(Received January 1984; accepted October 1984)

## Summary

The subseabed is currently being considered as a disposal site for nuclear waste, and if it does become an option, monitoring to detect escape of the disposed material will be essential. In this paper, we define types of nuclear waste and present the dimensions of the monitoring problems that would be encountered in ocean disposal. We then summarize the characteristics of a number of physical, chemical, biological, and ecological monitoring methods. We also describe the advances and developments that will be necessary before the monitoring functions and support systems can be employed.

## I. Introduction

Between 1946 and 1970, the United States disposed of 86,000 containers of low-level radioactive waste (LLW) at four sites in the Atlantic and Pacific Oceans***. The Environmental Protection Agency (EPA) monitored each site between 1974 and 1978, recovered three waste containers, and obtained samples of sediment and biota. While some sediment samples showed evidence of container leakage, these and other measurements did not suggest any potential harm to marine or human life. Nevertheless, the ultimate impact of past disposal remains uncertain because of the trace quantities present and the difficulty of scientifically measuring impact on marine organisms. Recently, hearings in California have called for expanded monitoring of existing LLW disposal sites [1].

While the United States discontinued disposal of LLW in 1970, domestic and international law does not prevent it from being done. In fact, several European countries use a single site in the northeast Atlantic Ocean to dis-

---

*Views expressed in this paper are the author's own and are not necessarily shared by The Rand Corporation or its research sponsors.

**Currently with Battelle, Pacific Northwest Laboratories, Richland, WA 99352, U.S.A.

***The low-level waste consisted of equipment, tools, and clothing contaminated with radioactivity. Wastes were generally packed in a concrete or other matrix and placed in 55-gallon drums. Some of the drums imploded because of hydrostatic pressure during disposal. (We provide a more formal definition of low-level waste in Section II.)

pose of LLW.* However, before the United States can continue ocean disposal of radioactive waste, the EPA must issue detailed standards for site selection, packaging, and monitoring. To support such standards, ongoing and future studies should focus on the potential environmental transport of radionuclides in candidate disposal sites. These studies should also address the survivability of man-made barriers to waste migration, e.g., packaging. To perform these studies, improved technologies will be needed to monitor all aspects of deep sea experiments, including test disposals.

U.S. and international law prohibits ocean disposal of high-level radioactive waste (HLW) directly into the ocean**. The legality of disposal beneath the ocean floor has not yet been established. The United States and at least four other countries — Canada, the United Kingdom, France and Japan — are studying the feasibility of using stable deep sea geologic formations (e.g., thick sediments) to permanently isolate radioactive wastes. While disposal in conventional land-based geologic formations (e.g., bedded salt) is the leading option in the United States, no agreement has been reached on an approach or site for a commercial repository. Consequently, other options for permanent disposal, including the subseabed, are still being considered.

Subseabed disposal is being considered as a disposal option for several reasons. First, the sediments that have accumulated continuously for 70 million years are predictable. Second, there are no known resources in deep sea regions of interest. Third, plasticity promotes closure of either natural or man-made openings. Fourth, sediments have a low permeability and high sorption for ions. Fifth, the subseabed is remote from man's normal activities.

Extensive studies of the deep ocean environment and the potential consequences of disposal operations are currently being performed to assess the feasibility of subseabed disposal of HLW. Existing and improved technologies will be required to obtain information on virtually every aspect of deep ocean geology and physical, chemical, and biological oceanography.

Deep sea disposal of radioactive waste, whether LLW or HLW, places some severe demands on monitoring capabilities. For example, deep sea biota are relatively sparse in the areas of interest, making it difficult to obtain good information on population sizes and transport potential. Furthermore, the most significant transport pathways for radionuclides are not fully known. Also, the small quantities of radionuclides that may escape (especially from existing LLW disposal sites) make it difficult to detect transport and to assess its effect on the marine environment.

Title II of Public Law 92-532 delegates to the National Oceanic and

---

*Since 1971, Belgium, the Netherlands, Switzerland, and the United Kingdom have used the site. Disposal is under the auspices of the Nuclear Energy Agency (NEA) of the Organization of Economic Cooperation and Development (OECD).

**We consider HLW to include spent nuclear reactor fuel and the liquid wastes resulting from chemical reprocessing of spent fuel elements. A more formal definition used by the International Atomic Energy Agency is given in Section II.

Atmospheric Administration (NOAA) the responsibility for monitoring the effects of ocean dumping and for conducting research on the long-range effects of pollutants in the marine environment. Public Law 95-273 directs NOAA to establish an ocean pollution research and development program and a monitoring program. As one component of this program, the Rand Corporation, assisted by the Scripps Institution of Oceanography/Marine Physical Laboratory, has analyzed and identified the existing capabilities and pertinent needs for advanced technology and engineering for measurement, sampling, and monitoring of the disposal of radioactive wastes in the deep seabed. A detailed description of the study appears in Ref. [2]. The purpose of this paper is to survey technologies that might be used to monitor nuclear low-level and high-level waste in the deep seabed. These data could then be used to select the most promising methods for meeting the monitoring requirements identified in ongoing research efforts.

In Section II, we present some definitions and background information on some of the aspects of radioactivity monitoring. We also discuss previous and current programs for monitoring LLW and HLW.

In Section III, we summarize our findings on the functions, goals, and required developments in monitoring technologies for the short and long term in the event that ocean disposal is judged viable.

## II. Background

In this section, we first describe the various types of nuclear waste and the dimensions of the monitoring problem if ocean disposal appears desirable. We then present considerable detail on the sources of marine radioactivity. Finally, we discuss earlier LLW monitoring programs and describe the ongoing Subseabed Disposal Program.

### *Radioactive waste — Definition and description*

Radioactive wastes* result from the use of nuclear materials in nuclear power reactors, commercial fuel cycle facilities, defense applications, and industrial, medical, and university research programs. For convenience of decision making, nuclear wastes are grouped into three broad categories: high-level waste (HLW), transuranic waste (TRU), and low-level waste (LLW). Table 1 displays the current and expected accumulations of each radioactive waste type.

---

*Radioactive wastes differ in their physical state (gas, liquid, or solid), thermal output, and radiation output (in quantity, energy spectrum, and form). Nuclear radiation emanating from radioactive waste typically consists of these forms: alpha ($\alpha$) particles — helium nucleus (2 protons and 2 neutrons), the principal mode of decay for $^{238}$U, $^{235}$U, $^{239}$Pu,$^{232}$Th, $^{226}$Ra; beta ($\beta$) particles — same mass as an electron, with either a positive or negative charge; the principal mode of decay for $^{3}$H, $^{40}$K, $^{87}$Rb, $^{90}$Sr; gamma ($\gamma$) similar to X-rays, but with much higher energy, released during the radioactive decay of most isotopes.

TABLE 1

Cumulative radioactive wastes in the United States: Generated through 1979 and anticipated through 2000

| Waste type | Generated through 1979[a] | Anticipated through 2000[b] |
|---|---|---|
| High-level waste (HLW) | | |
| Commercial | $80 \times 10^3$ ft$^3$ | c |
| Defense | $9.4 \times 10^6$ ft$^3$ | – |
| Transuranic waste (TRU) | | |
| Commercial | 0.123 metric tons | c |
| Defense | 1.1 metric tons | – |
| Spent fuel discharged | | |
| Commercial | $2.3 \times 10^3$ metric tons | $46.0 \times 10^3$ metric tons |
| Low-level waste (LLW) | | |
| Commercial | $15.8 \times 10^6$ ft$^3$ | $330 \times 10^6$ ft$^3$ |
| Defense | $50.8 \times 10^6$ ft$^3$ | – |

[a] Report to the President by the Interagency Review Group on Nuclear Waste Management, TID-29442, March 1979, p. 11.
[b] Based on our scaled down estimates of nuclear power demand applied to earlier waste generation forcasts as referenced in: (a) NRC, Environmental survey of the reprocessing and waste management portions of the LWR fuel cycle, NUREG-0116, October 1976, pp. 3—16; (b) NRC, Workshops for state review of site suitability criteria for high-level waste repositories, NUREG-0354, February 1978, pp. 8—13; and (c) DOE, Management of commercially generated radioactive waste, Vol. 1, DOE/EIS-0046-D, April 1979, p. 2.1.15.
[c] Value depends upon whether or not spent fuel is reprocessed and recycled.

*High-level wastes* arise from spent reactor fuel which may or may not have been reprocessed and consist of fission products, residual uranium and plutonium, and other actinides. HLW accounts for over 99 percent of the radioactivity in all reactor wastes, but comprises a relatively small volume. The IAEA's definition of HLW unsuited for ocean disposal is shown in Table 2. In effect, HLW is anything with activity levels greater than the specified limits which most accurately define low-level waste.

*Transuranic wastes* result from reprocessing and consist of long-lived actinides. TRU wastes differ from HLW in that they do not generate heat or extensive external radiation*. The dominant risk to man from TRU waste arises from inhalation.

---

*HLW, as spent fuel or reprocessing waste, contains substantial amounts of transuranics, and thus the long-term risks are similar. However, radiation and thermal activity in HLW are dominated by fission products. Thus transuranics, when separated, may be treated differently from HLW in terms of disposal.

TABLE 2

IAEA's definition of high-level radioactive waste unsuitable for dumping in the oceans

Source: International Atomic Energy Agency, Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, INFCIRC/205/Add. 1/Rev. 1, August 1978.

| | Radionuclide group | Allowed Ci/tonne of waste[a] |
|---|---|---|
| 1. | Radium-226 | $10^{-1}$ ($10^{4}$ Ci/yr)[b] |
| 2. | General alpha emitters | 1[a] |
| 3. | Strontium-90 and cesium-137[c] | $10^{2}$[a] |
| 4. | Tritium[d] | $10^{4}$[a] |

[a] Measured in units of curies per metric ton (tonne) of waste, and assumes an upper limit on the mass dumping rate of 100,000 tonnes per year.

[b] Measured in curies per year.

[c] This radionuclide group includes all beta—gamma emitters with a half-life in excess of six months.

[d] This group includes beta—gamma emitters with a half-life shorter than six months.

The need for monitoring ocean dumping operations arises from the legal requirements cited in Public Laws 92-532 and 95-273, as well as the necessity to assure the public that such activities do not entail unacceptable risks. Consequently, monitoring technologies are needed to support continued monitoring of existing disposal sites, setting of standards for future disposal operations, and monitoring of future disposal operations.

In this paper, the pollutants of interest are the radionuclides comprising the HLW or LLW and, to a lesser extent, the nonradioactive chemical constituents of waste materials. For radioactive wastes, man-made or geologic barriers isolate wastes from the environment. Consequently, the monitoring of disposed radioactive waste should focus on the integrity of the barriers (e.g., the waste container, sediments and geologic formations) designed to isolate the waste, in addition to the levels and trends of accidentally or intentionally released radionuclides. Figure 1 illustrates important monitoring functions for ocean disposal of LLW and HLW.

*Container monitoring* includes those functions that monitor the integrity of man-made barriers, especially the waste container. Thus, corrosion and other thermal, chemical, or radiological processes that could destroy the waste container or significantly alter the immediate environment are important. *Sediment monitoring* focuses on the integrity of the sediment barrier. These functions measure the ability of deep sea sediments to contain escaped radionuclides for a period long enough for them to decay to innocuous levels. *Biological monitoring* includes functions that measure the potential effect that radionuclides may have on marine organisms. Similarly, *physical oceanographic monitoring* addresses the movement of radionuclides throughout the water column. In addition, these functions monitor the movement of radionuclides into and out of sea floor sediments due to sediment resuspension, earthquakes, or other disruptive processes. The fifth category of monitoring function, *support systems*, includes four functions that facilitate the delivery, use, and recovery of monitoring instruments. Thus, we include delivery vehicles such as surface ships and submersibles, as well as information transmission.

### *Radioactivity in the marine environment*

Both natural and man-made sources contribute to radioactivity in the marine environment. Table 3 summarizes the contributions from both sources, which include nuclear waste disposal (by the United States and

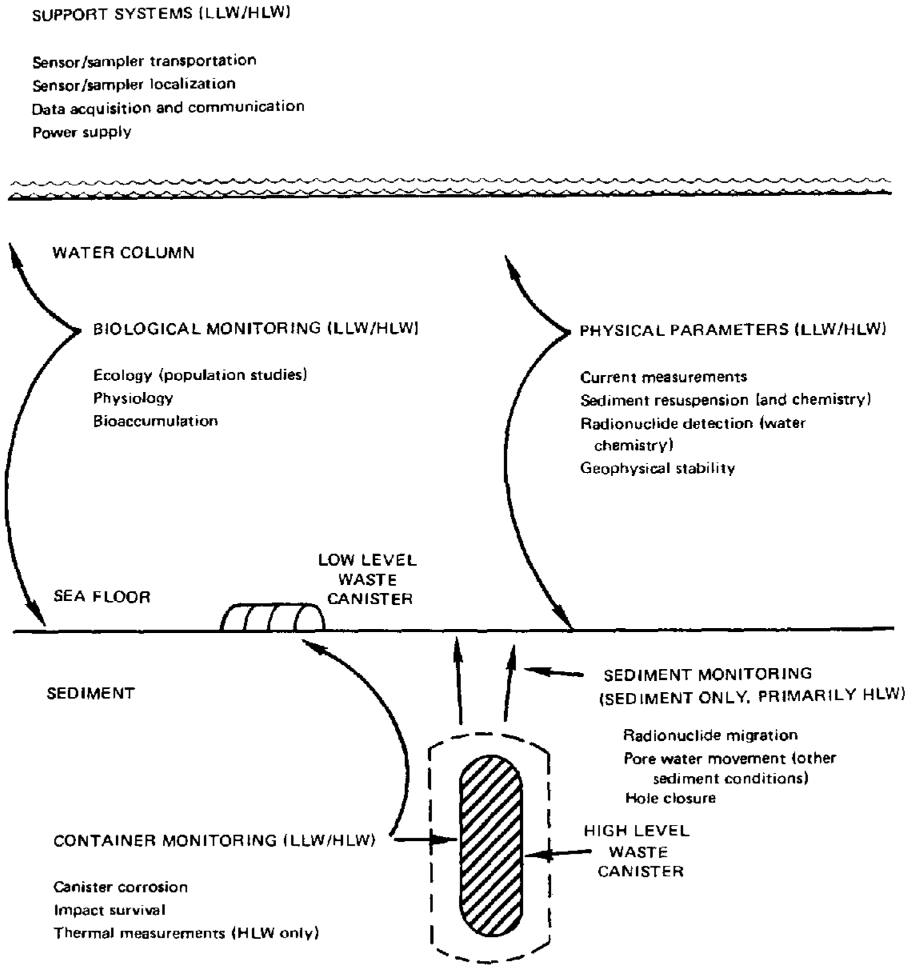


Fig. 1. Monitoring functions for ocean disposal of radioactive wastes.

European nations), nuclear power programs (especially reprocessing plants), nuclear weapons tests, and miscellaneous sources (e.g., sunken nuclear submarines). The data in Table 3 do not reflect all man-made sources*, but rather illustrate the magnitude of past LLW disposal relative to man's other intentional and unintentional releases.

According to Table 3, virtually all U.S. dumping occurred before 1961. European countries, under the auspices of the Nuclear Energy Agency (NEA), continue dumping LLW at a single site in the northeast Atlantic Ocean. Through 1970, the United States had disposed of more than 86,000 containers (55-gallon drums), or roughly 61,000 Ci; approximately 33,000 Ci of induced radioactivity in the *Sea Wolf* reactor vessel brings the U.S. total to 94,000 Ci. The United Kingdom and other NEA members through 1976 have disposed of 114,000 tons of material containing 340,000 Ci. More recently, Japan announced plans to begin dumping packaged LLW in the Pacific in the summer of 1981 [3]. Initial plans call for dumping 10,000 barrels containing a total of 500 Ci. Thus, in 30 years, waste disposal programs of the United States and Europe have dumped less than 500,000 Ci of mostly packaged waste at sites ranging in depth from 900 to 3,800 meters.

By contrast, a single nuclear fuel reprocessing plant in the United Kingdom releases more than 225,000 Ci *annually* to coastal waters. Reprocessing plants separate plutonium and reusable uranium from spent nuclear fuel and, in the process, generate high-level wastes and a large volume of low-level waste. The Windscale Plant in the United Kingdom releases the low-level wastes directly to coastal waters. The French reprocessing plant at La Hague also releases LLW to coastal waters (the English Channel), but data are not available on the amount. Italy and India also have reprocessing plants adjacent to coastal waters, but they are considerably smaller than Windscale**.

While reprocessing plants are the principal contributor to marine radioactivity from the nuclear fuel cycle, nuclear power plants also routinely discharge from 1 to 10 pCi/l in their cooling water [4]. For a 1,000 MWe reactor, this corresponds to an annual release of roughly 1—10 Ci. At the other extreme, Three Mile Island-2 released from 2.4 X $10^6$ Ci to 13 X $10^6$ Ci of $^{135}$Xe to the air during its accident [5]. $^{135}$Xe has a half-life of a few hours, however.

Fallout from nuclear weapons tests contributes to marine radioactivity, principally from deposition of airborne contaminants and from underwater bursts (see Table 3). $^{90}$Sr and $^{137}$Cs are two of the more prevalent fission pro-

---

*For instance, release data for only the Windscale reprocessing plant are shown. France, Italy, and India also have smaller reprocessing plants adjacent to or near coastal waters, but data were not available for them.

**The United States has had only one operating commercial reprocessing plant, the Nuclear Fuel Services plan in West Valley, NY, which closed in 1972. Defense reprocessing facilities operate at Handord, WA (along the Columbia River), and at the Savannah River Laboratory in South Carolina (along the Savannah River). Neither releases LLW directly to the marine environment.

TABLE 3

Radioactivity in the marine environment (illustrative examples)

| Source | Description | Activity level[a] |
|---|---|---|
| Natural radioactivity | | |
| Sea water | $^{40}$K accounts for most of the activity. $^{87}$Rb and $^{3}$H contribute significant but lesser amounts. Activity level is fairly constant in all parts of ocean. | 330 pCi/l[b] |
| Sediments | Activity levels vary significantly, with $^{40}$K a significant contributor throughout. Thorium isotopes and $^{226}$Ra are major constituents in deep sea. | Coastal sediments 2—32 pCi/g[c]<br>Deep ocean red clay 30—100+ pCi/g<br>Globigerina ooze 6—20 pCi/g |
| Radioactive waste disposal | | |
| United States | 1946—1970: Deposited over 86,000 containers (34,000 in the Atlantic dumpsites and in the Pacific dumpsites).[d] | 61,000 Ci (46,000 Ci, Atlantic sites; 15,000 Ci, Pacific sites) |
| | Pressure vessel of the *Sea Wolf* reactor. | 33,000 Ci Atlantic site[e] |
| United Kingdom and the Nuclear Energy Agency (NEA) | 1951—1978: 114,000 metric tons | 435,830 Ci[f] |
| Nuclear power programs | | |
| Reprocessing plants[g] | Windscale in the United Kingdom is restricted to a total beta activity release of 300,000 Ci/yr to coastal waters; total alpha of 6000 Ci/yr. Principal components of total activity are $^{137}$Cs, $^{106}$Ru, $^{90}$Sr, $^{241}$Pu, and $^{3}$H. | 225,000 Ci/yr[h] |
| Nuclear weapons tests | Through 1968, more than 350 weapons were tested, either above ground or in the ocean. These tests include: 2 underwater, 11 over the open ocean, 113 over or on coral islands, 79 on arctic islands.[i] | Releases to the atmosphere and earth's surface include $21 \times 10^6$ Ci $^{90}$Sr and $34 \times 10^6$ Ci $^{137}$Cs |
| Miscellaneous sources | | |
| Nuclear submarine losses | *USS Thresher* sank in 2590 meters of water in 1963.<br>*USS Scorpion* sank in 3050 meters of water in 1968. | Submarine nuclear fuel inventories are classified, but similar sized land-based power reactors contain from $10^8$ Ci to $10^9$ Ci.[j] |

TABLE 3 (footnotes)

[a] All activity data in this table are reported in curies (1 Ci = $3.7 \times 10^{10}$ nuclear transformations per second) to facilitate comparisons. This is an imperfect measure, as noted in the text, since the half-lives of isotopes vary and the resulting radiation (alpha, beta, gamma) also differs in its hazard posed to biological species.

[b] The average dose rate to fish from this activity level is about 0.1 mrem/h. D.W. Woodhead and R.J. Pentreath, A provisional assessment of radiation regimes in deep ocean environments, Second International Ocean Dumping Symposium, Woods Hole, Mass., April 15—18, 1980. Note: 1 pCi = $1 \times 10^{-12}$ Ci.

[c] The activity levels in coastal sediments yield dose rates of 270—3300 μrem/h (alpha activity), 1.6—21 μrem/h (beta activity), and 1.5—16 μrem/h (gamma activity). Activity levels in deep ocean red clays yield dose rates of 9900—38,000 μrem/h (alpha activity), 18—65 μrem/h (beta activity), and 23—86 μrem/h (gamma activity). Activity levels in globigerina ooze yield dose rates of 2200 μrem/h (alpha), 3.7 μrem/h (beta), and 5.2 μrem/h (gamma). Woodhead and Pentreath, op. cit.

[d] Activity levels have been rounded off from the data reported in D.A. Deese, Nuclear Power and Radioactive Waste, D.C. Heath and Co., Lexington, Mass., 1978, p. 50 (Table 2-1).

[e] Estimated in A.B. Joseph, Sources of radioactivity and their characteristics, in: Radioactivity in the Marine Environment, National Academy of Sciences, 1971, p. 37 (Table 22).

[f] The United Kingdom was responsible for waste dumping from 1951 to 1966. The NEA took control of dumping operations in 1967. The United Kingdom, France, Belgium, and Switzerland have recently used this site. See Deese, op. cit., and Demonstrations against low-level sea dumping, Nuclear News, August 1980, pp. 72—73.

[g] Data for reprocessing plants is illustrative and not meant to be complete. France, Italy, and India also have reprocessing plants adjacent to coastal waters, but Windscale is the largest and has readily accessible reports on its releases.

[h] This figure is based on average releases to coastal waters for 1977 and 1978. Included in the figure are approximately 32,000 Ci/yr of $^{3}$H and $^{241}$Pu, which are not specifically regulated. British Nuclear Fuels Limited, Annual report on radioactive discharges and monitoring of the environment 1978, Health and Safety Directorate, Risley, Warrington, Cheshire, U.K., July 1979, pp. 10—11 (Tables 1—3).

[i] Joseph, op. cit., p. 9.

[j] Core activity depends on fuel mix, fuel inventory, and burnup which we do not know, but we have based our estimate on a 1000 MWe PWR after 550 full power days. For a reactor of this size, a core activity of $4 \times 10^{9}$ Ci results. Source: WASH-1400.

ducts. The National Academy of Sciences estimates that $21 \times 10^{6}$ Ci of $^{90}$Sr and $34 \times 10^{6}$ Ci of $^{137}$Cs were released from airborne and surface nuclear tests [6]. Roughly $15 \times 10^{6}$ Ci of $^{90}$Sr were deposited on the earth's surface between 1945 and 1966 [7].

Another man-made source of marine radioactivity resulted from the sinking of two U.S. nuclear-powered submarines, the *Thresher* in 1963, and the *Scorpion* in 1968. While actual curie content of their reactor cores depends on the fuel mix, inventory, and burnup (which we do not know), based on a small conventional reactor, these submarines could have had from $10^{8}$ to $10^{9}$

Ci. Measurements of water, sediment, and debris at both sites have not shown any evidence of major radioactivity released from either submarine [8]; small amounts of radioactivity have been detected in the area. The reactor vessel itself or the fuel rods may still be intact, or sufficiently intact, to prevent significant contamination of the surrounding environment. Clearly, metallic fuel elements will not easily release their radionuclides, except during fuel melting.

### *Monitoring previous LLW disposal*

Between 1946 and 1970, the United States disposed low-level radioactive waste at sites in both the Atlantic and Pacific Oceans. Four sites received most of the radioactive waste [9], two Pacific Ocean sites off San Francisco near the Farallon Islands, and two Atlantic sites off the Maryland—Delaware coast. Wastes were generally contained in 55- or 80-gallon drums filled with concrete or other materials.

Figure 2 illustrates the period of dumping and major laws that have affected dumping practices. Most LLW disposal occurred before 1961, at which time the Atomic Energy Commission (AEC) stopped issuing new permits for disposal. By 1970, all dumping under old permits had ceased. In 1971, AEC disposal regulations were amended to prohibit ocean disposal unless the permittee showed that ocean disposal would result in less harm to man and the environment than other feasible methods*. This regulation is still in place under the Nuclear Regulatory Commission (NRC).

In 1972, the Marine Protection, Research, and Sanctuaries Act** (MPRSA) was passed; it prohibits ocean disposal of high-level waste and empowers the Environmental Protection Agency (EPA) with permit authority over all ocean dumping, including LLW. In 1977, EPA issued detailed regulations implementing the MPRSA***. A policy of containment of LLW is implied by these regulations, which differ from the earlier policy of dilution and dispersion held by the AEC†. Specific criteria for site selection, packaging, and monitoring were not issued at that time. EPA plans to issue site selection criteria and packaging criteria before 1985 [10].

The AEC and EPA have both monitored LLW disposal sites. The AEC commissioned two studies of the Pacific Farallon sites, one in 1957 and one in 1960; the Atlantic dump sites were surveyed in 1961. Surface ships towed underwater cameras and obtained over 11,000 photographs of the sites. However, not one of the more than 75,000 radioactive waste containers was located. In 1974, EPA began a series of disposal site surveys using manned and unmanned submersibles (Fig. 2). In terms of monitoring, the EPA survey found that manned and unmanned submersibles can locate and recover LLW

---

*10 CFR 20.302(c).

**Public Law 92-532.

***40 CFR 220-220.

†40 CFR 227.11.

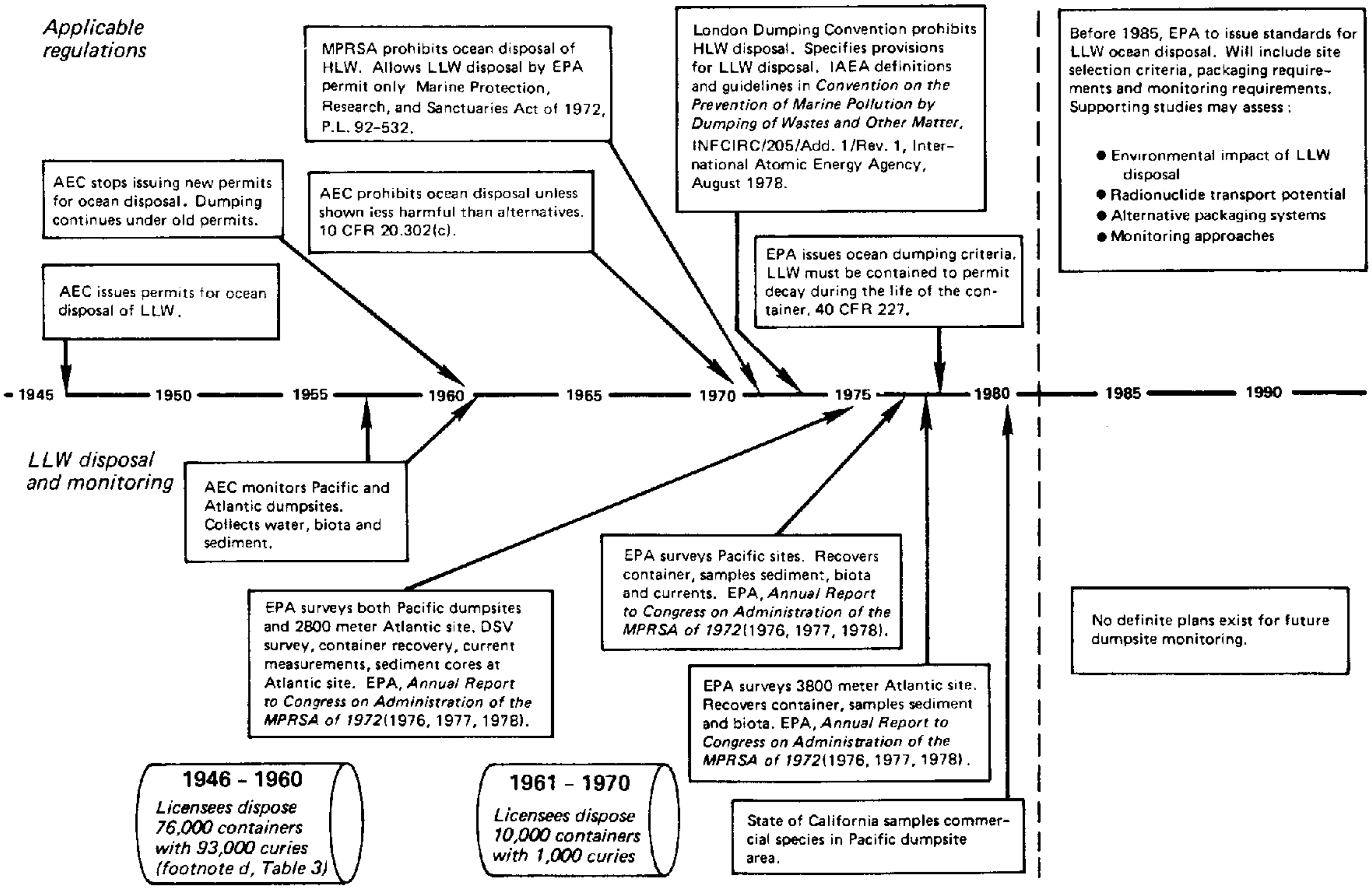


Fig. 2. Low-level waste disposal, past monitoring, and regulations.

containers from deep sea disposal sites; container location in rough terrain was difficult; camera systems were inadequate, i.e., insufficient resolution; sediment core tubes tended to disrupt the upper sediment layers, invalidating radionuclide migration data; and container markings were inadequate (not durable).

In terms of radionuclides, EPA found that containers have leaked some of their contents to the environment; $^{239}$Pu and $^{240}$ Pu levels in disposal site sediments range from 2 to 25 times the maximum expected level due to fallout [9]*; $^{137}$Cs levels in sediments range from 3 to 70 times the expected fallout level [9]; and concentrations found to date do not appear to represent a risk to man or to the marine environment [11].

In response to growing public concern over the potential impact of the Pacific disposal sites**, the Department of Health Services of California sampled and analyzed edible fish species from the vicinity of the Farallon disposal sites. Radioactivity levels were consistent with those expected from natural and fallout radioactivity [12]. The Health Services Department plans to continue monitoring edible species caught in the disposal site area.

### *U.S. Subseabed Disposal Program — Implications for monitoring technology development*

The U.S. Department of Energy Subseabed Disposal Program (SDP) began in 1973. Its primary objective is to assess the technical, environmental, and engineering feasibility of disposing of processed and package high-level waste and/or repackaged spent fuel in geologic formations beneath the world's oceans [13]. A secondary objective is to provide a capability for assessing seabed disposal programs of other countries. The subseabed option is viewed as a primary alternative to land disposal options. As shown in Fig. 2, both national and international laws prohibit disposal of HLW into waters of the ocean. The legality of placing the waste beneath the seabed within a suitable geologic formation has not yet been established [14]. Thus, actual disposal of HLW in the subseabed could not occur without substantial revision of U.S. laws and international agreements [14]. At present, then, the SDP aims to evaluate the feasibility of the subseabed option.

Subseabed disposal is viewed as a multibarrier containment system using a series of man-made (waste form and canister) and natural (rock and sediment) barriers [15]. Together, these barriers are intended to delay the move-

---

*These levels were found in a 1975 survey of the 900-meter Pacific site. Lower levels (2—4 times fallout levels of plutonium) were found at the 1700-meter site.

**Rising public concern (see "U.S. to Probe Nuclear Dumping in Pacific; Californians Demand Data on Any Hazard," *Los Angeles Times*, August 20, 1980) led to Congressional hearings by the House Subcommittee on Environment, Energy, and Natural Resources (see "Hearing Takes Up Peril Of Nuclear Waste off Coast," *Los Angeles Times*, October 13, 1980). Subcommittee Chairman Toby Moffett called for frequent monitoring of the Farallon site "perhaps every six months through a joint agreement between the EPA and NOAA".

ment of radionuclides for a period long enough for them to decay to innocuous levels. Ongoing studies will quantify barrier properties under actual HLW disposal conditions. At present, the reference disposal method calls for emplacement of waste canisters into stable clay sediments (such as in the mid-plate gyre region of the North Pacific). A penetrometer* could emplace the wastes in a controllable manner to some desired depth (e.g., 50—100 meters).

The SDP consists of four phases, as shown in Fig. 3. Phase 1, completed in 1976, reviewed historical data for evidence that would invalidate the subseabed disposal concept. In Phase 2 (scheduled for completion in 1985–1987), major research tasks (as shown in Fig. 3) address questions of technical and environmental feasibility from newly acquired data. Initial systems models (barrier properties and environmental models) are being built, and initial data from field and laboratory tests are being collected. Phase 3 (scheduled for completion in 1993—1995) involves model validation through extensive field tests and initiation of long-term (15-year) *in situ* experiments. In addition, engineering components (e.g., the penetrometer system) will be tested. Phase 4 (scheduled for completion in 2000) calls for complete testing of disposal facilities, including land, port, and sea systems. While a fully operational subseabed repository would not be ready until at least the year 2000 under this plan, improved monitoring capabilities will play an important role in the research and demonstration phases. Indeed, site characterization studies will provide baseline data from which to assess the impact of actual disposal operations. *In situ* experiments designed to investigate the physical properties of man-made and natural barriers, for example, are supportive of future monitoring programs.

Much of the current research for the subseabed option is being conducted at universities and oceanographic institutes. The National Academy of Sciences or other environmental organizations sponsor a review when the feasibility analyses are completed, perhaps in 1988. Assuming the review is positive, much more research and *in situ* experiments would be required before subseabed disposal could be implemented [16].

## III. Candidate monitoring technologies

The Interagency Review Group appointed by former President Carter recommended that mined geologic repositories be considered the most promising near-term option for the disposal of high-level radioactive wastes, and that research and development work on subseabed disposal and other options be continued. We examined a range of technological methods for measurement, sampling, and monitoring the disposal of radioactive wastes in

---

*A penetrometer is a projectile which could house HLW and when dropped from a ship or lowered from a winch, would penetrate soft sediments.

TABLE 4

Monitoring technologies needed in near term (1984—1989) — Physical and chemical methods

| Monitoring function | Monitoring goals | Needed developments |
|---|---|---|
| Canister integrity | Assess actual or potential release of radionuclides from LLW canisters deposited on the seafloor. | Combine improved optical inspection (high resolution TV) from DSVs/ROVs with *in situ* radiation detection (total gamma or gamma spectrometry; see "Radionuclide detection", below). |
| | | Detect impact forces on test penetrometers. |
| | | Detect corrosion rates of candidate materials during or after field tests. |
| Radionuclide migration | Determine changes in pore water pressure in sediments within 1—2 meters of a buried canister (for use with ISHTE). | Detect small pore water pressure changes (~0.1 psi at ambient pressure of 9000 psi) in heated deep sea sediment. |
| | Detect migration of radionuclides through sediments during field tests. | Method for precise location and removal of undisturbed sediment cores. |
| | | *In situ* radiation detectors for burial in deep sea sediments and information transmission to seafloor data collector. |
| Hole closure | Detect status of penetrometer entry hole during field tests. | Combine acoustic systems (e.g., side-looking sonar, bottom-penetration sonar, and borehole acoustic imaging systems) with optical systems to determine hole closure dynamics. |

| | | |
|---|---|---|
| Sediment resuspension and current measurement | Provide long-term measurement capability for key physical oceanographic parameters — baseline studies for the HLW disposal site. | Autonomous instrument stations for use throughout the disposal site (at all levels of the water column) which will provide long-term data on currents, sediment resuspension, and radionuclide levels; capability for remote readout of stored data. |
| | Detect the presence and measure the quantity and movement of sediments resuspended above the seafloor. | Rapidly deployable sensor system for seafloor observation and measurement of resuspended sediment concentration and motion. |
| | Record water mass movements including fronts and eddies. | Combine nephelometry with current measurements, sampling, sediment trapping, and filtering. |
| | | Rapidly deployable system for broad area measurement of bottom currents; remote access to data stored in current meter arrays. |
| Geophysical stability — seismic sensing | Obtain long-term readings of seismic activity in the area of the HLW disposal site. | Device for long-term sensing of seismic activity at a deep sea disposal site; capability for remove readout of stored data. |
| Radionuclide detection | Rapidly detect and quantify radionuclides in the water column and on bottom sediments. | Develop constant geometry spectrometer for use in deep sea disposal sites. |
| | | Develop a total gamma counter for use with ROVs and DSVs for rapidly assessing seabed radioactivity so as to guide detailed sediment sampling. |
| | | Develop radionuclide concentration and absorber techniques. |

TABLE 5

Monitoring technologies needed in near term (1984 –1989) biological and ecological methods

| Monitoring function | Monitoring goals | Needed developments |
|---|---|---|
| Ecological monitoring | Assess species (plankton, nekton, benthos) abundance and diversity to provide an inventory of disposal site biota. | Autonomous platforms for regular acoustic and optical surveys of deep sea fauna; long-term operation and remote readout of stored data. |
| Bioaccumulation/radiosensitivity, and radionuclide transport | Assess the transport and accumulation of radionuclides in the food chain as a result of field tests. | Systems for rapid examination of collected biological specimens to detect above-background-level radiation.<br>Methods for rapid segregation of radioactive samples to permit detailed analysis for radionuclide content.<br>Capability for *in situ* detection of radioactivity levels in benthic microfauna.<br>Automated sorting and classifying of biological samples for use on board ship.<br>Application of acoustic and photographic techniques to rapidly identify specimens from DSVs/ROVs.<br>Species-specific collection devices such as amphipod traps, which will capture the most important species in total radionuclide transport.<br>Reliable method for tag/trace indicator species. |

| | | |
|---|---|---|
| Sampling methods | Obtain unbiased (i.e., representative) samples of benthos, nekton, and plankton in the vicinity of past or potential disposal sites. | Increase sampling and species identification rates; reduce (or quantify) sampling bias by use of sampling methods (e.g., net tows) with optical or acoustic systems. |
| | | Improve horizontally towed controlled nets such as MOCNESS (Multiple Opening Closing Net Systems) to permit more rapid and effective coverage of all depth layers. |
| | | Vertically rising net-systems to capture larger and more mobile specimens. |
| Optical systems | Observe macrobiota throughout the water column. | Underwater photography system for remote sensing of data on biota throughout the water column; use with sampling devices (e.g., traps), platforms, and ROVs. |
| Acoustic systems | Use high-frequency acoustics to detect fish schools and individual fish in all layers of the ocean. | Develop controllable depth acoustic system for remote sensing of fauna. |
| Physiological monitoring | Retrieve live specimens for laboratory studies. | Develop pressure and temperature retaining traps for collection of species from throughout the water column. |
| | Measure physiological parameters (e.g., metabolism, respiration, fertility) of marine organisms *in situ*. | Adapt the free-vehicle-grab-respirometer concept to a broader range of species throughout the water column. |

TABLE 6

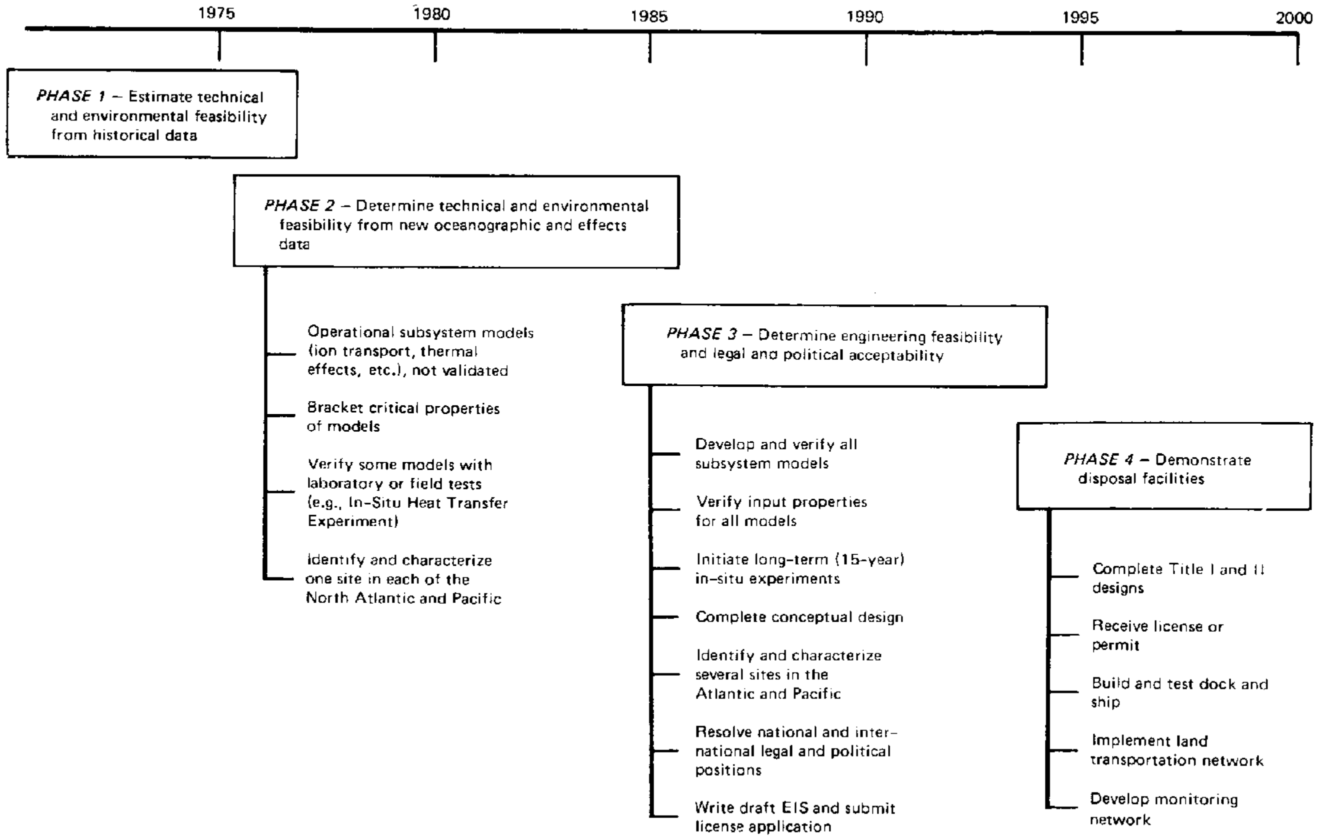
Monitoring technologies needed in near term (1984–1989) — Support systems

| Monitoring function | Monitoring goals | Needed developments |
|---|---|---|
| Sensor/sampler transportation and manipulation | | |
| DSV/ROV to inspect and sample LLW sites | Conduct inspection and sampling around LLW disposal sites | Improve capability for launch and recovery in adverse sea conditions; adapt existing DSVs or ROVs for increased sampling capacity and rate, e.g., increased storage capacity for sediment, water, and biota samples; reduce sediment disruption from DSV/ROV maneuvers. |
| | | Method for DSV/ROV-initiated recovery of selected LLW canisters. |
| ROV to conduct HLW experiments | Provide capability sample delivery and retrieval | Remotely operated vehicle for working on the deep sea floor. |
| Sensor/sampler localization, transport, and manipulation | Locate and map LLW containers deposited on the seafloor | Increase capability of acoustical and optical sea floor search systems to locate and classify containers in rough terrain. |
| | | Provide platforms for autonomous monitoring devices such as current measurement, seismic sensing, and ecological surveys. |
| Data acquisition and communication | | Develop higher data rate telemetry/support cables. |
| | | Provide remote readout capability for autonomous packages (e.g., instrumented penetrometer). |
| Power supply | | Provide power for long-term (approx. 20+ years) and short-term (less than 5 years) autonomous packages. |

TABLE 7

Monitoring technologies needed for long term (beyond 1990)

| Monitoring function | Monitoring goals | Needed developments |
|---|---|---|
| *Physical and chemical methods* | | |
| Canister integrity (HLW) | Assess the physical integrity of buried HLW canisters. | Remote or hardwired sensors to detect canister chemical and physical state — corrosion, stress, cracking, etc. |
| Thermal measurements (HLW) | Detect thermal fields surrounding full-scale HLW canisters. | Remote or hardwired sensors to detect sediment, thermal field around test canisters, i.e., during emplacement demonstration. |
| Radionuclide migration conditions | Detect changes in sediment structure and pore water pressure around full-scale HLW canisters. | Remote or hardwired sensors to detect sediment properties (temperature, density, clathrate formation, pore water pressure, acidity, dissolved oxygen).<br>Acoustic system to remotely assess structural integrity of near-field and far-field sediments.<br>System to extract sediment samples contiguous to buried canisters for shipboard or laboratory measurement of acidity and dissolved oxygen. |
| *Support systems* | | |
| Sensor/sampler transportation, manipulation — buried canister retrieval | Remove full-scale test canisters and surrounding sediment for detailed laboratory study. | Overcoring system for canister retrieval; extended lift capability from surface ships; containment system for recovered canister and sediment to minimize the potential for accidental releases. |
| Sensor/sampler localization — buried canister location and attitude | Detect any vertical or horizontal displacement or buried canisters from their original location. | Optimize bottom penetration sonar to detect canisters buried at a prescribed depth (e.g., 50 meters). |



SOURCE: *Subseabed Disposal Program Plan Volume I: Overview*, Sandia Laboratories, SAND 80-0007/1, January 1980.

Fig. 3. Subseabed Disposal Program phases and major tasks.

the deep ocean seabed. The results of this study are present in detail elsewhere [2]. In Tables 4—7, we summarize the findings.

In Table 4, we present some physical and chemical methods that might be used to monitor ocean-disposed waste. In the first column, we specify the function; in the second column, we describe the purpose of the particular monitoring function; in the third column, we present the advances that are necessary before the monitoring technology could be implemented.

In Table 5, we provide parallel information on the biological and ecological methods for the near term. In Table 6, we describe the developments that will be necessary in terms of support systems for the balance of the current decade. In Table 7, we summarize the long-term requirements of monitoring technologies.

## Conclusions

In this paper, we have discussed the historical and current practices of low- and high-level radioactive waste disposal in ocean environments. We have included a description of the cumulative radioactive wastes generated through 1979 and projected through 2000, and some representative examples of marine radioactivity. We have also provided details on the regulations and monitoring requirements of low-level waste disposal, and have described an ongoing investigation of the feasibility of subseabed disposal of high level waste.

The most important result of the research is a summary of physical, chemical, biological, and ecological technologies that might in ocean environments be used for monitoring radioactive waste in the event that disposal in ocean environments is judged feasible. We present a description of the required future developments of the technologies and the support systems in both the short and long term.

## References

1 R. O'Reilly, Hearing takes up peril of nuclear waste off coast, Los Angeles Times, October 13, 1980.

2 M.B. Triplett, K.A. Solomon, with C.B. Bishop and R.C. Tyce, Monitoring technologies for ocean disposal of radioactive waste, The Rand Corporation, R-2773-NOAA, January 1982.

3 R. Gale, Japan to start ocean dumping of low-level nuclear waste, The Energy Daily, November 26, 1979.

4 Q&A, Nuclear Power and the Environment, American Nuclear Society Publication, April 1976, Table 6-II,

5 NRC to speed own research in response to new radiation-release data, Inside NRC, December 1, 1980, pp. 8—9.

6 A.B. Joseph, Sources of radioactivity and their characteristics, in: Radioactivity in the Marine Environment, National Academy of Sciences, 1971, p. 9.

7 A.B. Joseph, Sources of radioactivity and their characteristics, in: Radioactivity in the Marine Environment, National Academy of Sciences, 1971, p. 19 (Table 7).
8 Environmental monitoring and disposal of radioactive wastes from U.S. naval nuclear powered ships and their support facilities, NAVSEA Rep., NT-79-1, January 1979, pp. 8—9.
9 R.S. Dyer, Environmental surveys of two deep sea radioactive waste disposal sites using submersibles, International Symposium on the Management of Radioactive Wastes from the Nuclear Fuel Cycle, International Atomic Energy Agency, Vienna, March 1976.
10 Nucleonics Week, October 30, 1980, p. 11.
11 EPA, Annual Report to Congress, Jan/Dec 1973, on Administration of the Marine Protection, Research, and Sanctuaries Act of 1972, June 1979, p. 22.
12 High radioactivity not found in Farallon fish, Los Angeles Times, November 8, 1980.
13 Subseabed Disposal Program Plan, Vol. I: Overview, Sandia Laboratories, SAND 80-0007/1, Livermore, CA, January 1980, p. 11.
14 C.D. Hollister, D.R. Andreseon and G.R. Heath, Sub-seabed disposal of nuclear wastes, Science, 213 (1981) 1321.
15 D.R. Anderson, Nuclear waste disposal in subseabed geologic formations: The seabed disposal program, Sandia Laboratories, Livermore, CA, SAND 78-2211, May 1979, p. 11.
16 K.R. Hingo, Disposal of high-level radioactive wastes by burial in the sea floor, Environ. Sci. Technol., 16 (1982) 28A.