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RADIOACTIVITY IN THE OCEAN: LAWS AND BIOLOGICAL EFFECTS

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ABSTRACT

This paper summarizes the literature on U.S. laws and international agreements, experimental and monitoring data, and ongoing studies to provide background information for environmental assessment and regulatory compliance activities for ocean dumping of low-level radioactive waste. The Marine Protection, Research, and Sanctuaries Act is the major U.S. legislation governing ocean disposal of radioactive waste. The major international agreement on ocean dumping is the Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter. The United States ended its ocean dumping of radioactive wastes in 1970, but other countries have continued ocean dumping under international supervision in the northeast Atlantic. Monitoring of former U.S. disposal sites has neither revealed significant effects on marine biota nor indicated a hazard to human health. Also, no effects on marine organisms have been found that could be attributed to routine discharges into the Irish Sea from the Windscale reprocessing plant. We must improve our ability to predict the oceanic carrying capacity and the fate and effects of ionizing radiation in the marine environment.

INTRODUCTION

Governments at all levels are taking a new look at ocean disposal, because many land areas are not appropriate for waste disposal. In 1982, the U.S. National Advisory Committee on Ocean and Atmosphere began an examination of radioactive waste disposal in the ocean (25). The United States has not dumped any radioactive wastes at sea since 1970, but ocean dumping is viewed as an alternative to land burial for several reasons:

- the possible economic advantages,
- the need to dispose of decommissioned nuclear-powered items such as naval submarines,
- the Department of Energy's (DOE) need to dispose of large amounts of slightly contaminated soils, and
- the requirement that states evaluate waste disposal needs according to the Low-Level Radioactive Waste Policy Act of 1980.

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Other countries have continued dumping under international supervision in the northeast Atlantic. In the United States, the Marine Protection, Research, and Sanctuaries Act (MPRSA) is the major legislation governing ocean dumping of low-level radioactive waste, and the major international agreement on ocean dumping is the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Dumping Convention).

"Ocean dumping" as defined in MPRSA is the seaward transport of land-generated wastes by ships, barges, platforms, or aircraft and the disposition of those wastes in the marine environment. Such wastes may be dumped in bulk or in containers, incinerated at sea, or buried in the seabed. Although radioactivity released to the ocean via cooling water or wastewater discharges contributes to the background radiation of the ocean, such disposal is not considered "ocean dumping." Because the objective of this review is to evaluate the effects from ocean dumping of low-level radioactive waste, all other sources of ionizing radiation in the ocean are considered to be part of the background levels (both natural and man-made radioactivity). This paper reviews U.S. laws and international agreements, experimental and monitoring data, and ongoing studies to provide background information for environmental assessment and regulatory compliance activities with respect to future ocean dumping proposals.

CLASSIFICATION OF RADIOACTIVE WASTE

The U.S. classification scheme for radioactive waste is based on the origin of the waste, whereas international and European classification schemes are based on the radioactivity of the waste. U.S. law and international agreements prohibit ocean dumping of high-level radioactive waste. In the United States, high-level waste is defined as the highly radioactive waste material resulting from the reprocessing of spent nuclear fuel and containing a combination of transuranic waste and fission products in concentrations that require permanent isolation. Transuranic wastes are radioactive wastes contaminated with alpha-emitting transuranic radionuclides (atomic number greater than that of uranium) with half-lives greater than 20 years and concentrations greater than 100 nanocuries per gram (100 nCi/g) [1 becquerel (Bq) = 2.7×10^{-11} Ci]. Low-level waste is any radioactive waste not classified as high-level, transuranic waste, spent nuclear fuel, or mill tailings (produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content) (39).

The International Atomic Energy Agency (IAEA) has defined high-level radioactive matter which is unsuitable for ocean dumping as a material with a radioactivity per unit of mass greater than that listed for the following radionuclide groups:

- Radium-226 and supported polonium-210 wastes in excess of 0.1 curies per metric ton (0.1 Ci/metric ton).
- General alpha emitters in excess of 1 Ci/metric ton.
- Strontium-90 and cesium-137 (all beta and gamma emitters with a half-life in excess of 6 months) in excess of 100 Ci/metric ton.
- Tritium and beta and gamma emitters (with a half-life shorter than 6 months) in excess of 1×10^6 Ci/metric ton.

The maximum dumping rate is assumed to be 100,000 metric tons per year at a single site (18, 22). These concentration and dumping-rate limits are derived from release rates determined by oceanic and human-exposure models. The IAEA is developing a definition of materials that would be considered "de minimus" for purposes of ocean disposal (e.g., materials that contain natural radionuclides) (15, 35). This definition could be important for the classification of contaminated soils.

U.S. LAWS

Two of MPRSA's three major subdivisions are relevant to ocean dumping: Title I establishes an Environmental Protection Agency (EPA) permit program for the dumping of materials into the ocean, and Title II requires the National Oceanic and Atmospheric Administration (NOAA), in coordination with EPA and the Coast Guard, to establish a program for monitoring and research regarding the effects of ocean dumping.

EPA may grant permits for ocean disposal of low-level radioactive waste according to MPRSA. An amendment to Title II in 1982 requires an impact assessment and approval by both the House and Senate before EPA may issue a permit. The MPRSA regulations allow dumping permits to be issued only when no alternative means of disposal exists, and only when waste is packaged in containers that will remain intact until the radioactivity has decayed to innocuous levels. These stringent restrictions help explain why EPA has received no permit applications for radioactive waste dumping since MPRSA was enacted. EPA eventually will issue low-level radioactive waste standards that will include site-selection criteria, packaging requirements, and monitoring requirements for ocean disposal (38). These new regulations should be consistent with, or take into account, the London Dumping Convention, the IAEA, and the Nuclear Energy Agency (NEA) guidelines and criteria, and other international agreements to which the United States is a party (40 CFR 220). The new regulations are expected to make ocean dumping is a more viable option for waste disposal (6, 28).

Several other laws are relevant to disposal of radioactive waste in the ocean. The Nuclear Regulatory Commission (NRC) is prohibited from licensing the disposal of material at sea unless the applicant "shows that sea disposal offers less harm to man or the environment than other practical alternative methods of disposal" [10 CFR 20.302(c)]. The Department of Energy Organization Act of 1977 (Public Law 95-91) gives DOE responsibility for planning and carrying out programs for the safe handling of all government-generated radioactive wastes. DOE has developed several internal DOE orders which should be consistent with EPA environmental standards (20). Figure 1 outlines the interactions between U.S. and international agencies with jurisdiction over ocean disposal of radioactive waste and the related U.S. laws and international agreements. The National Environmental Policy Act (Public Law 91-190) and the Coastal Zone Management Act of 1972 (Public Law 96-583) protect environmental resources, whereas the Hazardous Materials Transportation Act regulates transportation of radioactive waste. The Low-Level Radioactive Waste Policy Act of 1980 (Public Law 96-573) gives responsibility to individual states for providing disposal capacity for commercial low-level radioactive wastes

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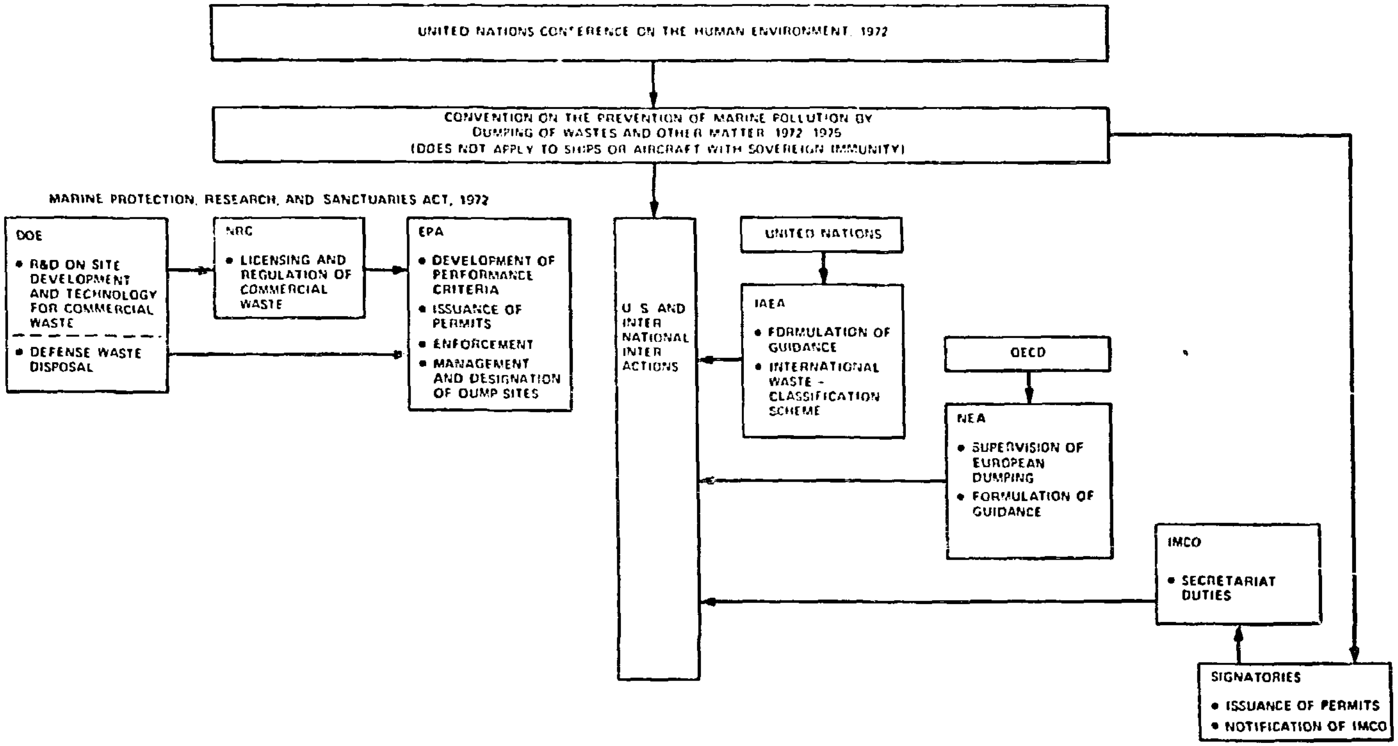

FIG. 1.--U.S. and international agencies with jurisdiction over ocean disposal of radioactive waste and the related U.S. laws and international agreements (20). (DOE=Department of Energy; NRC=Nuclear Regulatory Commission; EPA=Environmental Protection Agency; IAEA=International Atomic Energy Agency; OECD=Organization for Economic Cooperation and Development; IMCO=Intergovernmental Maritime Consultative Organization.)

generated within their borders, and stipulates that management of this waste should occur on a regional basis.

INTERNATIONAL AGREEMENTS

The United Nations Conference on the Human Environment, held in Stockholm in 1972, requires governments to control ocean dumping by their nationals or by other persons in areas under their jurisdiction. Subsequent to the Stockholm conference, two international conventions of significance to the regulation of radioactive waste disposal in the ocean were the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Dumping Convention) and the Third United Nations Conference on the Law of the Sea.

The London Dumping Convention prohibits the dumping of high-level radioactive waste, as defined by the IAEA, and forbids the dumping of other radioactive wastes unless a special permit is issued by the ship's flag state or the loading state. Fifty-six parties, including the United States, have ratified or acceded to this convention, which has over 90 signatory nations. At the Seventh Consultative Meeting of the Contracting Parties to the London Dumping Convention (1982), a nonbinding resolution was passed that called for the suspension of all dumping of radioactive materials at sea, pending a final report of the international scientific review committee in 1985. Each contracting party to this convention must designate an authority to issue permits, keep records, monitor conditions, and report to the Intergovernmental Maritime Consultative Organization (IMCO).

The Third United Nations Conference on the Law of the Sea (UNCLOS III) gives countries the obligation to protect and preserve the marine environment and to prevent, reduce, and control pollution of the marine environment. Enforcement is the responsibility of a coastal country for its territorial sea, continental shelf, and exclusive economic zone. In the high seas, enforcement requires international agreements. Ocean dumping has been addressed by at least two regional action plans under the United Nations Environmental Programme's Regional Seas Programme. A regional approach should provide tangible results and solutions to marine pollution problems.

Several international organizations address management of radioactive materials (Fig. 1). The IAEA, which is an independent organization belonging to the United Nations family, recently updated their guidance to national authorities on the disposal of radioactive wastes into the marine environment (23). This organization has reserved judgment on ocean dumping as a means of radioactive waste disposal, and although it feels international observation is desirable to ensure compliance with the London Dumping Convention, it has neither received nor assumed a specific mandate to act in an observer capacity. The NEA organizes and conducts European ocean dumping operations for radioactive waste, and is a semiautonomous subsidiary of the Organization for Economic Cooperation and Development (OECD). The United States is a member of both IAEA (34 member countries) and NEA (23 member countries).

BACKGROUND RADIATION LEVELS IN THE OCEAN

Background radiation includes natural and man-made isotopes and must be considered when assessing the effects of radioactive waste disposal in the ocean. Marine organisms experience different radiation exposures, depending on their life-cycles (e.g., pelagic eggs and larvae of a benthic adult form) or temporal behavior (e.g., diurnal or annual migration periods between differing environments). Radioactive isotopes also have nonuniform deposition and dispersion properties. One cannot equate the impact of a curie of one radioisotope to another without a determination of the doses from each, because every radioisotope is unique in its decay rate, degree of and pathway of receptor exposure, and effect per unit ionization at or in the receptor. Marine organisms are exposed to cosmic radiation and natural and man-made ionizing radiation in water, incorporated within themselves, incorporated in sediments, and in their food.

Several natural radionuclides exist in seawater. Potassium-40 accounts for 90% of oceanic radioactivity and is an important contributor to the background dose rate received by marine organisms. Organisms in the surface layers of the sea receive 4 µrad/h or 35 mrad/yr from cosmic radiation, but this dose declines to 0.5 µrad/h at a depth of 0.7 ft (20 cm) and is negligible at 328 ft (100 m) (21). Typical concentrations of natural radionuclides in marine organisms are given in Table 1. Cherry and Heyraud (7) reported significantly higher levels of polonium-210 in midwater shrimp and fish than those previously reported for surface waters.

Dose rates to marine organisms can be calculated for various sources using dosimetry models. Dose rates from natural radionuclides in seawater can be compared to dose rates from man-made environmental radioactivity (Table 1). The dose rate from the activity in water is small compared with that from either absorbed radioactivity or from activity incorporated into the sediments. Free-swimming organisms experience a variable external radiation regime. Exposure from beta-radiation is eliminated by a seawater layer of 0.4 in. (1 cm) thickness, and exposure from gamma rays is attenuated by a factor of 10^{-3} by a seawater layer of 4.9 ft (1.5 m) (29). Estimated dose rates in aquatic environments from natural background radiation range up to 40 µrad/h and are of the same order as those found in terrestrial environments. The greatest proportion of the background dose rate to phytoplankton, zooplankton, and pelagic fish is incorporated activity from alpha-emitting isotopes. Polonium-210 is the main source of this activity, and potassium-40 contributes most of the rest. Gamma radiation from the seabed is an equally important source of radiation exposure for benthic mollusca, crustacea, and bottom-dwelling fish. Only potassium-40, of the radionuclides in seawater, makes a significant contribution to the overall dose rates (21). Estimated dose rates from global fallout have declined with time and are now about the same as natural dose rates (21).

Nuclear reactors and fuel reprocessing facilities are point sources of ionizing radiation, which occasionally cause high concentrations of radioactivity in localized environments. At distances greater than a few hundred kilometers from the point of discharge, ionizing radiation is rarely detectable or distinguishable from fallout activity because of dispersion and decay processes. The Windscale reprocessing facility in the United Kingdom releases 225,000 Ci of low-level waste per year to coastal waters. The La Hague in France and reprocessing facilities in Italy and India also release low-level waste directly into coastal waters. A 1,000-MW(e) nuclear power plant releases 1-10 Ci/yr of ionizing radiation (38). Dose rates

TABLE 1.--Summary of Dose Rates (µrad/h)[a] to Marine Organisms from Environmental Radioactivity (21)

Source	Phytoplankton[b]	Zooplankton[b]	Mollusca[c]	Crustacea[c]	Fish[b]	Fish[c]
NATURAL BACKGROUND						
Cosmic radiation	0.5	0.5	0.5	0.5	0.5	0.5
Internal activity	1.9-7.3	2.6-15.7	7.4-14.9	7.9-21.4	2.7-4.2	2.7-4.2
Water activity	0.4	0.2	0.1	0.1	0.1	0.1
Sediment activity,						
gamma	-	-	1.5-16.0	1.5-16.0	-	1.5-16.0
beta	-	-	1.6-21.0	1.6-21.0	-	1.6-21.0
TOTAL[d]	2.8-8.2	3.3-16.4	9.5-31.5	10.0-38.0	3.3-4.8	4.8-20.8
FALLOUT						
Internal activity--^{3}H, ^{14}C, ^{90}Sr, ^{137}Cs, ^{239}Pu	0.01-0.88	0.23-13.4	0.06-0.32	0.004-0.097	0.02-0.06	0.02-0.06
Other nuclides	0.25-24.6	1.2-134	0.04-7.7	0.36	0.12-1.7	0.12-1.7
Water activity	5×10^{-5}-0.016	$4\times10^{-5}\times0.011$	$(0.2-32)\times10^{-4}$	$(0.2-32)-10^{-4}$	$(0.3-65)\times10^{-4}$	$(0.2-32)\times10^{-4}$
TOTAL[d]	0.26-25.5	1.4-147	0.10-8.0	0.36-0.46	0.14-1.8	0.14-1.8
WASTE DISPOSAL						
Windscale Reprocessing Facility						
Internal activity	200-2100	530-6900	15.3-58.9	6.9-67.9	0.5-1.5	0.5-1.5
Water activity	0.2-3.3	0.2-3.0	0.05-1.2	0.05-1.2	0.09-2.4	0.05-1.2
Sediment activity,						
gamma	-	-	36.4-3340	36.4-3340	-	36.4-3340
beta	-	-	207-5380	207-5380	-	207-5380
TOTAL [d]	200-2100	530-6900	51.8-3400	43.3-3410	0.6-3.9	37.0-3340
Bradwell Nuclear Power Plant						
Internal activity	NDA	NDA	1.37-1.81	NDA	NDA	NDA
Sediment activity,						
gamma	-	-	1.69	1.69	-	1.69
beta	-	-	1.32	1.32	-	1.32
TOTAL[d]	-	-	3.1-3.5	1.7	-	1.7

[a] A microrad (µrad) is equivalent to 1 x 10^{-8} Gray (Gy) or 1 Gy = 100 rad (radiation absorbed dose).

[b] 66-ft (20-m) depth, remote from seabed.

[c] 66-ft (20 m) depth, on the seabed.

[d] Excluding the contribution due to beta radiation from the sediment.

to organisms from reprocessing plants are 1 to 3 orders of magnitude larger than dose rates from the radioactivity of natural and fallout isotopes or nuclear power plant waste discharges (Table 1).

HISTORY OF RADIOACTIVE WASTE DUMPING IN THE OCEAN

U.S. Activity. The military service organizations of the Department of Defense, the Department of Energy, and the commercial nuclear industry (regulated by the Nuclear Regulatory Commission) were the sources of low-level waste dumped at sea. Between 1946 and 1970, the United States dumped 112,000 containers of waste (approximately 120,000 Ci) into waters ranging in depth from 49 ft (15 m) to more than 2.8 miles (4,600 m) (10, 35). Much of the waste consisted of contaminated laboratory clothing, glassware, experimental animals, and liquids from experiments. Some wastes derived from weapons production were also included. Most of this waste was packaged in 55-gal (242-L) drums with concrete so they would sink to the ocean bottom. The contents were expected to be eventually released into the ocean (10). The prevailing scientific thought guiding past ocean disposal activities was that low-level waste should be placed on the ocean floor where the currents would disperse and dilute the radioactivity.

Although the United States conducted ocean disposal operations at more than 35 dump sites, about 97% of the volume disposed was dumped at four areas in the Atlantic and Pacific oceans. The Atlantic sites are 140 miles and 219 miles (225 km and 354 km) southeast of Sandy Hook, New Jersey, and 15 miles (24 km) east of Boston in Massachusetts Bay. The Pacific site is located 50 miles (80 km) west of San Francisco.

Beginning in 1974, EPA's Office of Radiation Programs began a series of surveys at four of the major U.S. ocean disposal sites. The EPA plans to use information from the surveys in developing regulations and criteria for ocean disposal of low-level nuclear waste. All of the sites were successfully examined using submersible vehicles. Low concentrations of radioactivity were detected around the containers at both the Atlantic 9,184-ft-deep (2,800 m) disposal site and the Pacific Farallon Islands disposal sites at depths of 2,952 and 5,576 ft (900 and 1700 m) (10). Surface sediment samples from the Pacific sites have plutonium-239 and -240 concentrations at levels 3 to 30 times higher than the maximum expected concentration from weapons-testing fallout alone. At a distance of 2 in. (5 cm) from a waste canister at the Atlantic site, Dayal et al. (9) measured cesium-137 concentrations of 12 pCi/g in the top 0.8 in. (2 cm) of surface sediments and 1,040 pCi/g at a depth of 8 in. (20 cm). Only the top 1.6 in. (4 cm) of sediment had a measurable cesium-137 concentration at a distance of 1.6 in. (4 m) from the canister. Only about 0.3% of the total activity was released during 15 years to the overlying waters; the sediment at the study site appears to serve as a barrier to radionuclide migration. The mixing of sediments by organisms (bioturbation) is thought to be the primary mechanism for cesium redistribution. No radioactivity above normal background levels was found in sediments from the site in Massachusetts Bay (35).

The canisters appear to function as artificial reefs by attracting various organisms to the surface of the drums or to the vicinity (11). These organisms receive higher doses of ionizing radiation than they would have at farther distances. Several fish species have been observed near canisters--the deep-sea sole (Embassichthys), the thornyhead (<u>Sebastolobus</u>), and the rattail (<u>Nematonurus</u>). Sponges, sea urchins, and other invertebrates are found attached to the canisters (11). The EPA has analyzed bottom-dwelling fish collected at dump sites to determine if radionuclides from the disposed waste are entering the food chain. "No significant levels of radionuclides were found in the edible portions of any commercial species of fish" (35). When radionuclides are detected in fish, they are usually found in the internal organs or gut contents, not in the edible portions of the fish. Two researchers have stated that significant levels of radioactivity were measured in fish taken from former dump sites (33); however, the validity of both of these studies has been questioned by other scientists because of the scientific techniques used (35, 40).

The vast majority of U.S. scientists who are familiar with radioactivity in the marine environment, the EPA, the NOAA, and the National Academy of Sciences agree that the past dumping of low-level wastes in the oceans off the United States has not resulted in a hazard to human health or marine organisms. The ocean disposal of low-level radioactive waste in packages appears to be a much less significant source of radioactive material to the total oceans than worldwide fallout and the discharge of wastes from operating nuclear power reactors and fuel reprocessing plants (40). The EPA surveys have shown the following:

- o waste canisters can be recovered from a depth of 9,184 ft (2,800 m) using submersible vehicles;
- o an annual human consumption rate of 44 lb (20 kg) of fish from a disposal site would yield an annual dose that is approximately 1,000 times lower than the dose from radionuclides normally occurring within the human body; and
- o the water-soluble radioisotopes in low-level waste are dispersed and diluted to insignificant levels, whereas plutonium behaves as an insoluble particulate, settling rapidly to the ocean floor where it appears to be entrapped by sediments (11, 40).

However, Triplett et al. (38) recommend technologies that must be developed and federal actions that need to be taken to provide sufficient monitoring capabilities should the ocean be selected as a feasible disposal option for low-level waste disposal.

<u>Non-U.S. Activity</u>. Since 1967, Belgium, France, the Federal Republic of Germany, the Netherlands, the United Kingdom, Italy, Sweden, and Switzerland have participated in NEA-supervised disposal of low-level nuclear waste; however, only Belgium, the Netherlands, Switzerland, and the United Kingdom have used sea disposal since 1971 (10). Only the United Kingdom has dumped since 1982.

Some sea disposal of nuclear wastes was done by France and Japan in the early years of nuclear technology development, but the United Kingdom was the principal disposer between 1950 and 1966. Approximately 47,000 curies of alpha- and beta-particle-emitting wastes were dumped during this time in the Hurd Deep or near the Bay of Biscay in the northeast Atlantic. Beginning in 1967, all internationally supervised sea disposal has occurred in the northeast Atlantic Ocean at depths in excess of 2 miles (3,400 m). Foreign countries dumped between 500,000 and 600,000 Ci of nuclear waste in the ocean between 1967 and 1979 (10).

The northeast Atlantic dump site was reviewed by NEA in 1980 and found suitable for continued dumping for 5 years at the same annual rate. Thirteen OECD member countries (including the United States) are participating in a research and surveillance program, including physical oceanography, geochemistry, biology, modeling, and radiological surveillance. Hopefully, these data will help develop a site-specific model for more realistic assessment of doses to man. The biology program includes investigation of deep-ocean food webs, radioanalysis of deep-sea fauna, and dosimetry and radiosensitivity studies. Data are being collected on radionuclide concentrations in commercial seafood (32).

Needler and Templeton (27) calculated that the activity of alpha-emitters from the northeast Atlantic dump site (1967-1979) is equivalent to about half of the radioactivity from Windscale discharges (1957-1978) and only 13% of fallout levels received in the North Atlantic Ocean (early 1970s). For tritium the dump site activity is equivalent to 71% of the Windscale discharge but only 0.04% of fallout levels.

IONIZING RADIATION EFFECTS DATA FOR MARINE ORGANISMS

There is no convincing evidence that marine organisms respond in any way to ionizing radiation of any type at radiation levels present in their natural environment (8). Therefore, information produced by irradiation experiments on different types of organisms must be relied on to obtain an understanding of the tolerances and the structural and physiological responses of marine organisms to radiation. Doses used in many experimental studies are often hundreds or thousands of rads delivered at high dose rates rather than chronic low-level exposure.

Ionizing radiation produces both somatic effects and genetic effects in marine organisms. Organisms can be damaged by both internal and external radiation. If the organisms are irradiated continuously at low dose rates, there is an increase in the total dose necessary for death (or other injury) as compared with a single large dose. At low dose rates, repair of damaged cells occurs (8, 21). As a general rule, primitive forms of life are more tolerant of ionizing radiation than those with a more complex functional and structural organization, and significant differences exist in the radiotolerance of different species belonging to the same major taxonomic group (8).

Bacteria, Fungi, and Blue-Green Algae. Because relatively little is known about the responses of marine bacteria and blue-green algae to ionizing radiation, one must look at studies of nonmarine species. Zelle and Hollaender (43) reviewed the literature published prior to 1952 on the effects of ionizing radiation on bacteria; Pollard (30) did a more recent review. Bacteria, fungi, and blue-green algae are much more tolerant of ionizing radiation than are higher plants and animals. Doses that produce complete inactivation are generally in the hundreds of thousands of rads and sometimes reach a million rads. A rad (radiation absorbed dose) is the unit that expresses the amount of energy actually absorbed from radioactive fragments by tissue or other material (1 gray (Gy) = 100 rad).

Plants. Algae are able to survive exposures many times greater than those inducing severe damage and death in higher plants and animals. Godward (16) summarized the literature on the effects of ionizing radiation on algae. Generally, chronic exposure to radiation has less effect than a single acute exposure of the same magnitude. Recovery processes following radiation injury start promptly. The most apparent effect of ionizing radiation on algae is the failure of a population to increase in number as a result of an arrest of cell division, which is followed by cellular death. Many functions of algae are considerably more tolerant of ionizing radiation than cell multiplication. The LD_{50} (lethal dose to 50% of population exposed) values for algae range from 2,000 to 30,000 roentgens for X- and gamma-ray exposure [1 coulomb (C) per kilogram = 3.9×10^3 roentgens (R)]. Algae cultures survive (one viable cell) at beta-radiation doses of 10,000 - 1,000,000 rads and X-ray doses of 15,000 - 600,000 rads (8).

Marine algae are concentrators of radionuclides. This is significant because many species of seaweeds are used as food, feed, and fertilizer in certain countries. This ability to concentrate radioactivity is important when calculating doses via food chains.

Animals. Most of the experimental work on ionizing radiation effects on marine organisms has been done on animals. In marine invertebrates and fishes, exposure to long-term, low-level radiation is less harmful than an acute dose of similar magnitude. Actively metabolizing cells repair sublethal radiation damage rapidly, and systems responsible for recovery are not attenuated by repeated exposures. Results from ionizing radiation experiments on animals are summarized in Templeton et al. (36), Chipman (8), the IAEA (21), and Blaylock and Trabalka (4).

A general effect of ionizing radiation on aquatic animals is the retardation of growth, although growth stimulation from very low exposures has been observed in a few instances. Exposure to X-rays during early development of fishes results in a stunting of growth and marked abnormalities in the development of fins. Radiation injuries to the skin include damage to basal epithelial cells, scale sac cells, and mucous-secreting cells. High levels of radiation have been shown to affect the moulting process in a number of marine crustaceans. Irradiation tends to prevent or slow down the regeneration capabilities of marine organisms by injurying regenerative cells, but the structure of the regenerated part is not affected (8). Repair from radiation damage can also occur in fish; Woodhead and Setlow (42) found restoration of the intestine within 2 weeks after exposure to 1 kR. They were unable to demonstrate, however, any differences in lifespan or in the incidence of tumors in sublethally irradiated Amazon mollies.

Environmental factors can influence the response of an organism to ionizing radiation. Since the degree of damaging effects from radiation in marine organisms is closely related to their metabolic state and rate of cellular activity, mortality due to radiation is likely to change whenever environmental factors alter the rate of metabolism. Organisms that are exposed to variable physical conditions are less radiosensitive than those living in buffered environments (21).

EXPOSURE TO RADIATION IN WATER AND SEDIMENTS

Irradiation due to penetrating radiation from outside the body of an organism is referred to as external radiation and usually results from gamma rays. Radionuclides in water represent a radiation source to aquatic organisms, and physicochemical processes such as sorption can increase the dose to these organisms. Laboratory bioaccumulation experiments indicate that direct uptake of transuranics from sediments by benthic fauna is likely to be a quantitatively unimportant route of transfer to the marine food chain and man (2).

A number of investigators have demonstrated that some marine invertebrates and fishes appear to be quite resistant to irradiation over long periods of time. Plaice and lobsters have been maintained in radioactive sea water for 6 years with no obvious effects. A marine copepod maintained in seawater containing 45 µCi/L of cesium-137 revealed no deleterious effects, and the population was maintained at about its original level for 3 years (8).

Irradiation rates between 0.5 and 5.0 R/d from cobalt-60 (total dose of 355 R) administered to Chinook salmon from the fertilization stage to the feeding stage produced no damage that was sufficient to reduce the reproductive capability of the population over a period of several generations. Although abnormalities in young fish were increased at all exposures, the number of adults returning to spawn was not affected. The low-dose-irradiated population returned in greater numbers and produced a greater total of viable eggs than the control stock. At exposure rates of 10 R/d (total exposure of 810 R during incubation) and above, measurable radiation damage was evident, and the growth rate of the irradiated fingerlings was significantly less than that of the controls. Plaice exposed to 10 mR-1 R/h of cesium-137 (total exposure of 0.6-500 R) from fertilization to hatching showed no significant differences in hatching or survival (21). Acute doses of about 100 rads can produce some mortality in developing fish eggs (4).

A significant fraction of the total radioactive discharge into the Irish Sea from the Windscale reprocessing facility is accumulated by the seabed sediment. Dose rate contours range from 5,000 µrad/h near the outfall to 20 µrad/h at 12 miles (20 km) from the outfall. The radiation dose to plaice from beta and gamma radiation could reach 5 mrad/h. Such an exposure should not have a noticeable effect at either the individual or population level; comparisons of the length of plaice stock exposed to these levels of radiation for 20 years do not indicate an adverse effect (4). Effects on other natural populations exposed to chronic, low levels of radiation are discussed under "Ionizing Radiation Effects on Reproduction and Genetics."

Data from acute exposure experiments indicate that the sensitivity of blue crabs to radioactivity is representative of the sensitivity of other marine invertebrates. A significant number of deaths occurred only among the crabs receiving the highest radiation dose when they were exposed to a total of 5,105, 11,502, and 45,693 R over 70 days. Radionuclide concentrations in water of approximately 10^{-4} Ci/L and higher have adverse effects on the development of sea urchin and oyster larvae during short-term exposure tests. Studies on a marine copepod indicate density-dependent regulatory mechanisms, as found in fish populations (21).

IRRADIATION FROM INCORPORATED RADIONUCLIDES

There is a scarcity of information on the somatic effects of incorporated (metabolized) radionuclides on individuals and populations of aquatic organisms. The concentration factors for some artificial radionuclides in marine organisms indicate that some tissues could receive biologically significant beta doses. Radioisotopes that give off alpha particles usually have to be ingested by an organism to result in harmful effects, because the particles have a high ionization density but a range of less than 100 µm in tissue or water. When an isotope that decays by electron capture (e.g., iodine-125) is attached to DNA, it may produce a biological effect far in excess of that predicted on the basis of absorbed dose. One of the most controversial areas of radiation research on aquatic organisms is the sensitivity of developing fish embryos to incorporated radionuclides. Blaylock and Trabalka (4) review these data and suggest that the concentrations of radionuclides in the embryos, the stage of development at which exposure began, and the time required for embryonic development all contribute to the seemingly conflicting results found in the literature. Tritium in water delivers most of its radiation dose after the tritiated water mixes internally with tissue water. No effects were found on marine fish hatched in tritiated seawater until the concentration reached 10^{-2} Ci/L. At 1 and 10 Ci/L decreases in hatchability were observed, and at 10 Ci/L effects were noted on body shape and eye diameter of larvae. Tritium concentrations of 0.5 Ci/L affected freshwater fish. A tritium concentration of 0.5 Ci/L, if present in tissue water, would deliver approximately 150 rad/d to that tissue (21). Blaylock and Trabalka (4) suggest that for the species tested, developing fish eggs are probably sensitive to 10^{-3} Ci/L (strontium-90/yttrium-90).

IONIZING RADIATION EFFECTS ON REPRODUCTION AND GENETICS

Ionizing radiation has not been shown to affect the reproductive behavior of marine animals, but it does affect both sexual and asexual reproductive processes by cellular damage. Eggs of marine invertebrates and fish are usually more sensitive to X-ray irradiation than are the sperm. Sperm of marine fish have been reported to be radiosensitive at doses of 800 and 2,000 rad (8). In fish eggs, both irreversible and reversible (repairable) damage has been found, and the effect depends not only on the magnitude of the dose, but also on the stage of development at which radiation is administered (21). Egami and Hyodo-Taguchi (12) showed that eggs of the marine goby were more sensitive than those of the medaka. Examples exist of temporary and permanent sterility produced in fish by exposure to ionizing radiation (8).

Two classical concepts of radiation genetics are: (1) the lack of an apparent threshold in the dose-response relationship, and (2) the accumulation of genetic damage with successive dose increments. Radiation damage to genetic material is potentially repairable at the cellular level, and it depends on both biological and environmental variables (e.g., stages in the cell cycle, oxygen availability, etc.). A good inverse correlation between dose rate and fecundity or fertility in female and male fish has been determined (13, 14). Furthermore, the mutation rate does not depend on dose in any simple way if the energy deposition rate is fractionated or chronic. No significant differences were found in gross physical anomalies, lengths and weights, and mortality of first generation eggs and fry of irradiated and nonirradiated Coho salmon at exposures of 0.44 R/d (total dose of 40 R) (21).

A unique study looked at the fecundity of a natural population of freshwater fish exposed for many generations to chronic irradiation. The dose rate from the bottom sediments was estimated to be

350 mrad/d. The irradiated population had an increased brood size but more dead embryos and abnormalities than in the nonirradiated population. Blaylock (3) hypothesized that increased fecundity could be a mechanism by which a population of highly fecund organisms with a relatively short life cycle can adjust to increased environmental stress from radiation.

For fish, estimated mutation rates from ionizing radiation appear to be between those for Drosophila and the mouse (4). A predicted radiation-induced mutation rate in fish, assuming that all mutations are dominant lethals resulting in nonviable zygotes, indicates that less than one of every 1,000 embryos would be killed as the result of accumulation of an integrated dose of 0.5 rad by each parent. For highly fecund organisms, no significant deleterious effects at existing ambient dose rates are expected, since so few embryos survive to reproduce. Whales and sharks, which are less fecund, may not be affected because the dose rates likely to be received are generally less than the limits recommended by the International Commission on Radiological Protection (ICRP) (21).

Discussion. In general, marine ecosystems are thought to be more stable than freshwater ecosystems because they have larger, more complex food webs, the open ocean is flushed by currents, and there is a good opportunity for immigration of individuals into the affected area (21). However, the stability of the physical and chemical environment over long periods indicates that local effects of disturbance could be particularly severe because of the slow growth and recolonization rates of the organisms (1, 31).

Evidence indicates that marine microorganisms and algae are less sensitive to ionizing radiation than animals. Mitani, Etoh, and Egami (26) conclude that fish are more resistant to radioactivity than mammals at both the cellular and whole-body level. Laboratory experiments using doses to marine organisms in the range of 10^{-4} to 10^{-1} rad/h are needed before conclusions can be reached about the responses of wild populations exposed to low levels of radiation. The most sensitive aquatic organisms known are teleost fish, especially the developing eggs and young of some species. Some mortality has been observed at acute doses of 100 rad. Chronic exposure of 1 rad/d can result in minor effects on physiology or metabolism (21).

Fish eggs are sensitive to low levels of irradiation, and some researchers have concluded that the yield from commercial fisheries could be adversely affected by low concentrations of radionuclides in the sea. Survival of fish larvae depends to a great degree upon the availability of phytoplankton and zooplankton, except at the extremes of the range of a species, where hydrological conditions become of major importance. If the mortality of larvae is being enhanced by the low levels of irradiation presently existing in the marine environment, then recruitment to the stocks of highly fecund marine species of fish is unlikely to be adversely affected unless those stocks are already at risk because of severe overexploitation (21). Populations of commercially unexploited organisms should be able to withstand the effects of irradiation better than fish because they have not reached the limits of their density-dependent response mechanisms (21).

It is more difficult to predict effects on species with low fecundity, most of the elasmobranch species (rays, sharks, and dogfish) as well as the marine mammals. Most of these species produce live young; therefore, recruitment is closely related to parent stock size.

Available data suggest that the upper limit of fecundity has been reached by exploited stocks, and any further stress on the stocks would decrease their chances of survival. Because no data exist on the somatic effects of irradiation on these organisms, predicting the effects from low dose rates is impossible. However the IAEA feels that it is reasonable to assume that any effect is likely to be very small in comparison to the effects of harvesting.

Not much experimental work has been published on the effects of chronic, low-level exposure of marine animals to ionizing radiation. Observations appear to indicate that although negative effects on individual organisms may occur, overall effects on a population are not apparent. Two findings are especially significant for analysis of the effects of low-level waste disposal in the oceans: (1) the potential compensating effect of density-dependent responses in highly fecund species, and (2) the observations that repair processes may keep pace with injury at low dose rates.

PREDICTIVE TOOLS

Several types of models are needed to predict the environmental fate and effects from the dumping of low-level radioactive waste into the ocean. The particle size and other characteristics of the waste will determine the type of plume dispersion model that would be used if soils and solid waste are dumped from a barge. Most models of plume behavior in the ocean have been developed for calculating the physical fate of dredged materials. If wastes are containerized and dumped, the container size and weight would determine the distribution, and the waste would disperse once the containers break open or corrode. Such fate models predict the contribution of radioactivity from the waste to ocean water, sediments, and marine organisms. Dosimetry models are used to calculate the absorbed dose rate of organisms when one knows the concentrations of radionuclides in biota, water, and sediment. Dose rates depend on the geometry of the organisms; the IAEA (21) has developed separate models for phytoplankton; zooplankton; and mollusca, crustacea, and fish. Dose rate also depends on the type of particle emitted by the radioisotope of concern. As with most models, these are simplified and idealized versions of the real situation.

Our understanding of the deep ocean is insufficient to permit the construction of a single comprehensive oceanographic model that would allow predictions of radionuclide transport, except in generalized terms. Existing models (34, 41) determine the general distribution of the concentration field from simple estimates of mixing and transit times without considering the detailed mechanisms that can and do influence the distribution. Steady-state or equilibrium conditions predict that radionuclides with half-lives greater than a thousand years would be well mixed on the large scale, whereas those with half-lives less than a few hundred years are likely to be poorly mixed and show significant variation in concentration from place to place (19). The significance of short-term processes such as deep vertical upwelling, large-scale topographic features, undiluted lenses of water, strong convective currents, and removal by falling particles needs to be addressed. Such pathways are especially important when calculating a dose to a critical population. Some researchers are very concerned about biological vectors (1), whereas others say that transport by biological organisms and mixing of sediments do not significantly affect the concentration field established by physical processes (17).

Some short-term and "short circuit" processes exist. Radioisotopes of cesium, iron, americium, and plutonium can be moved up and down in marine sediments by water circulation and biological mixing (5, 9). Salps and rattail fish migrate vertically, and their buoyant eggs have been sampled near the surface. Planktonic larvae of molluscan species that dwell at depths of 6,560-13,210 ft (2000-4000 m) have been found in plankton samples within 984 ft (300 m) of the surface (31). Angel et al. (1) discuss the mobile benthic carnivore/ scavenger population, rays and sharks, and deep-diving mammals as possible links between the deep ocean and shallower waters.

The present acceptable dumping rates for solid, low-level radioactive wastes in the deep ocean have been calculated by the IAEA on the basis of a model such as the one by Webb and Grimwood (41). The resulting estimates are conservative, as is appropriate, since we do not understand the complexity of oceanic processes. The IAEA has estimated an annual release rate for an ocean basin slightly smaller than the North Atlantic of 10^5 Ci for alpha-emitters, 10^8 Ci for beta- or gamma-emitters, and 10^{12} Ci for tritium. The capacity of the world oceans for plutonium-239 is approximately 5×10^{10} Ci (based on the dose of alpha-emitters to critical groups). For long-lived radionuclides, the ocean has a finite capacity, which must be considered in oceanic models for radioactive disposal. The IAEA model assumes releases could continue for 40,000 years before the dose limit to man is reached. The NEA group of experts for research and environmental surveillance relevant to the Atlantic dump site is developing a site-specific model that contains a release model, a marine model, and a pathway model.

The IAEA has assessed pathways to man using the Shepherd model (34). The amount of low-level radioactive waste that can be disposed at the northeast Atlantic site is determined by a similar method. Release is assumed to continue for 40,000 years (the mean lifetime of plutonium-239); therefore, the concentrations in the marine environment of long-lived radionuclides will increase slowly over several thousands of years. For short-term processes of short-lived radionuclides, the IAEA assumes that the containment time on the seabed is 10 years and the time between release and exposure by consumption is 3 years. Several consumption and exposure pathways by which man might become exposed to radioactivity after its release on the ocean bottom have been evaluated by the IAEA. Release rate limits calculated by IAEA correspond directly, given the pathways and parameters used, to the dose limits established by the International Commission on Radiological Protection (ICRP) for individual members of the public. The ICRP maintains the value of 500 mrem for the annual limit, unless a really critical group is identified and realistic models are used, in which case the value is 100 mrem/yr) (37) [1 sievert (Sv) = 100 rem (roentgen equivalent man)].

There is also a need to validate with field data the models used. This has been done with some confidence for the releases from Windscale to the Irish Sea, but it is more difficult for the deep ocean, where transfer times from source to man and his marine resources are a function of long-term transport processes and where ambient levels are below detection limits.

The development of oceanographic models that account for biological processes, sediment-radionuclide interactions, and other significant processes that could influence critical pathway and limiting-capacity calculations is essential for continual disposal of radioactive waste in the ocean. Such developments would help refine the calculation of human exposures from ocean dumping of low-level radioactive waste. The ICRP feels that the level of safety required for the protection of human beings is likely to be adequate for the protection of marine species, though not necessarily individual members of those species (27). Modeling of radioactive waste disposal needs to be done on site-specific, regional, and world scales.

CONCLUSIONS

The ocean has significant levels of natural radioactivity. Several sources of man-made radioactivity, originating mostly from nuclear fuel reprocessing and weapons testing, also contribute to the background radiation levels to which the radioactivity from low-level waste must be compared. Marine organisms do not appear to respond to natural radiation levels. Predicted effects of ionizing radiation on marine organisms are based on experiments in which high doses of radiation are usually used to produce observable effects. Marine microorganisms and algae are less sensitive to ionizing radiation than animals. Teleost fish are the most sensitive aquatic organisms, responding to chronic exposures of 1 rad/d. At chronic levels of radiation, repair processes may be able to keep pace with injury. Another important observation is that although fish eggs are sensitive to low levels of irradiation, density-dependent responses can have compensating effects for highly fecund species.

The lack of observable effects from chronic-exposure experiments with marine organisms is consistent with the fact that very few effects have been observed from man-made radiation in the marine environment. No effects on marine organisms have been found that could be attributed to discharges from reactors on the Columbia River in Washington or to discharges of thousands of curies from the Windscale reprocessing plant into the Irish Sea. No gross effects or recognizable mutations were attributable to the radiation added to seawater from the testing of nuclear weapons in the Bikini-Eniwetok area of the Pacific Ocean. The monitoring of former U.S. disposal sites for low-level waste has not revealed significant effects on marine biota or contamination of these biota, and most authorities agree that these wastes have not been a hazard to human health or to marine organisms.

Many international agreements address the disposal of radioactive wastes in the ocean. Radioactive wastes are the only wastes whose disposal is subject to standards and recommended criteria developed by an international organization, for which international agreements require prior notification and for which dumping operations have been organized and conducted on a multilateral basis (15). The London Dumping Convention and UNCLOS III are the major international agreements governing ocean dumping. In the future, regional agreements could be important for ocean dumping of radioactive wastes.

Because the United States is a member of the IAEA and a party to the London Dumping Convention, EPA will have to make U.S. regulations under MPRSA consistent with international policy. However, the United States has sought a qualitative definition that would make it clear that dumping of high-level reprocessing wastes and spent fuel is prohibited in case the containment fails, whereas the IAEA criteria rely on release rate limits (15, 24). EPA is working on new regulations for ocean dumping, which may be issued in 1986 and which should bring the U.S. classification scheme for radioactive wastes into agreement with IAEA's classification and dumping rate restrictions.

Because only the European countries of NEA are now acknowledging ocean dumping, most disposal activities have been organized by one agency and restricted to one geographic area. However, if several other countries begin, or acknowledge ocean dumping of low-level radioactive wastes in different locations, an observer force, central record-keeping agency, and standardized monitoring systems may be necessary to protect the marine environment. Scientists must refine methods for determining the limiting capacity of the ocean for radioactive waste. Accurate data from all countries conducting ocean disposal of radioactive waste would be critical for calculating the exposure rates and assimilative capacity. Although existing amounts of low-level radioactive waste in the ocean do not appear to be harmful, our ability to predict the oceanic carrying capacity (how much waste, where, and for how long) needs to be perfected.

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APPENDIX I.—REFERENCES

1. Angel, M. V., Jusham, M. J. R., and Rice, A. L., "Marine Biology Needed to Assess the Safety of a Program of Disposal of High-Level Radioactive Waste in the Ocean," Marine Environmental Pollution, R. A. Geyer, ed., Elsevier, New York, 1981, pp. 298-312.
2. Aston, S. R., and Fowler, S. W., "Experimental Studies on Behaviour of Long-lived Radionuclides in Relation to Deep-Ocean Disposal of Nuclear Waste," Radioactive Waste Management, Vol. 5, International Atomic Energy Agency, Vienna, Austria, 1983, pp. 339-354.
3. Blaylock, B. G., "The Fecundity of a *Gambusia affinis affinis* Population Exposed to Chronic Environmental Radiation," Radiation Research, Vol. 37, 1969, pp. 108-117.
4. Blaylock, B. G., and Trabalka, J. R., "Evaluating the Effects of Ionizing Radiation on Aquatic Organisms," Advances in Radiation Biology, Vol. 7, Academic Press, Inc., New York, 1978, pp. 103-152.
5. Bowen, V. T, "Oceanic Distributions of Radionuclides from Nuclear Weapons Testing," Transactions of the American Nuclear Society, Vol. 26, 1977, p. 297.
6. Bureau of National Affairs, Inc., "EPA Nuclear Waste Ocean Dumping Plans Draw Fire from Union, Environmentalists," Environment Reporter, Vol. 12, No. 39, 1982, pp. 1221.
7. Cherry, R. D., and Heyraud, M., "Evidence of High Natural Radiation Doses in Mid-Water Oceanic Organisms," Science, Vol. 218, 1982, pp. 54-56.
8. Chipman, W. A., "Ionizing Radiation," Marine Ecology, O. Kinne, ed., Wiley-Interscience, New York, 1972, pp. 1579-1657.
9. Dayal, R., Okubo, A., Duedall, I. W., and Ramamoorthy, A., "Radionuclide Redistribution Mechanisms at the 2800-m Atlantic Nuclear Waste Disposal Site," Deep-Sea Research, Vol. 26, No. 12A, 1979, pp. 1329-1345.

10. Dyer, R. S., "Sea Disposal of Nuclear Waste: A Brief History," Nuclear Waste Management—The Ocean Alternative, T. C. Jackson, ed., Pergamon Press, New York, 1981, pp. 9-16.
11. Dyer, R. S., "A Review of Field Studies at United States Dump Sites. Nuclear Waste Management—The Ocean Alternative, T. C. Jackson, ed., Pergamon Press, New York, 1981, pp. 35-43.
12. Egami, N., and Hyodo-Taguchi, Y., "Species Difference in Radiosensitivity of Germ Cells Among Teleostean Fishes," Journal of Radiation Research, Vol. 13, 1971, p. 23.
13. Egami, N., and Hama, A., "Effects of Chronic δ-Irradiation on the Fish, Oryzias latipes, V. Further Study of the Sterilized Fish Exposed to δ-Rays During Development," Journal of Radiation Research, Vol. 20, 1979, p. 15.
14. Egami, N., and Hama-Furukawa, A., "Response to Continuous δ-Irradiation of Germ Cells on Embryos and Fry of the Fish, Oryzias latipes," International Journal of Radiation Biology, Vol. 40, 1981, pp. 563-568.
15. Finn, D. P., "Ocean Disposal of Radioactive Wastes: The Obligation of International Cooperation to Protect the Marine Environment," Virginia Journal of International Law, Vol. 21, No. 4, 1981, pp. 621-690.
16. Godward, M. B. E., "Invisible Radiations," Physiology and Biochemistry of Algae, R. A. Lewin, ed., Academic Press, New York, 1962, pp. 551-566.
17. Hagen, A. A., Bewers, J. M., and Needler, G. T., "Oceanographic Model and Radiological Basis for Control of Radionuclide Releases," Radioactive Waste Management, Vol. 5, International Atomic Energy Agency, Vienna, Austria, 1983, pp. 287-300.
18. Holcomb, W. F., "A History of Ocean Disposal of Packaged Low-Level Radioactive Waste," Nuclear Safety, Vol. 23, No. 2, 1982, pp. 183-197.
19. Hollister, C. D., and Rhines, P. B., "Oceanographic Processes and the Ultimate Disposal of High-Level Radioactive Waste," Transactions of the American Nuclear Society, Vol. 26, 1977, pp. 299-301.
20. Hunsaker, C. T., "Ocean Dumping of Low-Level Radioactive Waste," The Environmental Forum, Vol. 3, No. 7, 1984, pp. 24-31.
21. International Atomic Energy Agency, "Effects of Ionizing Radiation on Aquatic Organisms and Ecosystems," Technical Report Series No. 172, Vienna, Austria, 1976.
22. International Atomic Energy Agency, "Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, the Definition Required by Annex I, Paragraph 6 to the Convention, and the Recommendations Required by Annex II, Section D," INFCIRC/205/Add. 1/Rev. 1, Vienna, Austria, 1978.
23. International Atomic Energy Agency, "Control of Radioactive Waste Disposal into the Marine Environment," Safety Series No. 61, Vienna, Austria, 1983.
24. Lomio, J. P., "International Law and Disposal of Radioactive Wastes at Sea," New England Law Review, Vol. 15, No. 2, 1980, pp. 253-286.
25. Lounsbury, W. J., "Radioactive Waste in the Marine Environment: Guidelines for an Emerging National Policy," Radioactive Waste Management, Vol. 5, International Atomic Energy Agency, Vienna, Austria, 1983, pp. 331-338.
26. Mitani, H., Etoh, H., and Egami, N., "Resistance of a Cultured Fish Cell Line (CAF-MM1) to δ-Irradiation," Radiation Research, Vol. 89, 1982, pp. 334-347.
27. Needler, G. T., and Templeton, W. L., "Radioactive Waste: The Need to Calculate an Oceanic Capacity, Oceanus, Vol. 24, 1981, pp. 60-67.
28. Norman, C., "U.S. Considers Ocean Dumping of Radwaste," Science, Vol. 215, 1982, pp. 1217-1219.
29. Pentreath, R. J., Woodhead, D. S., Harvey, B. R., and Ibbett, R. D., "A Preliminary Assessment of Some Naturally-Occurring Radionuclides in Marine Organisms (Including Deep Sea Fish) and the Absorbed Dose Resulting from Them," 1980.
30. Pollard, E. C., "Phenomenology of Radiation Effects on Micro-organisms," Hanbuch der Medizinischen Radiologie u. strahlenbiologie, Vol. II, A. Zuppinger, ed., Springer, Berlin, 1966, pp. 1-34.

31. Rice, A. L, "Radio-active Waste Disposal and Deep-Sea Biology. Oceanologica Acta, Vol. 1, 1978, pp. 483-491.
32. Rüegger, B., Templeton, W., and Gurbutt, P., "The Nuclear Energy Agency Research and Environmental Surveillance Programme Related to Sea Disposal of Low-Level Radioactive Waste," Radioactive Waste Management, Vol. 5, International Atomic Energy Agency, Vienna, Austria, 1983, pp. 301-313.
33. Schell, W. R., and Sugai, S., "Radionuclides at the U.S Radioactive Waste Disposal Site Near the Farallon Islands," Health Physics, Vol. 39, 1980, pp. 475-496.
34. Shepherd, J. G., "A Simple Model for Dispersion of Radioactive Wastes Dumped on the Deep Seabed," Fisheries Research Technical Report No. 29, Ministry of Agriculture, Food and Fisheries, United Kingdom, 1976.
35. Sjoblom, G. L. and Johnson, R. H., "EPA Program for Ocean Disposal Permits and Ocean Monitoring for Low-Level Radioactive Wastes," Briefing for the National Advisory Committee on Oceans and Atmosphere, Office of Radiation Programs, U.S. Environmental Protection Agency, Washington, D.C., 1982.
36. Templeton, W. L., Nakatani, R. E., and Held, E. E., "Radioactivity in the Marine Environment," National Academy of Sciences, Washington, D.C., 1971, p. 223.
37. Templeton, W. L., "The Basis of the Revised International Atomic Energy Agency Definitions as Related to the Dumping of Low-Level Radioactive Wastes in the Deep Ocean," Nuclear Waste Management—The Ocean Alternative, T. C. Jackson, ed., Pergamon Press, New York, 1981, pp. 17-29.
38. Triplett, M. B., Solomon, K. A., Bishop, C. B., and Tyce, R. C., "Monitoring Technologies for Ocean Disposal of Radioactive Waste," RAND/R-2773-NOAA, Rand Corporation, Santa Monica, California, 1982.
39. U.S. Department of Energy, "Radioactive Waste Management," DOE Order 5820, U.S. Department of Energy, Washington, D.C., 1983.
40. U.S. General Accounting Office, "Hazards of Past Low-Level Radioactive Waste Ocean Dumping Have Been Overemphasized," EMD-82-9, U.S. Government Printing Office, Washington, D.C., 1981.
41. Webb, G. A. M., and Grimwood, P. D., "A Revised Oceanographic Model to Calculate the Limiting Capacity of the Ocean to Accept Radioactive Waste," NRPB-R58, National Radiological Protection Board, Harwell, Didcot, Oxon, United Kingdom, 1976.
42. Woodhead, A. D., and Setlow, R. B., "Response to and Recovery from Acute Sublethal Gamma-Radiation in the Amazon Molly, Poecilia formosa," Radiation Effects on Aquatic Organisms, N. Egami, ed., Japan Scientific Societies Press, Tokyo, 1980, pp. 171-182.
43. Zelle, M. R., and Hollaender, A., "Effects of Radiation on Bacteria," Radiation Biology, Vol. II, A. Hollaender, ed., McGraw-Hill, New York, 1955, pp. 365-430.

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