Contamination from Nuclear Wastes in the Arctic and North Pacific 2

Although popular perceptions of the Arctic might characterize it as a pristine area, it has become increasingly clear that this important ecosystem has not avoided the effects of industrialization and development. Evidence of contamination by persistent organic pollutants, heavy metals, and radioactivity has been gathered since the 1950s but has not garnered a great deal of public attention. However, in the last three years a tremendous amount of attention has been directed toward assessing the extent of, and identifying possible remedies to, the environmental contamination problem in the Arctic from Russian nuclear sources. Although the activities of several different countries have released radionuclides into the Arctic environment for decades, news of ocean dumping of submarine reactors and nuclear wastes by the former Soviet Union has generated particular interest and concern because it revealed previously secret activities and enhanced the traditional public fear of radioactivity. This chapter analyzes available information about the wastes dumped in the Arctic and North Pacific, what is known of their contribution to contamination of the marine environment, and the research efforts needed to address unanswered questions. Chapter 3 discusses the information required to understand the health and environmental impacts of this contamination. Chapter 4 addresses other potential sources of contamination of the Arctic and North Pacific environments.

Past dumping of nuclear submarine reactors and fuel assemblies, as well as significant amounts of other radioactive wastes, into waters adjacent to the Arctic and North Pacific Oceans was disclosed in some detail by the Russian Federation in a 1993 government white paper referred to as the "Yablokov report." The ultimate fate and effects of this dumping are currently unknown, but possible impacts on local and regional environments and public health have raised concerns not only in Russia but in other countries of the Arctic and North Pacific regions. People in the United States—in particular, Alaska and the Pacific Northwest—want to know about this dumping and other discharges of radionuclides into the oceans. They also want to know about other risks to these regions from Russian nuclear activities, both past and future, and the potential threat to the wider regional environment and population beyond Russian borders.

As discussed in chapter 3, a particular concern is the possible threat to Alaskan Native commu-

TABLE 2-1: Objects Dumped by the Northern Submarine and Icebreaker Fleets

Location	Objects	Depth (m)	Estimated activity in 1994 (kCi)
Ambrosimov Inlet	8 submarine reactors (3 with SNF)	20	37.9
Novaya Zemlya Depression	1 submarine reactor (1 with SNF)	300	7.8
Stepovoy Inlet	2 submarine reactors (2 with SNF)	50	22.7
Techeniye Inlet	2 submarine reactors	35–40	0.1
Tsivolka Inlet	3 reactors from icebreaker *Lenin* and shielding assembly from *Lenin* reactor assembly with SNF	50	59.4
Total	16 reactors (6 with SNF) 1 shielding assembly from icebreaker *Lenin* with SNF		127.9

KEY: kCi=kilocuries; SNF = spent nuclear fuel

SOURCES: Government Commission on Matters Related to Radioactive Waste Disposal at Sea ("Yablokov commission"), created by Decree No. 613 of the Russian Federation President, October 24, 1992, *Facts and Problems Related to Radioactive Waste Disposal in Seas Adjacent to the Territory of the Russian Federation* (Moscow, Russia: 1993), translated by Paul Gallager and Elena Bloomstein (Albuquerque, NM: Small World Publishers, Inc.); N. Lynn, J. Warden, Y. Sivintsev, E. Yefimov, M. Mount, K. Gussgard, R. Dyer, and K-L Sjoeblom, "Radionuclide Release from Submarine Reactors Dumped in the Kara Sea," presented at *Arctic Nuclear Waste Assessment Program Workshop*, Woods Hole Oceanographic Institution, Woods Hole, MA, May 1–4, 1995; Y. Sivintsev, "Study of Nuclide Composition and Characteristics of Fuel in Dumped Submarine Reactors and Atomic Icebreaker *Lenin,*" *Part I—Atomic Icebreaker* (Moscow: Kurchatov Institute, December 1993); M. Mount, Lawrence Livermore National Laboratory, personal communication, June 14, 1995.

nities, their traditional food supplies, and other Alaskan fisheries resources. The impact of radioactive wastes that have been dumped in Arctic waters is also a key concern of other nations, particularly Norway, which depends on a major fishery in the Barents Sea and is therefore very active in supporting research into such contamination in nearby waters.

The 1993 Yablokov report described the extensive past history of Russian dumping of damaged submarine reactors, spent fuel from the nuclear fleet, and other radioactive waste into the Kara Sea off Novaya Zemlya, into the sea of Japan, and in other locations. It was a remarkable document to emerge from the new government of the Russian Federation. The report represented the results of a tremendous effort to gather information, some of it decades old, from a multitude of Soviet ministries and agencies; declassify it; and report it frankly to the international community and to the Russian people. Other than the estimated inventory of the activity of the items dumped, which has been refined since the release of the report by an expert group working with the International Atomic Energy Association (IAEA) and the precise location of some of the dumped wastes, the information presented in the Yablokov report has not been disputed.

As the 1993 Yablokov report described, the Soviet Union dumped a multitude of materials in the Kara Sea and in fjords along the coast of Novaya Zemlya in the 1960s, 1970s, and 1980s, in violation of international as well as domestic laws. The wastes included containers, barges, and ships and submarines containing nuclear reactors both with and without spent reactor fuel. A total of 16 reactors were dumped at five different sites; six of these and an additional container held spent fuel (see table 2-1). The report estimated the maximum total radioactivity of these materials at the time of disposal as more than 2 million curies. Recent studies by Russian and U.S. scientists have reached the preliminary conclusion that about 0.13 million curies are present at these Kara Sea dump sites today.

The Yablokov report also listed similar dumping (of materials with lower radioactivity) in the Russian Far East (the Sea of Japan and near the Kamchatka Peninsula). In addition, the report described some accidents (most notably, the explosion of a naval reactor during refueling in Chazhma Bay near Vladivostok); solid, low-

TABLE 2-2: Solid Intermediate- and Low-Level Radioactive Waste Dumped in Northern and Far Eastern Seas

Location	Depth (m)	Activity in Sr-90 equivalents[a] (Ci)
Kara Sea, Novaya Zemlya Depression	380	3,320
Sedov Inlet, Novaya Zemlya	13–33	3,410
Oga Inlet, Novaya Zemlya	24	2,027
Tsivolka Inlet, Novaya Zemlya	56–135	2,684
Stepovoy Inlet, Novaya Zemlya	25–27	1,280
Abrosimov Inlet, Novaya Zemlya	12–20	661
Blagopoluchiye Inlet, Novaya Zemlya	13–16	235
Techeniye Inlet, Novaya Zemlya	up to 50	1,845
Near Kolguyev Island		40
Chernaya Bay, Novaya Zemlya		300
Barents Sea		>100
North, Total		**~15,900**
Sea of Japan (3 sites)	1,900–3,300	3,820
East coast of Kamchatka Peninsula	2,000–2,570	2,992
Far East, Total		**6,812**

[a]Information from original sources used by the Yablokov commission presented the activity of solid radioactive waste as "activity (strontium-90 equivalent) curies." These units appear to relate to the radiation measured outside the container or object and are not likely to have a consistent relationship to actual activity. The numbers therefore can be used for comparisons only within the low- and intermediate-level solid radioactive waste (SRW) category; more information is needed to understand the radioactivity they might represent today.

SOURCE: Government Commission on Matters Related to Radioactive Waste Disposal at Sea ("Yablokov Commission"), created by Decree No. 613 of the Russian Federation President, October 24, 1992, *Facts and Problems Related to Radioactive Waste Disposal in Seas Adjacent to the Territory of the Russian Federation* (Moscow, Russia: 1993), translated by Paul Gallager and Elena Bloomstein (Albuquerque, NM: Small World Publishers, Inc.).

level radioactive waste dumping; extensive low-level liquid waste discharge; the accident on and sinking of a nuclear submarine in the Norwegian Sea; and serious problems with the operation of current nuclear refueling vessels in both the Russian North and Far East (see tables 2-2 and 2-3).

The dumpings listed in the Yablokov report generated a number of questions about the potential impacts of the discharged radionuclides. Since radionuclides can affect human health and the environment only if and when the radionuclides come in contact with them, the key question is whether and how they may migrate toward populations and other ecosystems in the future. Over the past two years since the Yablokov report, a number of data collection efforts and investigations have been supported to address this question by U.S. investigators, Norwegians, Russians, other nations close to the Russian sites, and international agencies such as the IAEA. Some tentative conclusions have been reached, but the data collected by these efforts are not yet sufficient to accurately predict the impacts of this dumping.

Researchers have not found evidence of migration beyond the immediate vicinity of the dumped radionuclides that might affect human health in the short run. However, some key questions have yet to be addressed, for example: 1) there has been no inspection of many of the dump sites within the past two decades; 2) we have limited knowledge of the possible release rates and the long-term reliability of materials used to encase the waste; and 3) some of the critical pathways for radionuclides to affect humans, such as the biological food chain or ice transport, are only in the early stages of investigation.

TABLE 2-3: Liquid Radioactive Waste Dumped or Accidentally Released in Russian Northern and Far Eastern Seas

Location	Activity at time of dumping (Ci)
Barents Sea—open sea (3 sites)	11,779.0
Barents Sea—coastal (4 sites)	3,389.0
Kara Sea (1 site)	8,500.0
North, Total	**23,668.0**
Sea of Japan (6 sites)	11,984.8[a]
Sea of Okhotsk (1 site)	0.1
East coast of Kamchatka Peninsula (2 sites)	352.2
Far East, Total	**12,337.1**

[a]Includes 0.38 Ci dumped into the Sea of Japan by the Russians in October 1993.

SOURCES: Government Commission on Matters Related to Radioactive Waste Disposal at Sea ("Yablokov commission"), created by Decree No. 613 of the Russian Federation President, Oct. 24, 1992, *Facts and Problems Related to Radioactive Waste Disposal in Seas Adjacent to the Territory of the Russian Federation* (Moscow, Russia: 1993), translated by Paul Gallager and Elena Bloomstein, (Albuquerque, NM: Small World Publishers, Inc.); V.M. Zakharov, "Situation and Course of Action for the Problem of Managing Radioactive Wastes in the Russian Pacific Fleet," *Proceedings of U.S.–Russia-Japan Study Group for Radioactive Wastes in Sea of Japan, Sea of Okhotsk and North Pacific Ocean* (Biloxi, MS: January 1995); V.A. Danilyan, and V.A. Vysotsky, "Nuclear Waste Disposal Practices in Russia's Pacific Ocean Region," *Proceedings of U.S.-Russia-Japan Study Group for Radioactive Wastes in Sea of Japan, Sea of Okhotsk and North Pacific Ocean* (Biloxi, MS: January 1995).

Several other possible sources of contaminants that could affect the Arctic environment are also just beginning to be investigated. In the Kara Sea region, for example, one serious potential source is the large, northward-flowing Siberian rivers, at whose headwaters are located the major Russian nuclear weapons production facilities. Over the last few decades, the largest releases of radioactive wastes in the world have been recorded at several of these sites, such as Chelyabinsk, Tomsk, and Krasnoyarsk. Wastes totaling more than 100 million curies were discharged into lakes and rivers at one site, and over 1 billion curies were injected directly underground at two other sites. Consequences of these releases in the local areas are now under study. Whether high levels of contamination may migrate down rivers such as the Ob or Yenisey into the Kara Sea and the Arctic Ocean is currently under study.

Another related concern is the possibility of radioactive releases from a Russian submarine, the *Komsomolets*, that sank in deep water in the Norwegian Sea in 1989. Although recent surveys have not detected any significant releases and researchers believe that the future threat is minimal, some have advocated actions to continue monitoring and/or provide better barriers to future leakage.

Modeling and Risk Assessment

Research and data collection efforts within the U.S.-supported program under the Office of Naval Research (ONR), as well as research by other nations and international organizations, have provided only preliminary answers to questions about the ultimate fate of the radionuclide releases in the oceans and rivers and their potential impact on public health in the wider region. The traditional scientific approach to providing such answers, known as risk assessment, involves careful definition of the source (e.g., the dumped material, its condition, its potential for leaking and spreading over time, and its hazard); careful modeling of the most likely pathways (transport by ocean currents, by ice movement, through the biota or food chain, etc.); and estimating the risk of human exposure and consequent health impacts based on a number of scenarios. Some work on each of these components is in progress, including modeling of likely pathways through the marine environment. The modeling requires validation where possible, with real measurements and additional data for inputs. An integrated assessment of all of these factors has not yet been done for the radioactive dumping in the Arctic and North Pacific, although planning for such a risk assessment is now under way in the ONR program.

To produce a rigorous risk assessment would require more data and research in areas not yet well investigated (ice transport, biological pathways, human consumption patterns, etc.), as well as the conduct of a multi-year project with substantial investment in resources. Most experts agree that at least four years and several million dollars would be required. However, the size of the effort could be modified substantially, depending on the detailed plan and specific goals. Such goals would have to include (at least): a definition of the population to be studied for health risks; a definition of the region to be considered; a definition of the time frame for investigation; and a definition of the most likely scenarios for pollutant release and migration.

Monitoring

Another aspect of research and data collection that has not yet been undertaken is long-term monitoring of the environment and related indicators that may help provide early warning of potential future health or ecological risks from dumped radionuclides. The OTA review and many experts' conclusions point toward almost no immediate threat to human health beyond Russian borders, based on what is now known about the nuclear waste dumping and discharges under study. That conclusion, however, does not preclude future threats from contamination that has yet to leak and migrate. One possible way to answer the question of future threat is to undertake a rigorous, long-term scientific risk assessment as discussed above. Another way is to devise a monitoring program to facilitate early detection of future releases, anticipate possible migration, and prevent potentially adverse health and environmental impacts.

Many experts have thought about establishing a monitoring program for the nuclear dumping under study, but no specific plan has been put forward. Monitoring could take many forms. It could be tied to some form of leak detection devices at dump sites and possible discharge points (river mouths); it could entail continuous or periodic measuring of ambient concentrations of contaminants; it could involve testing of tissues from animal species important for human consumption (such as sampling Alaskan fish or Arctic mammals); it could involve sampling of some biological indicator. The first step in planning a specific monitoring program has not yet begun; therefore, no specific goals have been set.

If a planning process were initiated, it would be possible to evaluate other past and present monitoring efforts for similar purposes. For example, the Norwegians have initiated a program of measuring radioactive contaminants in fish, other seafood, water, and seaweed in their regions of interest in the Arctic. In the past, the U.S. Navy has conducted surveys at the sites of sunken nuclear submarines in the deep waters of the Atlantic Ocean to measure any discharges to the surrounding environment. Experience with these and other efforts could help develop a program for monitoring nuclear contamination in the Arctic and North Pacific. Information from previous efforts would be useful as a first step toward identifying possible goals and defining approaches needed to establish an effective monitoring program.

Remediation

If a significant risk is posed by radioactive materials dumped or discharged into the environment, it is possible to consider some means of recovery, improved containment, or improved barriers to prevent further releases. The term remediation has been coined in the United States to cover all of these possible measures. In the case of the dumped reactors and solid waste in the Kara Sea or the Russian Far East, much remains unknown about the quality of the containment technology used and its long-term integrity. Therefore, some experts have suggested that the sites be "entombed" in place with a major structure that would encase the material and prevent future leakage. Others have proposed recovering the dumped materials and providing a more secure storage on land. Studies are just beginning to examine the cost and feasibility of some remediation options. However, much more information is required about the condition of the dump sites and the characteristics of the materials themselves before any practical remedial approach could be investigated adequately.

The site that has received the most attention in terms of remediation or possible recovery is the location of the sunken submarine *Komsomolets*. This Russian submarine sank in about 5,000 feet of water in the Norwegian Sea with a nuclear reactor and two nuclear warheads. Expeditions to the site have identified a damaged hull with several holes, some of which were subsequently sealed to minimize water circulation through the vessel's torpedo compartments. Some planning for possible recovery of the submarine has been done, but most experts consider the risk of radionuclide contamination from the *Komsomolets* to be so low as to make its recovery unnecessary.

Remediation at other sites where major amounts of radionuclides have been released (such as the rivers flowing past Russian nuclear production complexes) is possible, and some work at places like Lake Karachai and the Techa River is under way. However, these efforts appear to be more focused on reducing exposure risk to the local population than on preventing future migration into the Arctic Ocean, which is more than a thousand miles downriver.

Some future remediation efforts at the Arctic or North Pacific dump sites may be worthwhile, depending on the findings of the ongoing assessments of potential radionuclide release rates. Norwegian authorities and the IAEA are planning some studies to determine the value of applying containment or recovery techniques to the Kara Sea sites, but no decisions have been made as to the value of any specific technology. Little information exists about implementation costs and funding sources for remediation projects at these sites, and studies to address these questions are just beginning to be considered. The United States has not initiated any such studies and probably could not justify them until much more information about the dump sites themselves is obtained and verified.

The situation described in this chapter provides only a first indication of current conditions and of needs for possible future research. It is evident, however, that when such material is discharged into the open environment, its fate is very difficult to predict in the long term. The only way to obtain answers about future risks is by conducting onsite investigations to identify possible problems. Practical and effective methods of monitoring may assist in observing suggestive trends or providing early warning of releases.

Even though the disclosures of Arctic dumping and other releases caused international reactions and are a serious concern, they are not necessarily the only major concern or the most serious releases or impacts from radionuclides. Other radioactive accidents and discharges of wastes into the Arctic environment (including those of nations other than the former Soviet Union) could be similarly relevant depending on many factors including, most importantly, whether they can lead to human exposure. For example, nuclear weapons testing in the 1960s and the Chernobyl accident in 1986 released large amounts of radionuclides into the atmosphere, and the resulting low-level contamination can be widely measured throughout the Arctic. Also, sea discharges of radioactive wastes from nuclear processing plants in the United Kingdom and France in the 1970s have been detected in Arctic waters thousands of miles away. Researchers have identified and traced specific migration of radionuclides from bomb tests, European reprocessing plants, and the Chernobyl accident, through the atmosphere and the water to various Arctic regions. In fact, since we have little indication of migration from Russian dumping activities, this other contamination, and the methods used to identify it, provide a context in which the impacts of the dumping or discharges from rivers may be investigated.

The following discussion summarizes the current understanding of the extent of radioactive contamination in the Arctic and North Pacific regions resulting from known sources. It evaluates how well the problem has been characterized to date and the uncertainties that remain. It also identifies information and research gaps and suggests important topics for future investigation.

TABLE 2-4: Large Global Releases of Radioactivity

Source	Time period	Amount released (Ci)	Comments
Fallout from atmospheric testing of nuclear devices	1952–1980	25 million, Cs-137 16 million, Sr-90 6.5 billion, H-3	Widely dispersed over the globe
European reprocessing plants	1952–present	5.2 million total to 1986	Discharged into the Irish Sea and English Channel, dispersed through the oceans
Chernobyl	1986	50–80 million total; 6.8 million of long-lived radionuclides	Injected into the atmosphere, with heaviest deposition in Belarus, Ukraine, and western Russia

KEY: Cs-137=cesium-137; H-3=tritium; Sr-90=strontium-90.

SOURCES: A. Aarkrog, "Radioactivity in the Polar Regions—Main Sources," *J. Environ. Radioactivity* 25 (1994); North Atlantic Treaty Organization, Committee on the Challenges of Modern Society, *Cross-Border Environmental Problems Emanating from Defense-Related Installations and Activities*, Final Report. Volume I: *Radioactive Contamination*, Phase I: 1993–1995; U.S. Navy, Office of Naval Research, Radioactive Inventories and Sources of Contamination of the Kara Sea by Riverine Transport, prepared by D.J. Bradley and U.P. Jenquin of Pacific Northwest Laboratory, PNWD-2316 (Richland, WA: Pacific Northwest Laboratory, 1995).

ARCTIC CONTAMINATION FROM NON-DUMPING SOURCES

Global Releases

Three major sources of radioactive contamination released globally have also been sources of radionuclides in the Arctic environment. Listed in table 2-4, these are: 1) global fallout from the testing of nuclear weapons; 2) discharge of nuclear wastes from European reprocessing plants; and 3) the explosion at the Chernobyl nuclear power plant.

The atmospheric testing of nuclear weapons by the Soviet Union, the United States, and other nations has been the single largest source of man-made radionuclides released into the global environment. Millions of curies of radionuclides were released high into the atmosphere and widely dispersed over the globe. As described in box 2-1, all of the largest atmospheric explosions carried out by the Soviet Union took place in the Arctic, on the archipelago of Novaya Zemlya. Underground and underwater tests took place there as well. Radionuclides from global fallout constitute a significant proportion of the radioactivity currently measurable in the Arctic Seas.

European reprocessing plants have also been an important source of radionuclides globally and in the Arctic. Box 2-2 summarizes the amounts of radioactivity that have been discharged over the years, and the movement of radionuclides into the North Sea and then to the Norwegian Sea and beyond into Arctic seas.

The reactor accident at Chernobyl released significant radioactivity into the environment, but the heaviest deposition was not in the Arctic region. Nonetheless, some cesium-137 (Cs-137) has been deposited and transported there, as described in box 2-3.

All three of these sources of released radionuclides have contributed to contamination of the Arctic seas (see table 2-5) and, in addition to the natural radiation sources discussed in chapter 3, provide a context in which further contamination or potential releases can be considered.

Komsomolets

Another cause for concern with regard to possible future Arctic nuclear contamination is the Soviet nuclear-powered submarine *Komsomolets* which sank on April 7, 1989, in the Norwegian Sea approximately 480 km off the Norwegian coast. The *Komsomolets* lies on the ocean floor in international waters at a depth of about 5,000 feet. According to Nikolai A. Nosov from the Rubin design bureau and the deputy chief designer of the *Komsomolets*, the submarine was powered by a single nuclear reactor of the PWR (pressurized water reactor) type and was carrying

BOX 2-1: Nuclear Testing

The first and largest source of radioactive contamination that has been measured throughout the Arctic, and throughout the Northern Hemisphere, was atmospheric testing and use of nuclear weapons. Beginning in the 1940s by the United States and the Soviet Union, and joined in the 1950s and 1960s by Britain, France, and China, more than 2,030 nuclear tests have been carried out worldwide, 511 of them in the oceans or atmosphere (47). In addition, the United States exploded two nuclear bombs over Japan during wartime in August 1945. The total yield of all of these explosions is estimated at 438 megatons, roughly equivalent to 30,000 Hiroshima-sized bombs (48).[a]

The contribution of atmospheric testing to global radioactive contamination has been substantial. It is estimated that 25 million curies of cesium-137 (Cs-137), 16 million curies of strontium-90 (Sr-90), and 6.5 billion curies of tritium (H-3) were released to the atmosphere from these tests (80). Most of the fallout occurred between 1955 and 1966, but the annual amount of fallout from the tests has decreased steadily since the partial test ban treaty in 1963. Atmospheric nuclear explosions have not taken place since a Chinese test at Lop Nor in October 1980 (48).

Many of the tests carried out by the Soviet Union took place at Novaya Zemlya (adjacent to the Arctic Ocean), including all of the very large explosions. At Novaya Zemlya, 132 tests were carried out between September 1955 and October 1990: 87 in the atmosphere, 3 underwater, and 42 underground (71). Despite the fact that about 94 percent of the total yield of all Soviet nuclear tests has been released at Novaya Zemlya (3), there does not appear to have been proportionately greater atmospheric fallout in that region. Available data suggest that the larger explosions took place at more than 1 km in height, so that almost all of the fallout was distributed globally, rather than locally. Indeed, based on data from 1964 to 1969, the Cs-137 accumulation was lower on Novaya Zemlya than in Sweden or Finland (48). In general, nuclear fallout at the two poles is less than at lower latitudes (80), and measurements suggest that fallout near Novaya Zemlya was similar to that in other Arctic areas (see figure 2-1). Similarly, low fallout deposition would be expected throughout the Barents and Kara Seas. However, atmospheric transport was generally toward the east, so it is reasonable that some close-in fallout may have been deposited over the Kara Sea at this time (33).

Carried out in adherence to safety requirements, underground nuclear tests should not lead to the release of radioactive fission products into the atmosphere. However, Russian scientists reviewing the test site at Novaya Zemlya have reported that 25 of the 42 underground tests there released radioactive inert gases and two "were accompanied with dynamic venting to the atmosphere of gaseous and evaporated products (venting of radioactivity)" (71). There have been no investigations about the ultimate fate of these releases in the local or regional environment, but they could contribute to the general problem.

The three underwater nuclear tests conducted at the edge of the Barents Sea on the south side of Novaya Zemlya contributed to contamination of the sediments in this area. Estimates of the inventory expected now in Barents Sea water and sediments from this source, after radioactive decay, are very low. Some recent measurements of sediments in the vicinity of the tests reported higher concentrations over a limited area, thought to stem from the underwater tests (68).

Global fallout on land in the watershed of the Arctic seas constitutes another contribution to the contamination of the Arctic as rivers wash the fallout into the ocean. Rough estimates of the radionuclide contribution to the Arctic from land runoff of global fallout and other sources are shown in table 2-5.

(continued)

BOX 2-1: Nuclear Testing (Cont'd.)

In addition to nuclear tests for weapon development, the former Soviet Union also used nuclear devices for other purposes. The Soviet Peaceful Nuclear Explosion program was active from January 1965 to September 1988, carrying out 116 nuclear explosions. The explosions were used primarily in support of the oil, gas, and mineral industries; to explore geological features at great depths; to create underground storage cavities; and to help extract gas and oil or extinguish burning wells. Eighty-one of the explosions were carried out in Russia (47). It is not known whether or how much these explosions may contribute to nuclear contamination in the Arctic, although they have certainly caused significant contamination of local areas.

[a]One megaton (Mt) is equivalent to the power of 1 million tons of TNT.

SOURCE: Office of Technology Assessment, 1995.

two torpedoes with nuclear warheads as well as conventional torpedoes (18). Much international attention has been drawn to the *Komsomolets* as a potential source of long-term radioactive contamination, especially to the extensive fisheries resources known to exist in this region of the Norwegian and adjacent seas within the Arctic.

As of August 1994, Soviet and Russian authorities had sponsored a total of five expeditions to the *Komsomolets*, with another expedition planned for the summer of 1995. The expeditions served to investigate the extent of the damage to the submarine, study the physical oceanographic characteristics of the area, take samples for measuring the level of contamination, seal holes in the torpedo sections, and determine the future course of action.

Russian authorities have released little information concerning the design and construction of the nuclear reactor aboard the *Komsomolets*. However, they have revealed that the reactor had a capacity of approximately 190 megawatts (MW) and have provided an estimate of the radioactive inventory of the reactor core. According to the Yablokov report, the reactor core contained approximately 42 kilocuries (kCi) of strontium-90 (Sr-90) and 55 kCi of Cs-137 (25). More recently, Russian experts from the Kurchatov Institute have revised the estimated inventory of radionuclides in the reactor of the *Komsomolets* to 76 kCi of Sr-90 and 84 kCi of Cs-137 (48).

Russian officials have reported that the reactor was successfully switched to stable cool-down mode before the submarine was abandoned, the structural integrity of the reactor compartment appears adequate, and water exchange in the region of the reactor compartment is very limited (25). These are all factors that would limit the potential migration of radioactive materials to the outside environment.

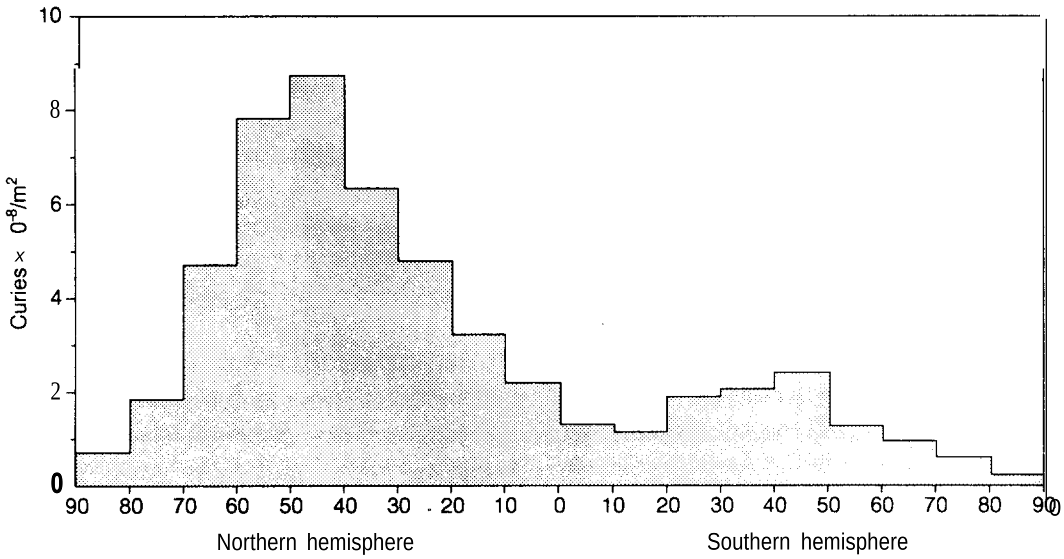
Two nuclear-tipped torpedoes located in the nose section of the *Komsomolets* present another possible concern. Both the Yablokov commission and researchers from the Kurchatov Institute estimate a plutonium (Pu) activity of about 430

TABLE 2-5: Estimated 1993 Inventory of Uncontained Radionuclides in the Arctic Seas

Source	Sr-90 (kCi)	Cs-137 (kCi)
Fallout from atmospheric testing of nuclear devices	70	111
Runoff from fallout on land	41	14
Sellafield Reprocessing Plant	27–54	270–405
Chernobyl		27–135

SOURCE: A. Aarkrog, "Radioactivity in the Polar Regions—Main Sources," *J. Environ. Radioactivity* 25 (1994).

FIGURE 2-1: Latitudinal Distribution of Strontium-90 Deposition from Atmospheric Nuclear Testing



SOURCE: United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), "Sources and Effects of Ionizing Radiation," UNSCEAR 1993 *Report* (New York: 1993).

BOX 2-2: European Reprocessing Facility Discharges

A significant source of contamination that has been documented to have migrated into many areas of the Arctic Ocean is nuclear waste discharged from reprocessing facilities in Europe. Civilian plants at Sellafield and Dounreay in Great Britain, and Cap de la Hague in France, reprocess spent fuel from nuclear reactors, Sellafield began discharging wastes from reprocessing operations into the Irish Sea in 1952, and Dounreay in 1958; Cap de la Hague began discharging into the English Channel in 1966. Between their start-up dates and 1986, when a comprehensive report on radionuclide discharges was released, the three plants discharged a total of 5.2 million curies of radioactivity. The largest contribution by far was from the Sellafield plant (4.3 million curies), followed by the plants at Cap de la Hague (0.6 million curies) and Dounreay (0,3 million curies). The discharges include at least 38 different radionuclides, but the elements of most concern for potential health effects are the beta-emitters cesium-137 (Cs-137), strontium-90 (Sr-90), and plutonium-241 (Pu-241), and the alpha emitters Pu-239 and americium-241 (Am-241) (48), Sellafield, in particular, has bean responsible for "a substantial increase in the inventories of a number of radionuclides (e.g., Sr-90, technetium-99 (Tc-99), Cs-137, Pu-239 and 240) in the North Atlantic as a whole and, in particular, the latitude band into which the discharges were initially dispersed (50-66° N)" (33). Recently the new Thermal Oxide Reprocessing Plant (THORP) at Sellafield began reprocessing spent fuel, so that increases in some radionuclides and decreases in others are projected. The Dounreay facility may increase its output of radionuclides from present levels as it processes fuel from the Prototype Fast Reactor shut down in 1994. Discharges from La Hague continue but have been substantially reduced in recent years (48).

(continued)

BOX 2-2: European Reprocessing Facility Discharges (Cont'd.)

Contributions to contamination in the Arctic from European reprocessing centers have been estimated based on the movement of traceable radionuclides out of the Irish Sea and around the coast of Scotland into the North Sea. From there, the contaminants are carried north through the Norwegian Sea by the Norwegian Coastal Current. The current splits, part traveling east into the Barents Sea, while the remainder travels with the West Spitsbergen Current up through the Fram Strait into the Nansen Basin.

Based on a variety of assumptions (see below), an estimate has been made that about 22 percent of the Cs-137 discharged by Sellafield enters the Barents Sea, en route to the Arctic Basin. At this time, it appears that Atlantic waters entering and mixing with Arctic waters are diluting the Cs-137. Since discharges have been reduced from Sellafield, the Atlantic waters have lower contamination, and older discharges from Sellafield are now flowing out from the Arctic through the Fram Strait (33). Transit time for the movement of Cs-137 from Sellafield appears to be 5 to 6 years to the Barents Sea (33); movement to the Kara Sea takes somewhat longer. Transit time from the plant at Cap La Hague is thought take about two years less.

There are many uncertainties inherent in estimating reprocessing waste contributions to Arctic contamination and the transit times of radioactive contaminants. The inflow into the Barents Sea is subject to strong influences from wind and is therefore highly variable, making estimates of radionuclide transport there difficult. Uncertainty in the contribution from reprocessing also stems from uncertainty in the "background" contribution from global fallout. As pointed out by Kershaw, water masses originating from different latitudes or water depths may have differing amounts of contamination from bomb test fallout. Values of 8-16 x 10^{-11}Ci/m^3 of Cs-137 have been reported for waters of the Arctic region. Higher levels may reflect the movement of waters from the Atlantic, at latitudes where higher levels of fallout occurred. Further uncertainty stems from the sampling itself, which can cover only a limited portion of such a huge volume (33).

In addition to contributions from reprocessing plants of radionuclides such as cesium and strontium, which move with the water, the behavior of particle-reactive compounds such as plutonium could also be of concern. Most of the plutonium released by Sellafield remains bound in the sediments of the eastern Irish Sea (33). However, some fraction of the plutonium, mostly in the higher oxidation state, stays in solution and can be readily detected in the North Sea. Whether it has been transported as far as the Arctic Basin is less clear. Analyses of plutonium isotopes suggest that indeed plutonium from Sellafield has been transported as far as the Barents and Greenland Seas. To date, it has not been possible to quantify the magnitude of this contribution (33,48).

SOURCE: Office of Technology Assessment, 1995.

BOX 2-3: The 1986 Chernobyl Accident

The reactor accident at Chernobyl, Ukraine, in 1986 was another significant contributor to global nuclear contamination, but its specific impact on the Arctic is difficult to estimate. About 2.7 million curies of cesium-137 (Cs-137) were released to the atmosphere and deposited in the northern hemisphere, particularly in Ukraine, Belarus, western Russia, and elsewhere in Europe (2). Based on the deposition of Cs-137 recorded at different sites in Greenland, a total deposition in the Arctic of 27,000 curies of Cs-137 has been estimated by one researcher, with perhaps a total of 135,000 curies including additional contamination transported northward by the West Norwegian Current (2). Others have estimated that Chernobyl contributed 1–2 percent of the 1991 total Cs-137 concentration in the Arctic basin (33).

SOURCE: Office of Technology Assessment, 1995.

curies (approximately 94 percent from Pu-239 and 6 percent from Pu-240) in the two warheads of the *Komsomolets* (6–10 kg of Pu) (48). Russian authorities note that the outer shells of the two nuclear warheads were damaged during the sinking of the *Komsomolets*, and because the hatches of the torpedo tubes are open, nuclear materials in the warheads are now in direct contact with seawater. It is impossible to predict the precise rate of corrosion of the warheads and the rate of release of nuclear materials without specific knowledge of the materials used for the protective coating of the warheads and the titanium hull of the submarine. This information has not yet been made available by Russian authorities. However, according to researchers from the Khlopin Radium Institute in St. Petersburg, analyses of water samples, bottom sediments, surface sediments, and biota taken from 1991 to 1994 indicate that releases of Pu-239 from the nuclear warheads into the environment have thus far been insignificant (37).

Efforts have been made by the Russians to seal the holes in the torpedo section of the *Komsomolets* in order to slow the rate of corrosion of the sections of the warheads that contain nuclear materials. During the expedition to the *Komsomolets* in August 1994 by the Russian research vessel the *Academician Mstislav Keldysh*, nine holes, including two in the torpedo sections containing the nuclear warheads, were sealed with plugs made of rubber and titanium as a means to prevent seawater from contacting the missiles (7,69). Most Norwegian and Russian experts agree that this process should minimize the likelihood of immediate corrosion of the warheads. However, since this type of operation is unprecedented, it is not possible to predict its long-term effectiveness.

Considerations of the potential hazard from the sunken submarine have focused on the eventual release of fission products such as cesium and strontium from the reactor, and plutonium from the nuclear warheads. It is impossible to estimate precisely the fission product release rates without more specific information regarding the reactor, but a recent effort using assumptions about the reactor construction and corrosion rates both for the reactor compartment and for spent fuel, arrived at an upper-bound release rate of Cs-137 of about 13.5 curies per year. Release rates of other radionuclides are likely to be at least an order of magnitude lower (48). As described further in chapter 3, information about the amount of curies released does not by itself provide enough information to indicate what the health and environmental impacts will be, but 13.5 curies per year represents a small source term. Understanding of the movement of the radionuclides and how they could come in contact with humans is required.

Given the estimate of the release rate of fission products such as Cs-137 and Sr-90 from the submarine, the next question is where and how quickly they might be transported through the marine environment. In general, little is known about the ocean currents at various depths. The Yablokov report states that the hydrology of the area in which the submarine sits is extremely complex, and the speed and direction of the currents can change significantly in a short period of time. Bottom currents in this area have been measured at up to 1.5 m/s by Russian scientists (25). Measurements taken by the Norwegian Institute of Marine Research at various depths near the *Komsomolets* site also indicate a strong and variable current, with very limited exchange between the deeper water layers (below 1,000 m) and the surface (5,48).

Norwegian modeling studies suggest movement of the water-soluble fission products up into the Arctic Ocean. Estimates of the potential doses to humans through the food chain from this movement suggest negligible contributions to typical doses. Fishing does not occur at the great depths where the submarine is located, and the radionuclides are diluted tremendously when they reach surface waters.

The model used does not describe the movement of radionuclides such as plutonium, which are not very soluble in water. It is expected that most of the plutonium will adhere to sediment particles in the ocean bottom, as has been observed near the Sellafield reprocessing plant.

Over the last 30 years, discharges into the Irish Sea from this plant have included 200 to 400 kg of plutonium. Ninety percent of this plutonium remains in the sediments close to the discharge point (18). It is expected similarly that almost all of the 6 to 10 kg of plutonium from the *Komsomolets* will also remain localized in the nearby sediments.

Given the present rate of releases and what is known about the condition of the *Komsomolets* and the physical characteristics of the region, most experts agree that the *Komsomolets* does not pose an immediate or long-term threat (15,22,48). In addition, the Russians have taken steps to delay the rate of release of contaminants by sealing up holes near the nuclear warheads. Future expeditions are planned to conduct further research and possibly to seal up more holes, or build a containment shield around the *Komsomolets*, and to continue radiological monitoring to estimate future rates of radioactive releases.

Russia's Nuclear Production Complexes

Like the United States, the Russian Federation has an extensive legacy of environmental contamination at its major weapons production sites. The sites with the largest radioactive releases in Russia are located along rivers that, thousands of miles downstream, ultimately feed into the Kara Sea. The heavy contamination at and around some of these sites could contribute to Arctic contamination if radionuclides are transported by these rivers to the northern seas. Boxes 2-4 through 2-6, covering the weapons production sites of Chelyabinsk, Tomsk, and Krasnoyarsk, describe some of the large releases of radionuclides into the environment that may contribute to contamination of the Arctic as they are washed downstream. They also describe the nuclear wastes still stored or being produced at these sites, which have the potential for release and eventual Arctic impact.

BOX 2-4: Environmental Contamination from Mayak Production Association near Chelyabinsk

The Chelyabinsk region in the southern Urals of Russia is a severely contaminated area, considered to be one of the places most polluted by nuclear waste in the world. Tremendous amounts of radioactive contamination are present at the site from the Mayak production complex, and the cleanup problems posed at the site will be a challenge for many decades to come. Human impacts among the workers and the regional population have been large and efforts are still underway to understand their extent.

The Mayak production association complex, situated about 70 km north of the city of Chelyabinsk in the southern Urals and built in 1948, was the Soviet Union's first plutonium production plant. The last of the five uranium-graphite reactors that produced weapons-grade plutonium was shut down in 1990. The complex now consists of two nuclear reactors including one to produce plutonium-238, a plant for reprocessing nuclear fuel called RT-1, a complex for vitrification of liquid high level wastes and storage of the resulting containers of waste glass, storage facilities for spent nuclear fuel and recycled plutonium and uranium, and several other facilities engaged in defense nuclear activities (52). The Mayak complex is located on mostly flat terrain amidst lakes, marshes, and the floodplains of several rivers, with groundwater in the area at depths from 0.9 to 4.0 m from the surface (74). The complex is located along the Techa River, a tributary of the Ob River system that flows northward into the Kara Sea.

(continued)

BOX 2-4: Environmental Contamination from Mayak Production Association near Chelyabinsk (Cont'd.)

According to Russian sources, approximately 1 billion curies of radioactive wastes has been generated at Mayak over the period of its operation (52). The bulk of this inventory is in the form of high-level liquid radioactive waste and is stored in about 60 special stainless steel tanks reinforced with concrete "shells" (60). In addition, Mayak's solid radioactive waste burial grounds contain 500,000 tons of contaminated materials, with an estimated activity of 12 million curies (50). Moreover, Russian sources acknowledge that at least 130 million curies of radioactivity has been released directly into the environment from Mayak, a sum that is about 2.6 times greater than the amount of radioactivity released from the Chernobyl accident in 1986 (75).

Today, 120 million curies remains in Lake Karachai (50) and continuing release of radioactive products into the lake is a major concern. Though most of the cesium in the waste is apparently bound to the clays at the lake's bottom, the strontium-90 and some nitrates appear to be migrating in a ground water plume which has spread at a rate of up to 80 meters per year and has reached the nearby Mishelyak River (44). Some Russian specialists are concerned that the contaminated water will break into the open hydrologic systems, contaminating the Ob River basin and ultimately flowing out to the Arctic Ocean (75).

In addition to intentional discharges and releases of radioactive wastes and materials, a severe contamination event occurred at Mayak in 1957 when a high level waste storage tank exploded, releasing 20 million curies of radioactivity. Most of the radioactive wastes fell near the tank, but 10 percent of the radioactivity was ejected into the atmosphere and carried great distances eastward. The contaminated area extended northeast from the Mayak complex, covering about 23,000 km^2 (74). Though 10,700 people were ultimately evacuated, more then half of them were not moved for eight months, and the people of the entire region consumed contaminated food from the 1957 harvest (12). The present activity of the radioactive materials released to the environment is now estimated at about 44,000 curies, of which strontium-90 is the primary contaminant (50).

Another contamination event occurred at Mayak in 1967 when a severe drought exposed a dry shoreline on Lake Karachai that had been used since 1951 for storage of radioactive waste. Winds carried about 600 curies over a 2,700 km^2 area up to 75 km from the site (50).

Some steps have been taken or planned to try to minimize further spread of contaminants into the surrounding atmosphere or groundwater. Since 1967 the Russians have been filling in Lake Karachai to limit further air release of radionuclides (50). A plan for removing the contents of the lake for reprocessing and disposal of high-level wastes was ruled out for financial reasons. Instead, large concrete blocks designed to trap sediments inside them as the lake is filled are being put into the lake. Once the blocks are placed and covered with rock and soil, the Russians may pump contaminated water from nearby wells and treat it to remove radionuclides and try to minimize their migration (50). In the meantime, however, liquid low-level wastes are still being discharged into Lake Karachai (24,58).

(continued)

BOX 2-4: Environmental Contamination from Mayak Production Association near Chelyabinsk (Cont'd.)

In addition to Lake Karachai, there are 7 other contaminated reservoirs present at the Mayak site which are a concern from a contaminant transport perspective. Inventories of reservoir volumes and contaminants were presented at a workshop on the environment in October 1992 (75). Russian experts include among the problems needing immediate attention the water regulation of these reservoirs, including both seepage out of the most downstream reservoir and overflow into the Techa River. For example, the water level in one of the Techa River reservoirs has been rising steadily, necessitating raising the height of the dam as a short term solution. With an increase in dam height, seepage of contaminated water out of the dam increases, releasing more radioactive contamination into the Techa River system (75). The migration of contaminated groundwater mentioned above is another serious issue, raising concerns that it will contaminate the Ob basin which leads to the Arctic Ocean (75). The Asanov Swamps, an area of 30 km^2 in the upper reaches of the Techa, are estimated to contain 6,000 curies of strontium-90 and cesium-137 and pose a contamination source to the river system (12,70). Furthermore, flooding that occurred this past spring substantially widened the area of contamination (58).

The extensive contamination that has occurred at and around the Mayak complex has taken a human health toll. As a result of the handling of weapon materials at Mayak, the large releases into the Techa River system, the 1957 high-level nuclear waste tank explosion, and the resuspension of contaminated wastes in 1967, radiation exposures of workers at the plants and some of the general population around the plant exceed the average doses experienced by atomic bomb survivors. According to a 1991 internal Soviet government report, more than 124,000 people were exposed to elevated levels of radiation from living along the river, and more than 28,000 to doses that "may have caused significant health effects" (52). Several thousand plant workers were also exposed. Studies in these populations have indicated increased rates of chronic radiation sickness, as well as increases in leukemia and other cancers (26,35,36). More studies are planned to better characterize the relationship between long-term, low-level exposure to radiation and disease development in these populations. Meanwhile villagers who have only recently learned of their many years of radiation exposure are under tremendous psychological stress as they struggle to understand how it might have affected them. Many are convinced that they have gotten sick or will get sick as a result of the radioactive contamination (21).

SOURCE: Office of Technology Assessment, 1995.

BOX 2-5: Environmental Contamination from Tomsk-7

The Siberian Chemical Combine (SCC), also known as Tomsk-7 or Seversk, is located near the Tom River approximately 16 km from the city of Tomsk in western Siberia. One of the largest weapons production facilities in the world, the site contains five graphite-uranium plutonium production reactors, a uranium enrichment plant, a reprocessing plant, and other plants engaged in the military nuclear fuel cycle (65). Three of the plutonium-producing reactors have been shut down, and the remaining two are dual-purpose reactors that provide heat and electricity for Tomsk and Seversk, as well as weapons-grade plutonium. Tomsk-7 remains an extremely sensitive military installation and is "surrounded by double, electric security fences, guard towers, and patrolled by armed guards between the fences" (73).

(continued)

BOX 2-5: Environmental Contamination from Tomsk-7 (Cont'd.)

Tomsk-7 came to international attention in April 1993, when a chemical reaction caused an explosion in a tank containing uranium nitrate solution during reprocessing of irradiated fuel. The explosion blew a hole in the roof of the building and sent a shock wave which passed down a 100 m gallery and knocked out a brick wall at the end (23). About 40 curies of radioactivity was released through a 150 m stack contaminating an area of more than 40 km^2 to the northeast of the site (24,76). Localized release in the plant was reported to be 4 curies of beta and gamma emitters (23). According to an international team visiting the site soon after the incident, some decontamination had already been carried out, and it appeared that no further offsite decontamination would be necessary (23).

A recent report from the Russian Federation Security Council presents some information on the contamination situation at Tomsk-7 resulting from the production and reprocessing activities of the last 40 years. The report estimates a total inventory of radioactive wastes stored within the industrial zone of the site at 1.2 billion curies at the time of burial (65). The majority of this inventory is in the form of liquid radioactive waste, part of which was discharged into several reservoirs. From the mid-1960s to 1982, an estimated 127 million curies of long-lived radionuclides was released into these reservoirs (48). Efforts are under way to fill in one of these reservoirs with soil (65). According to reports from workers of Tomsk-7, up to 850 kg of plutonium may have been discharged into reservoirs, and 1.5 to 3 kg per month was discharged into a "special sewer" from metallurgical and machining operations (59). Cooling water from the production reactors (low-level waste) was discharged to the Tom River in amounts up to 42,000 cubic meters per day (11). Discharges of cooling waters continue from the dual use reactors. The Tom River feeds into the Ob, which flows northward to the Kara Sea.

In addition to surface discharges, Tomsk-7 is one of three sites in Russia where underground injection has been used as a means of disposal for large volumes of waste. Information from the Tomsk Oil and Gas Geology Association in 1991 indicates that radioactive waste has been pumped into sandy layers 220-360 m deep, 10 to 13 km from the Tom River (50). Russian specialists estimate that 38 million cubic meters of liquid radioactive waste with an activity of 500 million curies has been injected underground (65). A more recent estimate suggests that the current activity of injected wastes at Tomsk-7 is as high as 1 billion curies (50).

Over the last few years, the Russian Ministry of Atomic Energy and the U.S. Department of Energy have had talks about the injection of the radioactive wastes, and Pacific Northwest Laboratory (PNL) began a study of the hydrology of the West Siberian Basin (which encompasses Chelyabinsk, Tomsk, and Krasnoyarsk). A study circulated in April 1994 acknowledges "massive contamination" as a result of nuclear fuel cycle activities there. It observes that though the basin is geologically stable, it is very wet (8). PNL is continuing its study and modeling efforts to better understand how the contaminants injected underground might be expected to move (77,78). Extensive studies have also been carried out by Russian scientists (62).

At a meeting in May 1994 in which Russian scientists discussed waste injection with U.S. scientists, several papers were presented that provided more details on the practice. In most cases, shallow geological layers were used for low-level wastes, and higher-level wastes were injected more deeply. In some instances, water is pumped out to create low-pressure areas that draw the wastes in desired directions (8).

(continued)

BOX 2-5: Environmental Contamination from Tomsk-7 (Cont'd.)

Although "accepted rules of nuclear waste disposal" require it to be isolated in impermeable containers for thousands of years, Russian scientists say the practice of underground injection is safe because of the impermeability of the shale and clay separating them from the earth's surface (50). It is not clear if or when the injected wastes could make their way into contact with human beings. Ideally, migration will be slow enough to isolate the wastes for thousands of years, allowing many of the radioactive elements to decay to less dangerous elements. However, further study of the hydrology of the region is necessary before conclusions can be made.

SOURCE: Office of Technology Assessment, 1995.

BOX 2-6: Environmental Contamination from Krasnoyarsk-26

The Krasnoyarsk Mining and Chemical Combine (MCC), also formerly known as Krasnoyarsk-26, Devyatka, Atomgrad, and now renamed as Zheleznogorsk, is situated approximately 60 km from the city of Krasnoyarsk, along the bank of the large Yenisey River, which flows north into the Kara Sea. Constructed in the 1950s, most of the facility is located 250 m to 300 m underground (48). The combine consists of three RBMK-type graphite-moderated, water-cooled reactors for the production of weapons-grade plutonium; a reprocessing plant to separate plutonium, uranium, and other fission products; and storage facilities for radioactive wastes. Two of the three production reactors at the combine have been shut down since 1992, but the third reactor is a dual-use reactor and continues to operate, supplying heat and electricity to the region. The two shut-down reactors had an open primary circuit that used water from the Yenisey River to cool the reactor core and released the water directly into the river after use. The current operating reactor has a closed primary circuit and uses water from the Yenisey River in its secondary cooling circuit (48).

Construction of a new aboveground reprocessing plant (RT-2) began in 1983 but was suspended in 1989 as a result of public opposition and economic problems (39). However, the Russian President has recently issued a decree calling for the continuation of construction of RT-2, which when completed would reprocess both domestic and foreign spent nuclear fuel.[a] Most of the liquid radioactive waste at the site is from reprocessing activities; the completion and operation of RT-2 would greatly increase the amount of radioactive wastes generated there.

Similar to the Mayak and Tomsk-7 nuclear complexes but to a lesser extent, local reservoirs and ponds are used as receptacles for the discharge of liquid radioactive wastes at Krasnoyarsk-26. Four reservoirs there reportedly hold up to 50,000 of curies (50). Efforts are reportedly under way to fill in one of these reservoirs with soil and sorbents for cesium (50).

Liquid radioactive waste generated by the Krasnoyarsk Mining and Chemical Combine has primarily been disposed via underground injection at the Severny site located within the sanitary protection zone of the combine for the past 25 years. Severny is located on a terrace, 100 m above and 750 m from the east bank of the Yenisey River, approximately 20 km north of Krasnoyarsk-26. A large part of the injected waste is transported to Severny through a reportedly leaky pipeline, which has spilled an unknown amount of liquid radioactive waste of all levels along its path to the injection site (10,48). Overall, Russian specialists estimate that more than 4.5 million cubic meters of liquid radioactive waste with more than 0.7–1 billion curies of activity at time of disposal has been injected at Severny at three different levels (84). The current activity of this injected waste is estimated by Russian experts at 450 million curies (17).

(continued)

BOX 2-6: Environmental Contamination from Krasnoyarsk-26 (Cont'd.)

Studies carried out by Russian institutes have determined that the injection site is satisfactory and has not negatively affected the surrounding environment (10), However, local Russian specialists have revealed a number of potentially serious concerns associated with the use of Severny as an injection site, including insufficient understanding of the geology and hydrology of the region. Specialized geomorphological, hydrogeological, and engineering studies have not been conducted there in the past 30 years. It has yet to be determined conclusively that the clay boundaries of the injection strata are continuous and thus able to prevent seepage of the liquid radioactive waste. Furthermore, the injection site is located in a zone of possible seismic activity. Potential earthquakes at the injection site may lead to the migration or discharge of injected radioactive waste into the basin of the Greater Tel and Yenisey Rivers (1 O).

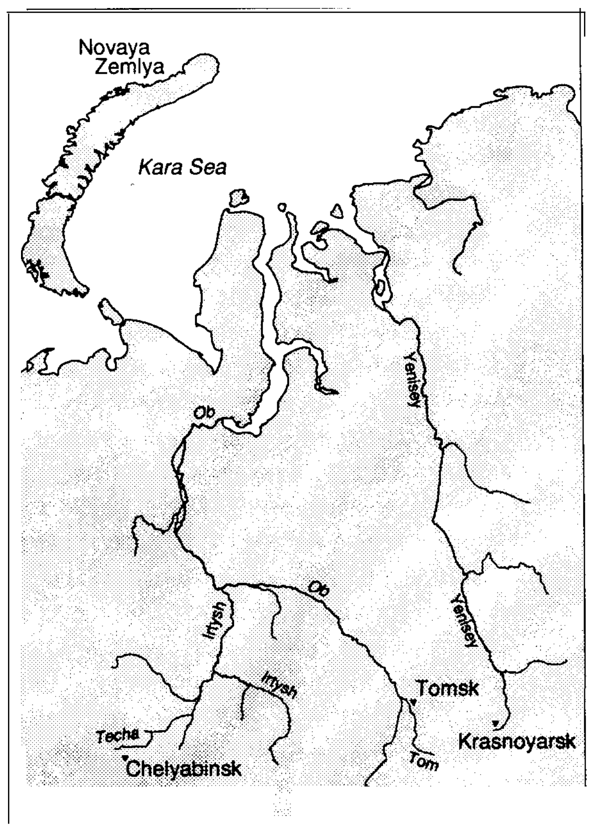
[a] On January 25, 1995, President Yeltsin signed the Edict on Structural Reorganization and Conversion of the Nuclear Industry in the City of Zheleznogorsk in Krasnoyarsk Kray. This document orders continuation of construction of RT-2 after a mandatory study by ecological experts.

SOURCE: Office of Technology Assessment, 1995.

Almost nothing was known about Chelyabinsk, Tomsk, and Krasnoyarsk before the increased openness of the Soviet Union in the late 1980s. These sites were among the secret cities established by Josef Stalin to work on military projects. They were not listed on maps, and few Soviet citizens even knew of their existence. Information about the status of radioactive sources and releases from these sites continues to be, for the most part, very limited. The most information has been forthcoming about the Mayak production facility near the city of Chelyabinsk. The Russians have openly discussed the challenges posed by this site, and these are now being studied jointly by the U.S. Department of Energy and Russia's Ministry of Atomic Energy.

Despite still somewhat limited information on the sites, it is clear that significant contamination of water bodies and soils has taken place at the three nuclear production complexes. A large proportion of the releases has been in the form of underground injection, but the human and environmental effects caused by these disposal practices-how, where, and when the radioactive materials may resurface or make their way into drinking water or the rivers-are still unknown. The three nuclear production sites are located on rivers that ultimately feed into the Kara Sea in the Arctic (see figure 2-2). Because of the great

FIGURE 2-2: The Ob and Yenisey Rivers



SOURCE: Office of Technology Assessment, 1995.

distances between these three sites and the Arctic, no large quantities of radionuclides appear to have reached the mouths of the rivers at this time (41,83). Over the long term, however, the potential contribution of these sites requires further study because several possible scenarios of floods or dam failures could trigger more extensive releases downriver into the Arctic seas. Box 2-7 describes the current findings from sampling in the Ob and Yenisey rivers and the modeling being carried out to better understand future risks.

RADIOACTIVE CONTAMINATION FROM SOVIET NUCLEAR WASTE DUMPING

Revelations in recent years have brought to light two sources of nuclear waste contamination from the former Soviet Union that have the potential to contribute to contamination in the Arctic and North Pacific. The extensive radioactive contamination at the inland nuclear production facilities located along rivers that empty into the Arctic is discussed above and in boxes 2-4 to 2-7. The remainder of the chapter focuses upon the dumped liquid and solid wastes described in the 1993 Yablokov report and what has been learned about contamination they have contributed to the Arctic environment.

BOX 2-7: Siberian Rivers as a Source of Nuclear Contamination of the Arctic

The Ob and Yenisey Rivers are large north-flowing Siberian rivers which empty into the Kara Sea. The Ob is about 3,700 km long, with a catchment area of almost 3 million km^2 and an average flow of almost 400 km^3 per year (81). The Yenisey River has an even larger average annual flow of 630 km^3 (34). The location of both rivers is illustrated in figure 2-2. Because of the extreme temperatures in the Arctic, the rivers and their estuaries are frozen about 10 months of the year, severely reducing water flow. When the snow in the southern parts of the catchment areas melts, tremendous volumes of water rush downstream carrying with them sediment and ice. The ice itself also often contains sediments and particles (57). These rivers are of concern as a source of radioactive and other pollutants to the Arctic Seas.

Potential radionuclide contributions to the Arctic Seas from these rivers come from two sources: global nuclear fallout from atmospheric testing, and releases into the environment at the nuclear production sites. It appears that global fallout onto land from nuclear weapons testing is by far the predominant contributor to radionuclide flow in the Ob and Yenisey rivers to date.

Starting in 1961, measurements of strontium-90 (Sr-90) in the Ob and Yenisey waters as they entered the Kara Sea were taken by the USSR Hydrometeorological Service. These measurements permit the estimate of the contribution of Sr-90 for the years 1961-1989 as totaling about 30,000 curies from the Ob and Yenisey rivers together (66,82). Based on an observed ratio of Cs-137/Sr-90 of 0.1 in the river waters, the output of cesium-137 (Cs-137) into the Kara Sea is estimated at 3,000 curies.

These estimates are consistent with nuclear fallout as the predominant source. Though most are retained in the soil, a certain proportion of radionuclides deposited on land as fallout is ultimately washed into these rivers. Aarkrog has estimated that the runoff of Sr-90 in an area is 10 percent of the deposition inventory, while the runoff of Cs-137 is 2 percent (1). The catchment area of the Ob is roughly 3 million km^2, the largest among all of the rivers feeding into the Arctic. Based upon estimates of fallout deposition at different latitudes in the Northern Hemisphere (80), it is possible to estimate a contribution to the Kara of 13,500 curies of Sr-90 and 4,590 curies of Cs-137 from the Ob River from global fallout (uncorrected for decay). The contribution from the Yenisey River's smaller catchment area would be lower.

(continued)

BOX 2-7: Siberian Rivers as a Source of Nuclear Contamination of the Arctic (Cont'd.)

Discharges and accidents at the nuclear production complexes provide another large potential source of radioactive contaminants to the rivers and ultimately the Arctic. As described in boxes 2-4, 2-5, and 2-6, tremendous inventories of radioactive materials are known to contaminate the areas surrounding three of Russia's largest nuclear production complexes that are located near rivers that ultimately feed into the Ob and Yenisey rivers. The Mayak Production Facility near Chelyabinsk is at the Techa River which ultimately feeds the Ob River via the Iset, Tobol and Irtysh rivers; Tomsk-7 is on the Tom River which also empties into the Ob River; and Krasnoyarsk-26 is situated close to the Yenisey River.

Despite the large releases at the Mayak Production Association and clear evidence of contamination in the Techa and Iset rivers, it does not appear that measurable levels of radionuclides from Mayak or from Tomsk have made their way down the entire length of the Ob River from the weapons complexes to the Arctic. Cesium measurements made in sediment samples from the Ob Estuary in 1993 indicated low levels consistent with fallout as a source (9). These samples were taken in areas where rapid flow regularly disturbs and mixes the sediments. Sediment cores collected further upstream in more sheltered pools and channels of the Ob River were also collected in 1994 (41). Since these cores are from sites where water flow is not as turbulent, they can provide some information about the timing as well as the presence of radionuclides. Analysis of these samples to date suggests no measurable contribution at these sites from the production facilities at Mayak or Tomsk. Instead, the data are consistent with a major signal contributed by nuclear testing fallout, and an additional signal perhaps contributed by venting from underground tests carried out in Novaya Zemlya (41,42).

An additional source of information about the possible nuclear contamination contributions to the Arctic from the Ob River comes from measurements of the radionuclide iodine-129 (I-129). From a limited sample set, I-129 measurements in the Kara Sea and the Ob River suggest that the Ob may contribute slightly to the I-129 inventory in the Kara Sea, though the larger source of I-129 there appears to be from the Sellafield Reprocessing Facility (61). More information is needed to reconcile this information with the lack of reprocessing signals observed to date in the lower Ob sediments.

Measurements of radionuclides in the waters and sediments of the Yenisey Estuary and River have also been taken. Levels of Cs-137 in the Yenisey Estuary area were higher than those seen in the Kara Sea or the Ob Estuary (9). Plutonium concentrations were higher than those observed in the Ob Estuary, but not higher than at some sites in the Kara Sea (9). The higher concentrations may come from more concentrated weapons testing fallout. However, there is also evidence that radionuclides from the direct flow reactors at Krasnoyarsk have migrated down the Yenisey. Short-lived radionuclides characteristic of those created in reactor cooling waters were measured in samples collected as far as 890 km from the discharge point (83). Another Russian investigator also reports measurement of long-lived isotopes in the river water, sediments, and biota that are thought to be from cooling waters of the reactors at Krasnoyarsk-26 (38).

(continued)

BOX 2-7: Siberian Rivers as a Source of Nuclear Contamination of the Arctic (Cont'd.)

All told, however, from data analyzed to date it does not appear that the majority of radionuclides released to the environment through discharges and accidents at the nuclear production sites have made their way down the rivers to the Kara Sea as yet. At Mayak, many of the radionuclides are thought to remain in the Asanov Marshes, while large amounts are also held in reservoirs of the Techa River. Since the inventories are extensive, efforts are being made under the auspices of the Department of Defense's Arctic Nuclear Waste Assessment Program to model the migration of radionuclides down the rivers either in a steady release, or in a sudden pulse that might result from a reservoir dam breaking or a large flood. Using existing data and data currently being gathered and analyzed on the characteristics of the radioactive sources and the rivers and estuaries, the modelers will try to estimate river contributions of Sr-90, Cs-137, and Pu-239 to the Kara Sea. The models will address two different scenarios, a steady continuous release of contaminants and a sudden large release of radionuclides as from dam breakage or a flood.

Sources of radioactivity to be entered into the steady stream model are discharges from reactor cooling, from reprocessing facilities, and effects of nuclear testing at Semipalatinsk. U.S. experts have estimated the radionuclides released to lakes and rivers from operation of the Russian plutionium reactors (50). Sources for modeling a pulse-like release of contaminants include reprocessing plant wastes now in ponds and reservoirs, wastes injected into deep wells, and some other smaller potential sources. The latter sources require additional modeling to estimate movement of contaminants through groundwater to reach the river. The movement of some of these sources is fairly well understood, such as the contaminated groundwater plume under Lake Karachai at Mayak, while movement of other contaminants, such as from the large injection wells at Tomsk and Krasnoyarsk, are more difficult to predict. Efforts to carry out this source modeling involve several different Russian and U.S. organizations, and will probably take several more years to complete (54).

In the meantime, for purposes of understanding potential shorter-term transnational contamination, modelers are focusing on the most reasonably likely and significant sources of radioactive contamination into the river which could lead to a radiation dose many kilometers away in the Kara Sea. These are migration of radioactive contamination from the Asanov Marshes, seepage of radioactive contaminants under the dams holding back radioactive reservoirs, and the possibility of reservoir dams giving way. Emphasis has been heavier on modeling the Ob River, because potential sources are more readily available to the river and represent a more probable risk of catastrophic release (53,55).

Additional models are being used to consider the river transport of the contaminants. Hydrography and radionuclide concentration data collected at various points along the Ob and Yenisey will be used to calibrate and validate the models. The estuaries at the mouths of the Ob and Yenisey are also complex systems which are challenging to model. Information to be incorporated includes behavior of the salt wedge, mixing, tidal versus river flow, and the behavior of the ice in the estuary.

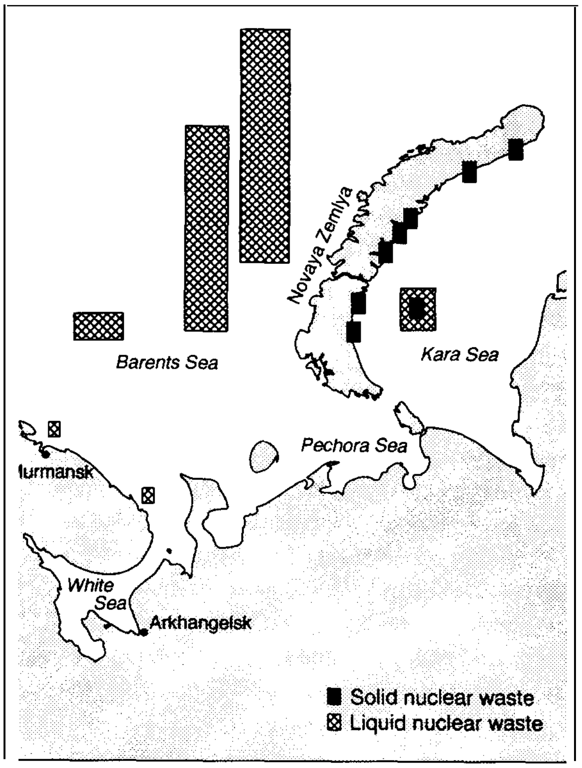
A large amount of data has been collected to incorporate in this series of models, and work is ongoing to refine the models. The data demands of the modeling have lead to the accumulation of a tremendous amount of data, which should be helpful both for addressing the basic science questions and for answering the more immediate question of potential risks from the rivers to the Arctic seas.

SOURCE: Office of Technology Assessment, 1995.

Disclosures About the Dumping at Sea

The Yablokov report on radioactive wastes disposed at sea described the dumping of liquid and solid wastes into the Arctic and North Pacific by the Soviet Navy and Murmansk Shipping Company at several different areas in the Barents and Kara Seas and in the Pacific Ocean (east coast of Kamchatka) and Sea of Japan. It also detailed

FIGURE 2-3: Locations of Nuclear Waste Dumping in the Russian Northern Seas

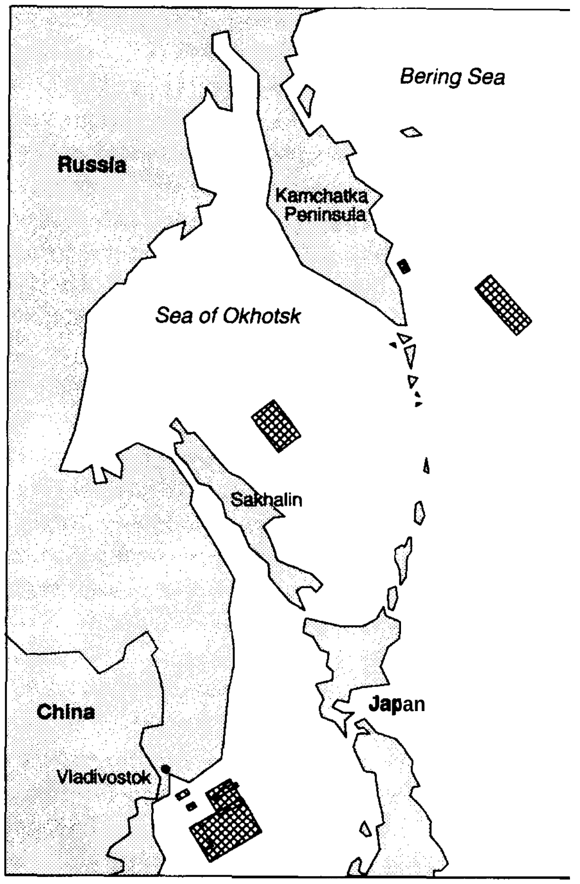


SOURCE: Office of Technology Assessment, compiled from data from Government Commission on "Matters Related to Radioactive Waste Disposal at Sea ("Yablokov commission"), created by Decree No, 613 of the Russian Federation President, October 24, 1992, *Facts and Problems Related to Radioactive Waste Disposal in* Seas *Adjacent to the Territory of the Russian Federation (Moscow,* Russia: 1993),

releases from leaks and accidents. Figures 2-3 and 2-4 show the locations of the solid and liquid waste dumping in the Russian North and Far East, respectively.

Liquid wastes were reported dumped at five different areas in the Barents Sea (along with six other accidental releases in bays and elsewhere) and nine areas in the Pacific Ocean (east coast of Kamchatka) and the Sea of Japan (table 2-3). In the Russian North, this dumping yielded over 189,634 m^3 of waste with more than 20,653 curies of radioactivity. The report also notes leaks from storage and an accident aboard a nuclear submarine that contributed further contamination. In the Russian Far Eastern seas, the

FIGURE 2-4: Locations of Nuclear Waste Dumping in Russian Far Eastern Seas



SOURCE: Office of Technology Assessment, compiled from data from Government Commission on Matters Related to Radioactive Waste Disposal at Sea ("Yablokov commission"), created by Decree No. 613 of the Russian Federation President, October 24, 1992, ***Facts and*** *Problems Related to Radioactive Waste Disposal* ***in Seas Adjacent to the Territory of the Russian Federation (Moscow,*** Russia: 1993).

volume of dumped liquid waste reported was more than 123,497 m^3, with 12,337 curies of radioactivity. Little information about the origin and radionuclide composition of this liquid waste is available, but it is likely to have originated from cleaning operations at shipyards and from reactor cooling systems (48).

Solid wastes were in a multitude of forms, including containers, barges, ships, and submarines containing nuclear reactors both with and without spent reactor fuel. According to the

Yablokov report, most of the volume dumped was low- and intermediate-level waste produced during the operation of nuclear submarines, surface vessels, and icebreakers (table 2-2). The report also described dumping of high-level radioactive wastes in the form of spent fuel and reactors from nuclear submarines and an icebreaker (table 2-1). A total of 16 reactors dumped at five different locations in the Kara Sea are listed; spent nuclear fuel remains in six of the reactors and an additional container from the icebreaker *Lenin*. Attempts were made to contain the fuel. For example, the damaged fuel assemblies from the *Lenin* were reported to be encased in a concrete and metal container, stored on land for a period, and then dumped with the *Lenin* reactor section. Nonetheless, the reactors with spent nuclear fuel constitute the greatest amount of radioactivity and thus the potential for the most serious future releases. The Yablokov report included an estimate that at the time of disposal, the upper limit on the activity of all of this spent nuclear fuel was 2.3 million curies. The two largest dump sites are Abrosimov Fjord where 1.2 million curies was deposited, and the East Novaya Zemlya Trough, into which 799,200 curies was dumped.

Since the time of the dumping, natural radioactive decay has reduced the inventory of radioactivity. Radioactive decay calculations performed at the Lawrence Livermore National Laboratory, along with revised estimates of the nuclear reactor working histories developed through the work of the IAEA, suggest that less than 130,000 curies of radioactivity remains in the reactors and spent fuel (43,46).

The Yablokov report states that until 1983, monitoring of the waste disposal areas was carried out by the Northern and Pacific fleets of the Soviet Navy, with surveys to measure levels of "biologically hazardous radionuclides in seawater, bottom sediments, and commercial and marker species of water life in radioactive waste disposal areas" (25). In addition, more extensive radiological studies were carried out at different times between 1960 and 1990 by various research facilities to determine optimal conditions for radioactive waste discharge by the Navy (25). After 1983, responsibility for monitoring radiation conditions in radioactive waste discharge and dumping areas was given to Goskomgidromet, the State Committee for Hydrometeorology. The Yablokov report lists expeditions carried out in 1975 in the Sea of Japan, in 1982 in the Kara Sea, and the Joint Russian–Norwegian expedition in 1992 in the Barents and Kara Seas.

Despite these expeditions, however, the report stresses that none of the surveys carried out after 1967 came closer than 50-100 km to solid radioactive waste disposal sites (25). This is repeated in a recent report by Gosatomnadzor, the Russian nuclear regulatory agency, "For 25 years no surveillance has been conducted at the solid waste dump sites which results in that it is practically impossible to define the condition of solid waste protection barriers, the speed and scale of radionuclide release" (24). This remained the case until joint Russian–Norwegian expeditions visited some of the dump sites in 1993 and 1994. Furthermore, even though monitoring data were collected by the Northern fleet and many related research institutes, these collections did not constitute a coordinated system of monitoring the radioactive objects dumped at sea, according to the Yablokov report (25).

Much of the remainder of this chapter reports research done and questions remaining about these dump sites and the nature of their contribution to Arctic and North Pacific contamination.

TABLE 2-6: Conferences and Congressional Hearings on Arctic and North Pacific Contamination from Dumped Nuclear Waste

Location	Dates	Topic
Washington, DC	Aug. 15, 1992	*Hearing*: Radioactive and Other Environmental Threats to the United States and the Arctic Resulting from Past Soviet Activities
Arkhangelsk, Russia	Oct. 14–18, 1992	Ecological Problems in the Arctic
Oslo, Norway	Feb. 1–5, 1993	Consequences of Dumping of Radioactive Waste in Arctic Seas
Anchorage, AK	May 2–7, 1993	Arctic Contamination
Woods Hole, MA	June 7–9, 1993	Radioactivity and Environmental Security in the Oceans
Kirkenes, Norway	Aug. 23–27, 1993	Environmental Radioactivity in the Arctic and Antarctic
Washington, DC	Sept. 30, 1993	*Hearing*: Nuclear Contamination in the Arctic Ocean
Biloxi, MS	Jan. 12–13, 1995	Japan–Russia–United States Study Group on Dumped Nuclear Waste
Woods Hole, MA	May 1–4, 1995	Arctic Nuclear Waste Assessment Program Workshop
Oslo, Norway	Aug. 21–25, 1995	International Conference on Environmental Radioactivity in the Arctic

SOURCE: Office of Technology Assessment, 1995.

RESEARCH AND MONITORING OF RADIOACTIVE CONTAMINATION IN THE ARCTIC, THE NORTH PACIFIC, AND ALASKA[1]

The response to the information provided in the Yablokov report was international consternation and the birth or adaptation of a host of projects and programs to characterize the situation. The issue is, *does the amount and disposition of this waste pose any large short- or long-term risk to public health or the environment?* Because so few data were available to the international community at the time, major efforts were made to gather more. Interest in and research activity on the topic are reflected in the number of workshops, international conferences, and congressional hearings held over the past few years (table 2-6).

In the United States, Department of Defense (DOD) funds were used to launch the Arctic Nuclear Waste Assessment Program (ANWAP), administered through the Office of Naval Research (ONR).[2] Internationally, the IAEA began the International Arctic Seas Assessment Project (IASAP) (described in chapter 5). The Norwegians, whose large fishing industry is potentially threatened by concerns over radioactivity in the Arctic seas, were also active in addressing the problem through a joint Russian–Norwegian expert group formed in 1992 for this purpose.

Findings from the Joint Russian–Norwegian Expert Group

Expeditions carried out by the Joint Russian–Norwegian Expert Group in the summers of 1992, 1993, and 1994 have made important con-

[1] Much of the information presented in this section was excerpted from a paper prepared for OTA by Drs. Burton Hurdle and David Nagel of the Naval Research Laboratory. Additional information was drawn from a paper prepared for OTA by Dr. Lee Cooper of Oak Ridge National Laboratory.

[2] ANWAP has been funded through DOD at $10 million per year for FY 1993, 1994, and 1995.

tributions to the state of knowledge of the contamination levels in the Kara Sea and some of the dump sites along Novaya Zemlya. Although the research ship *Victor Buinitskiy* did not visit the specific sites of the dumped nuclear wastes in 1992, researchers took water and sediment samples at 13 stations, two in the Barents Sea and the remainder in the Kara Sea. The radiation measurements from these samples, analyzed in five countries, were presented at a meeting in Kirkenes, Norway.

The final report of the 1992 cruise states:

> "At present time, the level of contamination of radionuclides in the southern Barents Sea and the Kara Sea can be attributed to global fallout, releases from [the] Sellafield [U.K.] reprocessing plant, contribution from the rivers Ob and Yenisey, and contribution from the Chernobyl fallout... The possible radiological impact on man and the environment as a result of the observed levels of contamination is extremely low...at present, the influence of the dumped radioactive wastes on the general level of radioactive contamination in the Kara Sea is insignificant. However, local effects in the vicinity of the dumping sites cannot be excluded, as these areas were not adequately investigated."[3]

The 1993 Norwegian–Russian cruise was able to investigate some of the dump sites. The *Victor Buinitskiy* visited dumpsite areas in Tsivolky and Stepovogo Bays in Novaya Zemlya and the Novaya Zemlya Trough in the Kara Sea to provide a general assessment of potential radioactive contamination in the water, sediments, and biota (31). Analyses of the Cs-137, Sr-90, and Pu-239 and 240 in collected samples indicate that the level of radioactive contamination in the investigated areas is low, comparable to that observed in 1992 in the open Kara Sea. In the Tsivolky Bay, where the *Lenin* reactors were reported to be dumped, Cobalt-60 (Co-60), which may have originated from the dumped nuclear waste, was measured in the upper sediments, but components of the *Lenin* were not located. The expedition located one of the submarines dumped with nuclear fuel in the outer part of the Stepovogo Bay, and analysis of sediment samples from near its hull may suggest some leakage of fission products from the submarine reactors. In the inner portion of Stepovogo Bay where the bottom waters are isolated by a "sill," elevated Cs-137 values were found. Cobalt-60 was also present in these samples, which may be a sign of possible leakage from the dumped waste. Only a detailed study of Stepovogo Bay will answer this question. Concentrations of Cs-137 in surface sediments of the Novaya Zemlya Trough, also mentioned in the Yablokov report as a site for nuclear waste dumping, were similar to those in the open Kara Sea in 1992.

The 1994 Norwegian-Russian cruise visited the Abrosimov Bay and returned to the Stepovogo Bay. The expeditions located three of the four nuclear submarine reactor compartments reportedly dumped in the Abrosimov Bay (32). Preliminary data gathered on the cruise indicated elevated Cs-137 gamma-ray levels near two of these reactors, while only Co-60 radiation was observed near the third. Sediment and water contamination levels were low overall, comparable to the open Kara Sea, except for elevated Cs-137 in sediment near the dumped objects.

From the limited information available, it appears that any leakage that may have taken place so far from dumped wastes has at most led to very local contamination. More extensive inspection of the dumped objects (in particular, all of the reactors with spent fuel) and sampling of the environment nearby are necessary.

U.S. Arctic Nuclear Waste Assessment Program (ANWAP)

The research program undertaken by DOD's Office of Naval Research to address the concerns

[3] Joint Russian–Norwegian Expert Group for Investigation of Radioactive Contamination in the Northern Seas, "A Survey of Artificial Radionuclides in the Kara Sea. Results from the Russian–Norwegian 1992 Expedition to the Barents and Kara Seas" (Osteras, Norway: Norwegian Radiation Protection Authority, 1993).

posed by nuclear materials dumped in Arctic seas has been a large and broad research effort. Administered through the ONR, the program has focused on five topics: 1) the environment through which dumped nuclear materials might move; 2) the character and containment of the materials themselves; 3) their potential motion and disposition as determined by physical, chemical, and biological factors; 4) possible risks to people and nature; and 5) future monitoring of the materials. The Office of Naval Research organized its program around these topics while utilizing existing academic, industrial, and government capabilities. The primary objective of the program is to determine whether or not the radioactivity dumped in the Arctic Seas by the former Soviet Union (fSU) presents a threat to the economy or to the health of U.S. citizens. Box 2-8 discusses these five topics, the research questions they engender, and the current knowledge base.

Over the past few years, water, sediment, and biological samples were collected by five ships in the eastern Arctic near the dump sites and major river estuaries, and five ships collected samples in the western Arctic near Alaska. In 1993 and 1994, research cruises to investigate radioactive contamination in the Arctic were conducted by U.S., Canadian, and German icebreakers, the University of Alaska Research vessel *Alpha Helix*, a U.S. submarine, and five Russian vessels. A summary of the ships, cruise regions, stations, and samples obtained in the Arctic and nearby seas in the summer of 1993 is given in table 2-7. The locations sampled from these ships in 1993 and 1994 are illustrated in figure 2-5. More than 11,000 samples were obtained from 600 ocean stations in order to assess background radiation from fallout and other sources, and to search for elevated radiation levels associated with Soviet and Russian nuclear waste.

BOX 2-8: Key Research Topics and Knowledge Base of the Arctic Nuclear Waste Assessment Program (ANWAP)

Topic	Knowledge Base
1. The environment through which the dumped radioactive materials might move: What is the background radioactivity already in the environment due to naturally occurring radioisotopes and the effects of testing and discharge from nuclear reprocessing plants? Further, what are the physical, chemical, and biological environmental factors that will determine the transport and disposition of unconfined radionuclides in the environment?	A great deal was known and has been learned in the first two years of ANWAP regarding radioactivity in the Arctic. The information is either already in the geographic information system database set up for this program or will be incorporated as soon as it is made available. There remain, however, significant gaps in knowledge of the spatial and temporal distributions of radioactive materials in the Arctic.

(continued)

BOX 2-8: Key Research Topics and Knowledge Base of the Arctic Nuclear Waste Assessment Program (ANWAP) (Cont'd.)

2. The dumped materials themselves (the so-called source terms): What radionuclides have been dumped, and in what quantities, chemical states, and containers? When, if at all, will these materials be released, and at what rates?

Three reactor compartments dumped with their nuclear fuel have been located during the past two summers by joint Norwegian-Russian expeditions. However, a reactor with fuel, a container carrying spent fuel from the icebreaker *Lenin,* nine of the ten reactors dumped without their fuel, and virtually all of the thousands of containers dumped with low levels of radioactivity have not been found. Location of all the reactors, assessment of their material condition by optical examination at least, and sampling of reactor materials and the surrounding seafloor remain major unsatisfied program requirements. This is particularly evident for the fueled reactor dumped in the East Novaya Zemlya Trough.

3. The movement and disposition of dumped materials: How will the nuclear materials move under the influence of physical, chemical, and biological factors? When and where will they finally come to rest (e.g., sorption onto particles, precipitation on the seafloor, burial by sediments)?

Major progress has been made in calculating the physical circulation of the radioactive materials, by assuming that they are free and mobile in the environment, with attention to riverine inputs as well. However, benchmarking the ability of the models to predict deep as well as surface circulation, and the inclusion of chemical processes such as particle binding of radionuclides and biological processes such as bioturbation, remain for the future. Further, the potential role of ice in influencing or determining the motion and fate of radioactive materials in the Arctic seas is not known in even the broadest outlines.

4. The risks to and impact on people and nature due to the movement and disposition of the dumped materials: What portion of the ecosystem, if any, will be affected by the radioactive materials carried in the water column, deposited in sediments, and incorporated in living creatures? Will concentrations of radionuclides in the food chain, or any other process, threaten human health or economics?

To date, several calculations have been made by different organizations to estimate risks to humans from the dumped nuclear materials. Although complete in the sense that they yield a numerical prediction of human risk, these calculations are quite superficial. Elaboration of the models used and acquisition of the many major parameters required as input need to be carried out.

(continued)

BOX 2-8: Key Research Topics and Knowledge Base of the Arctic Nuclear Waste Assessment Program (ANWAP) (Cont'd.)

5. Potential monitoring of regions of interest near the sources, along transport paths, or at locations where people or the environment may be at risk: What instrumentation should be in place at which locations? What samples should be taken and measured, and over what time scales, to ensure that transported radionuclide materials do not exceed concentrations of concern from any viewpoint?

Monitoring by sampling when possible, with associated laboratory measurements, is a well-developed practice that has been employed in the first two years of the program. However, open-sea monitoring of radioactivity on demand is in a rudimentary stage in terms of available technologies and strategies. The relative efficacy and costs of monitoring near the source regions, which may or may not be susceptible to potential remediation of any kind, or near a region of interest such as Alaskan fishing grounds, requires study.

SOURCE: B.G. Hurdle and D.J. Nagel, "Nuclear Contamination of the Arctic Seas and Estuaries; Current Status of Research and Future Requirements," paper prepared for the Office of Technology Assessment by the Naval Research Laboratory, Washington, DC, April 1995.

Measurements on samples from these Arctic surveys have just begun. Previously available information, and the limited data obtained so far from materials collected through this program, have not indicated migration of radionuclides from Russian sites to the wider regional environment. Data from localized regions in the Kara Sea do show radionuclide concentrations that suggest an influence of inputs from local nuclear bomb tests, dumping, or discharge from the Ob and Yenisey Rivers. However, limited measurements to date in the Kara Sea show generally lower concentrations than those in the Baltic Sea from Chernobyl and in the Irish Sea where radioactivity has been discharged from the Sellafield reprocessing facility in the United Kingdom.

This research is continuing during 1995, and studies should provide further useful data. Emphasis in FY 1995 is on carrying out a risk assessment, examining strategies for monitoring, communication of results to concerned stakeholders, consideration of all sources of Arctic contamination, increased Russian participation, and increased participation in national and international forums to prevent duplication (16).

Radioactivity in Water, Sediment, and Biota

A major thrust of the Department of Defense program, the Norwegian-Russian collaboration, and other international efforts has been to characterize the present level of radioactivity in the Arctic seas, the Sea of Japan, the Ob and Yenisey River estuaries, and other regions of interest. The results from the DOD Arctic Nuclear Waste Assessment Program for FY 1993–94 are given in the annual report ONR 322-95-5 (51). Some of the major findings are as follows:

1. Radionuclide concentrations in Alaskan waters are low and can be explained mainly by fallout from atmospheric testing of nuclear weapons. There may also be a weak signal from the 1957 accident at Chelyabinsk-65.
2. Investigations by the United States and by collaborating programs from Norway, the fSU, Korea, and Japan suggest that levels of radionuclide activity in the Arctic and Pacific regions are low.
3. To date, measurements and analyses of radionuclide contamination in the Arctic marine environment indicate that they come mainly from:
   a. atmospheric testing of nuclear weapons,

TABLE 2-7: Arctic Research Cruises Sponsored by the Office of Naval Research to Investigate Radioactive Contamination, 1993

Cruise	Location	Stations	Sediment	Water	Biota
Alpha Helix[a]	Bering and Chukchi Seas	196	500	4,700	250
G. Fersman	Kara Sea (dump site)	66	1,000	50	
Mendeleev[b]	Kara Sea and Ob River	30	300	300	100
Okean	Bering and Chukchi Seas	64	1,000	300	500
E. Ovsyn	Ob and Yenisey Rivers, Kara Sea	77	450	400	500
Polar Star	North American Arctic	62	200	200	12 trawls
Polarstern	Laptev Sea		22	24	
USS Pargo	Arctic Ocean	15		150	
D. Zelensky	Barents and Kara Seas	7	100		
H. Larsen	Chukchi Sea	66		100	
Various[c]	Laptev, East Siberian, Chukchi, Beaufont, and Bering Seas		400		

[a]Some samples collected from the *Alpha Helix* in the Chukchi Sea during 1992 will also be analyzed by this program.
[b]Many samples obtained by the Shirshov Institute of Oceanography from the *Mendeleev* will be measured.
[c]Sediment samples collected with U.S. Navy sponsorship in the 1960s and 1970s.

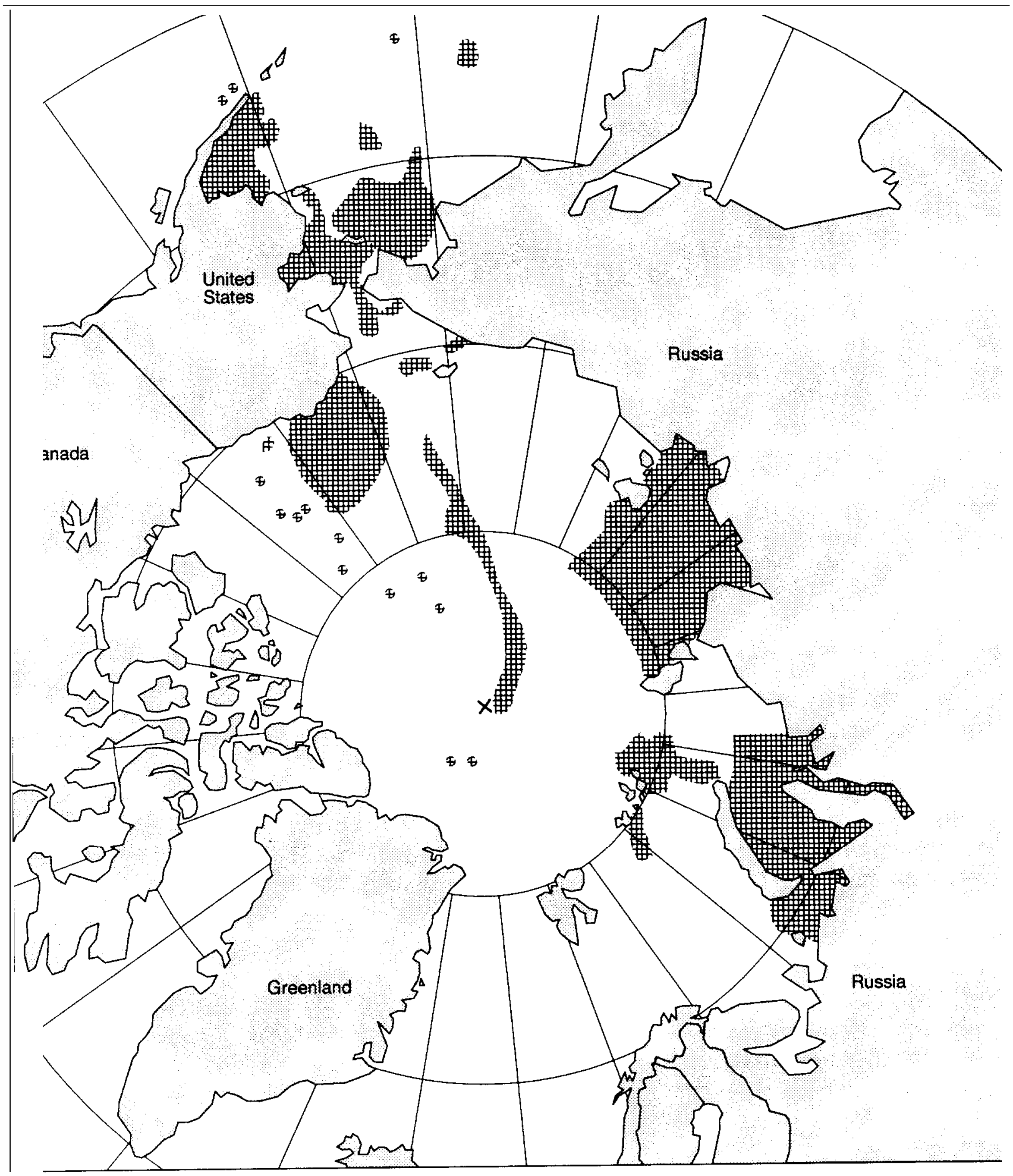
SOURCE: B.G. Hurdle and D.J. Nagel, "Nuclear Contamination of the Arctic Seas and Estuaries; Current Status of Research and Future Requirements," paper prepared for the Office of Technology Assessment by the Naval Research Laboratory, Washington, DC, April 1995.

b. nuclear fuel reprocessing wastes carried into the Arctic from reprocessing facilities in Western Europe,
c. accidents such as Chernobyl and the 1957 explosion at Chelyabinsk-65, and
d. Chernaya Bay weapons tests in southwestern Novaya Zemlya.

Because the signals from sources a and b have decreased with time, region-wide concentrations of radionuclides in the water column and in surface sediments appear also to have decreased from their peak levels.

4. Based on preliminary data analyses, the Yenisey and Ob Rivers appear to have had only a modest impact on radionuclide levels in the Kara Sea and the Arctic Ocean region in general. Small but detectable signals from nuclear facilities on these rivers have been measured over large areas, and there is a zone of enhanced Cs-137 concentration near the mouth of the Yenisey River.
5. Calculations based on Russian data of initial inventories suggest that the total activity of the radioactive waste dumped in the Kara Sea region by the fSU over the last 40 years has decayed to a level of approximately 0.13 million curies today (43). Most of this radioactivity is from the nuclear reactors that still contain fuel, and most of this radioactivity still appears to be contained.
6. Local sites of elevated radionuclide concentration arising from Soviet dumping and weapons testing have been identified in the Kara Sea region. Studies in Chernaya Bay in southwestern Novaya Zemlya where nuclear weapons were tested are similar to those at

FIGURE 2-5: Areas Sampled During ONR-Sponsored Expeditions in 1993 and 1994



SOURCE: Office of Technology Assessment and Office of Naval Research, 1995

Eniwetok Atoll, a U.S. test site. Joint studies by Norway, the fSU, and the IAEA have found elevated concentrations in highly localized regions in Novaya Zemlya bays where the Soviet Union dumped waste containers and nuclear reactor compartments, some still containing fuel. The preliminary results of this trilateral program suggest little leakage from the reactor compartments containing fuel. Zones with elevated concentrations of Cs-137 have been identified in the Novaya Zemlya Trench.

7. Very preliminary large-scale numerical modeling studies of water transport, run for a simulated period of 10 years, suggest that radionuclides released to the Kara Sea region would have their concentrations substantially reduced by the time they reached Alaskan coastal waters. More work is needed to substantiate and enhance this model, however, including incorporation of the role of sediments in sequestering radionuclides.

Recently, Cs-137 activity has been reported for sediment trapped in the sea ice in the central Arctic. This has heightened concern over the potential for the long-range ice transport of radionuclide-bearing sediments. The activity in one sample taken north of the Chukchi Sea was reported comparable to the elevated levels present in the Yenisey River estuary. However, other sources are possible, and the origin of this sea ice contamination has not yet been determined. Another report of interest was the identification of a characteristic ratio of radionuclides in the central Arctic that would most likely come from Sellafield.

Database Development

Adequate data sets for the distribution of man-made radionuclides in the Arctic Ocean and its surroundings do not exist because of the lack of data, particularly in the western Arctic Ocean near North America, in the central Arctic Ocean, and north of Siberia. Recent work related to the current programs has made improvements in the quantity and quality of these data but much more needs to be done.

There are significant Russian data sources, but these still need to be collected, compiled, and integrated into western databases to facilitate assessing the concentrations of radionuclides in the water (marine, lakes, and rivers), sediment, ice, flora, and fauna and determining how these concentrations have varied over space and time. It is also important to gather data collected in the neighboring seas to determine the degree of radionuclide pollution in the Arctic relative to the rest of the world.

As part of the Arctic Nuclear Waste Assessment Program, the Naval Research Laboratory (NRL) is currently setting up a geographical information system (GIS) to computerize, among other items, the extensive body of information collected from the various scientific expeditions sponsored by ANWAP since 1993. Completion of the GIS would enable: 1) creation of a database of existing radionuclide data on the water, sediment, ice, and biota; 2) development of databases of bathymetry, rivers, sedimentation, and biota, as well as physical and chemical oceanographic, riverine, and estuarine processes; and 3) compilation of the information needed to predict the degree of risk posed by these radionuclides to the Arctic environment and its inhabitants and others who utilize Arctic marine resources.

Efforts by NRL to set up its Arctic database have included compiling preexisting radionuclide data, developing connections with Russian colleagues, and developing collection efforts for new data. In addition, some efforts are directed toward developing a system that would enable individuals to query databases to gather statistical information. Attempts have been made to develop a more inexpensive and user-friendly GIS operating system so that individuals can perform their own analyses.

As of December 1994, databases were constructed at the Naval Research Laboratory for: 1) the location of stations and ship tracks; 2) the distribution and concentration of radionuclides in sediments and the water column; 3) the distribution of nuclear tests, accidents, etc.; 4) the location of dump sites; 5) the distribution of various nuclear facilities and sites of interest; and 6) digitized bathymetry, rivers, and marine resources.

The NRL work has been extended by cooperation with international programs. By 1996–97, NRL plans to have a comprehensive radionuclide GIS that should serve as an international platform from which information can be extracted to carry out a risk assessment program. One possible destination of this GIS could be the database of the Arctic Monitoring and Assessment Program (AMAP)[4] in Arendal, Norway. Other major exchanges of data could be carried out with the IAEA as well as with major national and international contributors to the GIS. NRL will also investigate, together with the Norwegian Radiation Protection Agency, the efficacy of installing its data in the United Nations Environmental Program's environmental GIS facility in Arendal, Norway.

The GIS system being developed at NRL has already proved useful in disseminating archived information to investigators from many countries and agencies and in sharing data.[5] Data exchange efforts have led to further cooperative projects, such as the collaboration between the Naval Research Laboratory and the Okeangeologia Russian Scientific Research Institute on the research vessel *Professor Logachev* in a trip to the Svayataya Anna Trough and other areas in the Kara and Barents Sea region during the summer of 1994.

Status of Modeling

Although observations such as those compiled in the Naval Research Laboratory's GIS database can provide useful pictures of past and present levels of radioactivity at certain locations within the Arctic seas, it would be difficult to monitor all or even several regions of the Arctic for long periods of time. For this purpose, tested and validated numerical models can provide information that will both compliment and enhance the existing database. Numerical models can help explain the dynamic transport pathways for the contaminants once they enter the ice or ocean system. In addition, numerical models can "forecast" the dispersion of radioactive materials with either known or estimated sources. Numerical models can illustrate processes that are determined to be the most important for the transport of radioactive materials. Several numerical models are presently being tested by the ANWAP community and the European scientific community. A majority of these models are regional, focusing on one particular oceanographic basin such as the Kara or the Chukchi Sea. In addition, numerical models of the river systems that may serve as major present and future sources of radioactive contamination are also being modeled in ANWAP.

In 1993, the NRL developed a numerical model to include a radioactive tracer component. The model was then tested using sources defined by the Yablokov report; both low-level solid and liquid radioactive waste were used, as well as the high-level solid waste located along the eastern side of Novaya Zemlya. In all cases it was assumed that each source was leaking at a continuous rate based on the total amount of radioactive material dumped at that site and the period of time over which it was dumped. A major conclusion of those studies was that at the end of a simulated 10-year release, the levels of radioactivity in the waters along the north Alaskan coast were approximately five orders of magnitude lower than those found in the Kara Sea. These results were described in the DOD Preliminary Report to Congress entitled "Nuclear Pollution in Arctic Seas" (72). However, research on the circulation of Arctic waters using tracers present in these waters suggests that the model might over-

[4] AMAP is a program carried out by the eight Arctic countries to monitor, assess, and report on the environmental health of the Arctic. It is described more fully in chapter 5.

[5] Data have been exchanged with the Norwegian Radiation Protection Agency; Tokai University in Japan; University of Edinburgh; Norsk Polar Institute; the Netherlands; the IAEA in Vienna; the IAEA Marine Environmental Lab in Monaco; KORDI, the Republic of Korea Institute of Oceanography; the German Hydrographic Service; the VNII Okeangeologia in St. Petersburg; and the Shirshov Institute of Oceanology in Moscow.

estimate the dilution. These studies suggest that the surface waters that flow across the pole and through Fram Strait are diluted by about a factor of 10 (4,63,64). Such findings illustrate the need to use experimental data to calibrate models used to predict or estimate the movement of pollutants. Once the models of the movements of water have been validated with experimental data, the modeling can be further developed by accounting for the important roles of chemistry and sediments, which should be important influences in the movement or sequestration of radionuclides.

With FY 1994 funding, NRL continued the FY 1993 studies by adapting the model to accept river outflow and using data from the Yablokov report to simulate rivers as a source of contaminant release into the Arctic. Levels of radioactivity resulting from these simulations show good agreement with observations from the Kara Sea. Other modeling efforts are currently underway within both ANWAP and IASAP, which will add to current knowledge of the ultimate fate and effects of this radioactive contamination.

Monitoring

Long-term monitoring of the environment and related indicators to help provide early warnings of potential health or ecological risks from dumped radionuclides has not yet been undertaken. Monitoring can serve a variety of purposes, and the type of monitoring to be carried out, if any, must be discussed in conjunction with the goals to be achieved. For example, monitoring can help to fill critical data gaps about radionuclide transport. The sudden release of radioactive waste from reservoirs, storage ponds, underground storage, or marine dump sites into the Arctic environment poses a potentially significant long-term environmental problem. Since measurements of the radioactivity in the Kara Sea and the Ob and Yenisey Rivers are typically conducted during the two- to three-month ice-free summer, the transport and fate of radionuclides during the rest of the year is poorly characterized. Many researchers believe that a monitoring system is needed to provide a better understanding of transport processes during the ice-covered times of the year, as well as annual cyclical events such as the spring thaw. This monitoring capability is not presently available. The difficulty and expense of collecting data on radioactivity using traditional oceanographic cruises limit spatial and temporal coverage. In situ monitoring could improve this situation if the monitoring device could be deployed by air or a convenient ship and were of low enough cost to be considered expendable.

Other types and scales of monitoring are also under discussion for other purposes. One Russian official, who participated in the Woods Hole, Massachusetts, conference on Radioactivity and Environmental Security in the Oceans: New Research and Policy Priorities in the Arctic and North Atlantic, suggested that a global marine radiation monitoring organization be established (49). The organization's mission, as proposed, would be to forecast radiation impacts and to support decisionmaking on actions to be taken regarding radioactive marine objects. The functions of this proposed organization could be conducted in the Russian Arctic, as a case study, to determine how effectively the organization might operate. Nosov (49) recommends that the organization:

- conduct ongoing radiation monitoring of identified objects to predict their structural integrity;
- assess the accuracy of prediction models and update these models accordingly;
- develop an environmental database of this information; and
- provide information to support decisionmaking on protection and associated mitigation options.

As part of any monitoring strategy, scientists need to know what instrumentation to place at which locations, what samples to take and measure, and over what time scales. NRL is investigating various semiconductor and scintillator detectors in sturdy, waterproof housings. It is also developing new gamma-ray detectors (27). Communication channels will have to be established for these continuous, remote, bottom-stationed devices to transmit their finding to scientists for analysis.

However, as in Nosov's proposal, monitoring does not stand on its own but fits within a structured plan of response to a particular need. Since the needs have not yet been fully characterized, there is little agreement among scientists on the proper strategies to use in monitoring these regions or even the necessity of monitoring. No determination has been made as to the level of radioactivity that needs to be monitored. Should the existing level of contamination be monitored, or is it sufficient for a monitoring capability to detect only radioactivity at a level resulting in a biologically significant dose? Many other questions also have to be addressed more fully, such as the capabilities of in situ measurement technologies, suitable sensors, and testing of prototype systems. Most important, the purpose and goals of monitoring require clear definition.

RESEARCH AND MONITORING: DATA GAPS AND FUTURE NEEDS

The conclusions from research to date must be considered as preliminary because of the gaps in data and analysis that remain. This section identifies some significant gaps in knowledge that must be addressed to fully understand the potential impacts of nuclear waste dumping.

■ Source Terms

Much remains unknown about the source terms for the major nuclear waste dump sites in the Kara Sea. Important work is being carried out on land by the IAEA International Arctic Seas Assessment Project Source Term Working Group to learn more about the design of the reactors, their working histories, and their containment. The information should be available in early 1996 and will be critical for understanding the risks posed. Nonetheless, there remains a need for more information to be gathered at the sites themselves, such as that collected in the 1993 and 1994 expeditions of the Joint Russian–Norwegian Expert Group. Their explorations extended to four of the areas in which reactors with spent fuel were reportedly dumped, but only three out of five of the reactor compartments or containers with spent fuel have been located thus far.

Investigations at these sites should include:

- a comprehensive survey and assessment of conditions around the dumped objects—especially at those sites that have not been visited for long periods (decades);
- location of each of the reactors and assessment of their condition through photographs, video, in situ gamma-ray measurements, and systematic water and sediment sampling for radionuclides; and
- similar assessment of containers and other objects located during the search for the reactors. Russian Navy and Russian scientific and technical participation is needed.

For a better understanding of the potential impacts of nuclear wastes washed into the Arctic from the large, north-flowing Siberian rivers, the extent and condition of riverine contamination from land-based sources, including groundwater hydrology, must be more fully assessed to determine how much and how far contamination has traveled downstream, and what the effects of such contaminants might be to the Arctic.

■ Container Materials

To understand the potential for future releases, further study of the dumped containers is necessary. The lifespan and integrity of container materials has had only brief consideration whether they are submarines, reactors, or other waste material containers. For example, some of the reactors and containers have been enclosed in furfural, a resinous material designed to prevent contact of the reactors with seawater for several hundred years. However, data to support this estimate are not available. Similar uncertainty exists about the lifespan of other container materials in seawater.

Environmental Factors and General Sampling

A great deal still needs to be learned about the physical oceanography and geophysics that control transport mechanisms within the Kara Sea and northward into the Arctic basin. Surface and bottom circulation in the Kara Sea needs to be comprehensively examined, and the question of ice transport should be investigated.

One need is to develop an understanding of the dynamics of circulation characteristics, including advection, mixing, and dispersion, of Kara Sea waters and their interaction with adjacent seas. Knowledge of the relationships among currents, wind forcing, tidal forcing, density structure, and sediment resuspension is required for this understanding. Other issues to be investigated are the ice motion in the Kara Sea, the impact of the Siberian Coastal Current on the ice, and possible sediment transport via sea ice into the Arctic basin.

Finally, it is important that field operations collect a complete set of water column and sediment measurements of radionuclide levels in the Kara Sea.

Benthic Biota

It is important to improve the database on bottom-dwelling organisms to identify and quantify benthic biological pathways and radionuclide transport relevant to the radiation exposure of man as well as marine organisms. To this end, it is necessary to investigate benthic food webs to help identify potential exposure pathways, to examine the sedimentation rates of particles that scavenge radionuclides from the water column, and to make an assessment of the radionuclide exposure of key bottom-dwelling organisms.

Marine Mammals

Our knowledge of the density of marine mammals such as bears, whales, and seals, of their food chains, and of their use and consumption by indigenous peoples is limited. Available data on stable element concentrations should be used to develop biological concentration factors for these animals.

Marine Geology

The marine geology database should be developed to identify the pathways for transport of water, particles, and sediment-borne radionuclides brought about by variations in seafloor morphology and sediment type, as well as the degree of redistribution of sediment-bound radionuclides caused by local instabilities of the seabed. Detailed information is required on sediment properties, bathymetry, acoustics, and bottom dynamics, among other factors.

Physical Oceanography

The transport and disposition of radionuclides also depend on the physical characteristics of the ocean. Relevant data include compilations of temperature, salinity, density, and oxygen content; seasonal oceanographic and riverine information; and compilations of ice movement and transport.

Pathway Analysis and Modeling Research

There is a lack of information on radionuclide concentration factors for biota, as well as distribution factors between sediment and water, in the Russian Arctic region (28). Although current ANWAP models can predict surface circulation, there is a need to benchmark the ability of the models against experimental data; to develop and evaluate models that predict deep circulation patterns; and to include chemical processes such as radionuclide binding and biological processes such as bioturbation in these models (27).

Substantial gaps exist in our understanding of the potential role of ice in influencing or determining the motion and fate of radioactive materials in the Arctic seas (27). Specifically, data are needed on the transport process during the ice-covered times of the year, as well as during annual cyclical events such as spring thaw. Data on ice gouging are also needed to understand its potential as a means for damaging containers and releasing radionuclides. Data are lacking with which to assess the relative contribution of these ice mechanisms to the redistribution of contaminants in the Arctic region (56,57).

To understand the transport and fate of radionuclides in Russian rivers and in Arctic and Pacific seas, it is necessary to use a combination of numerical models, field observations, and remotely sensed data. This requires building integrated numerical models composed of different modules such as ice; physical oceanographic, biological and chemical processes; and riverine sources. A numerical modeling system is necessary that can be made available to all interested parties for studying this and other possible future waste dumping problems in the Arctic and its marginal seas.

Monitoring Requirements

Ultimately, monitoring requirements will depend on the needs identified in other phases of research, particularly through a systematic risk assessment. The monitoring required to address some specific data gaps has been described. Measurements of the radioactivity in the Kara Sea, and in the Ob and Yenisey Rivers are typically conducted in the two to three ice-free summer months. The transport and fate of radionuclides during the rest of the year is poorly characterized, due mainly to regional inaccessibility. Continuous, remote monitoring of radionuclide concentrations and other environmental data at dump sites or in rivers is necessary to complete the research on radionuclide transport in or to the Arctic seas and as an early warning for any episodic change. A monitoring system could provide a better understanding of transport processes during the ice-covered times of the year, as well as during annual events such as the spring thaw. This monitoring capability is presently not available for the Arctic environment.

Monitoring systems do not exist that could be deployed for a long duration in the Arctic. More efforts are needed to organize and bring together groups of experts in the fields of marine radiochemistry, radiation sensor technology, communications, risk assessment, ocean systems, oceanography, and marine geology to begin to address some of the important issues related to monitoring.

Data Availability

An understanding of the effects and potential implications of radioactive waste dumping in the Arctic depends entirely on the availability of reliable data indicating the extent of current contamination and the likely future disposition of the contaminating radionuclides. A variety of factors combined to make such data fairly scarce, however, at least as the problem first attracted attention and concern (1991–93). First, the Arctic by its nature is an area in which research that might be considered routine in other parts of the world is extremely difficult. Ice, extreme cold, and rough seas limit the times of year that research vessels can safely or productively go out. Relatively few investigators specialize in the distinctive systems of this part of the earth, and the difficulty means that the research is more expensive.

Second, the areas that are the immediate focus of concern (at least in the Russian North) are within the territorial waters of Russia, formerly the Soviet Union, which for more than 40 years during the Cold War did not welcome international investigators into its seas. Indeed, because the dumping was carried out by the military, it was secret even within the U.S.S.R. until declassified by the Yablokov commission in 1992. However, efforts are continuing to make information more available and to improve access.

Since the break-up of the Soviet Union and publication of the Yablokov report, however, information from the Russians about the environmental status of the Arctic and North Pacific Seas has been increasingly available. Russian scientists and technical experts have been active participants in conferences to facilitate data exchange, presenting relevant information to the international community.

A tremendous amount of information has been collected from research under the auspices of

ANWAP, but it has not become rapidly available. Analyses are time-consuming, and many data will first appear through publication in the scientific literature, which is a slow process. Otherwise, abstracts are available from presentations at workshops and meetings, and project descriptions along with a general summary of findings are provided in the FY 1993–94 report of the program (51).

Reliability/Comparability

Since a multiplicity of institutions representing several different nationalities have participated in data collection to contribute to understanding the extent of radionuclide contamination in the Barents and Kara Seas, questions of comparability of data collection methods and analysis are natural.

In the analysis for the 1992 joint Russian–Norwegian cruise, the issue of data comparability was addressed scientifically through intercomparison and intercalibration exercises carried out with the help of the IAEA laboratory in Monaco. These showed the analytical results of the two countries to be in reasonable agreement, with measurements of radionuclides in sediments in better agreement than those in water (31). Similar comparisons were carried out for the 1993 cruise, and again fairly good agreement was found for measurement of Sr-90 and Cs-137.

Data collected through the Arctic Nuclear Waste Assessment Program is consolidated and provided to Congress through annual reports without peer review. Ultimately many of the findings will be reported in the scientific literature after having been subjected to peer review.

The comparability of data may be of most concern for historical data. For example, as data from the past are combined in a GIS database, is there any means of ascertaining the methods used for analysis or otherwise gauging their reliability? In some cases the data were published in the form of contour lines, without the raw numbers to indicate whether they represent the average of many individual samples or simple single data points connected together. In such instances it will be impossible to judge data quality. All information collected in the future should be subjected to quality assurance standards.

REMEDIATION OPTIONS

Background

To reduce or eliminate the risk posed by radioactive material dumped in the Arctic region, decisionmakers must consider what type of remediation, if any, should be adopted to protect public health and safety and the environment. No attempt is made in this section to recommend an option for remediating the dump sites. Instead, the following material describes the information which decisionmakers will need and outlines a framework which could be used in the remediation decision process. Information from the two major efforts currently underway (i.e., IASAP and ANWAP) to gather information about transport models, pathway analyses, and possible exposures and doses that could be received from these dumped materials will be needed to reach these decisions. This analysis also draws on the work by the Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP).

The only official forum in which remediation options are being considered is through the IAEA's International Arctic Seas Assessment Project. This group of experts is asked to make recommendations regarding what response(s), if any, should be taken to the nuclear wastes dumped in the Arctic (67). The scope of their effort does not include consideration of the wastes dumped in the Russian Far East.

In terms of remediation options, IASAP's Remedial Measures Working Group is the most relevant. The first meeting of experts participating in this group was held in Vienna on January 23–27, 1995. Although the group has not yet issued a report from its initial meeting, background materials in support of the meeting (referred to as "Report of Working Party 3") were drawn on to develop the decisionmaking framework presented here (29). The Remedial Measures Working Group plans to wait for the results of IASAP's Source Term and Modeling

Working Group before making any recommendations on specific remedial actions that should be taken (50). IASAP expects to complete its work in 1996 (40).

In the United States, the Office of Naval Research is also involved via ANWAP, in assessing the risk posed by the radioactivity dumped in the Arctic region. ONR's goal is to "determine with high confidence whether the dumped and discharged radioactive material presents a threat to the Alaskan economy or the health of U.S. citizens" (72). ONR's research and monitoring in this region are intended to support the risk assessment and the decisionmaking process to determine what remediation measures, if any, should be employed.

Information Needed to Assess Mitigation Options

The specific information required to begin to assess mitigation or remediation options can be divided into two principal areas:

1. the condition of dump sites (physical, chemical, and biological factors), and
2. the status of dumped material (burial status, structural integrity of containers, waste form, and concentration of radionuclides, etc.).

Condition of Dump Sites

Prior to selecting a particular remedial option, experts must obtain adequate information on the physical and chemical characteristics of the environment surrounding the dump site. Important physical conditions are the depth of the site; the bathymetry of the surrounding areas to identify prominent seafloor features; and the physical stability of the site. For example, researchers want to know whether there are strong turbidity currents in the region that could destabilize the seabed sediment. Ocean currents around the sunken *Komsomolets* submarine, for example, have been measured up to 1.5 m/s (25). Knowledge of sedimentation rates in the region is also important.

The weather is a crucial factor. There are only two months of reasonably good working conditions in the Kara Sea (August–September). Tides may also be important—the tides in the Novaya Zemlya fjords reach 180 cm (6).

Chemical conditions to be measured include distribution coefficients (K_d) which describe the degree to which radionuclides will be retained or bound by sediment particles. Biological factors include determining whether the site serves as an artificial habitat and spawning location for organisms, identifying benthic organisms that are likely to be exposed to radionuclides, and measuring sedimentation rates of biogenic particles that scavenge radionuclides from the water column.

Status of Dumped Material

The burial status of the dumped material is important in assessing possible remediation actions. Is the material uncovered, partially covered, or totally buried? A good understanding of the structural integrity of the objects containing the material (e.g., drums, boxes, submarine hulls) is critical.

It is generally believed that the sunken barrels or containers dumped in the Arctic seas are probably made of mild steel. Knowing the corrosion rates and identifying any breach points in these barrels or containers are critical in estimating release rates of radionuclides. In addition, it is important to be aware of the structural integrity of submarine hulls (particularly the pressure vessels of fueled submarines). There is some indication, for example, that small amounts of radioactivity may be leaking from the NS 601 submarine sunk in the Stepovogo Bay of Novaya Zemlya (32). There is also concern about the spent fuel from the damaged *Lenin* reactor; this was placed in a concrete-steel box, on top of a larger box containing three *Lenin* reactor components without fuel. Both boxes were placed inside another box which was sunk in the Tsivolka Fjord. The box containing the spent fuel might not have been welded to the box on which it was placed and could have shifted in the process of being sunk. This box containing spent fuel constitutes the largest single radioactive source, by a factor of three, that has been sunk in the Kara Sea (6).

Other important factors include knowing the waste form of the dumped material and determining its integrity and estimated time of failure. Furfural is a compound that was used by the Soviets to enclose reactors and containers, and as previously mentioned, its effective lifetime is not known with confidence. It is important to estimate the lifetime of particular radioactive wastes or materials more accurately in order to estimate the release rates of encapsulated materials and to identify possible remediation needs and options.

Researchers also need to know the types of radionuclides contained in the dump sites and their concentration in the environment. This information is collected on expeditions such as those undertaken by the Joint Russian–Norwegian Expert Group in 1993 and 1994. Samples of sediment, water, and biota were collected and analyzed for radionuclides such as Cs-137, Pu-239 and 240, Co-60, and europium-152 and 154 (Eu-152, 154) for indications of whether and what amounts of radionuclides have been released from reactors or containers. In 1993, samples taken close to the hull of a dumped submarine indicated higher concentrations of Cs-137 than in the surrounding area, and the element europium was identified. These results suggested that radioactivity was leaking from the submarine reactor (32). Preliminary results from the 1994 cruise to two bays in which nuclear wastes were dumped suggested some local Cs-137 and Co-60 contamination from dumped containers of nuclear waste, with less contamination currently present near dumped reactors containing spent nuclear fuel. Elevated levels observed in 1993 near the submarine reactor with spent fuel in Stepovogo Bay were not supported by repeated onsite measurements during this expedition (19).

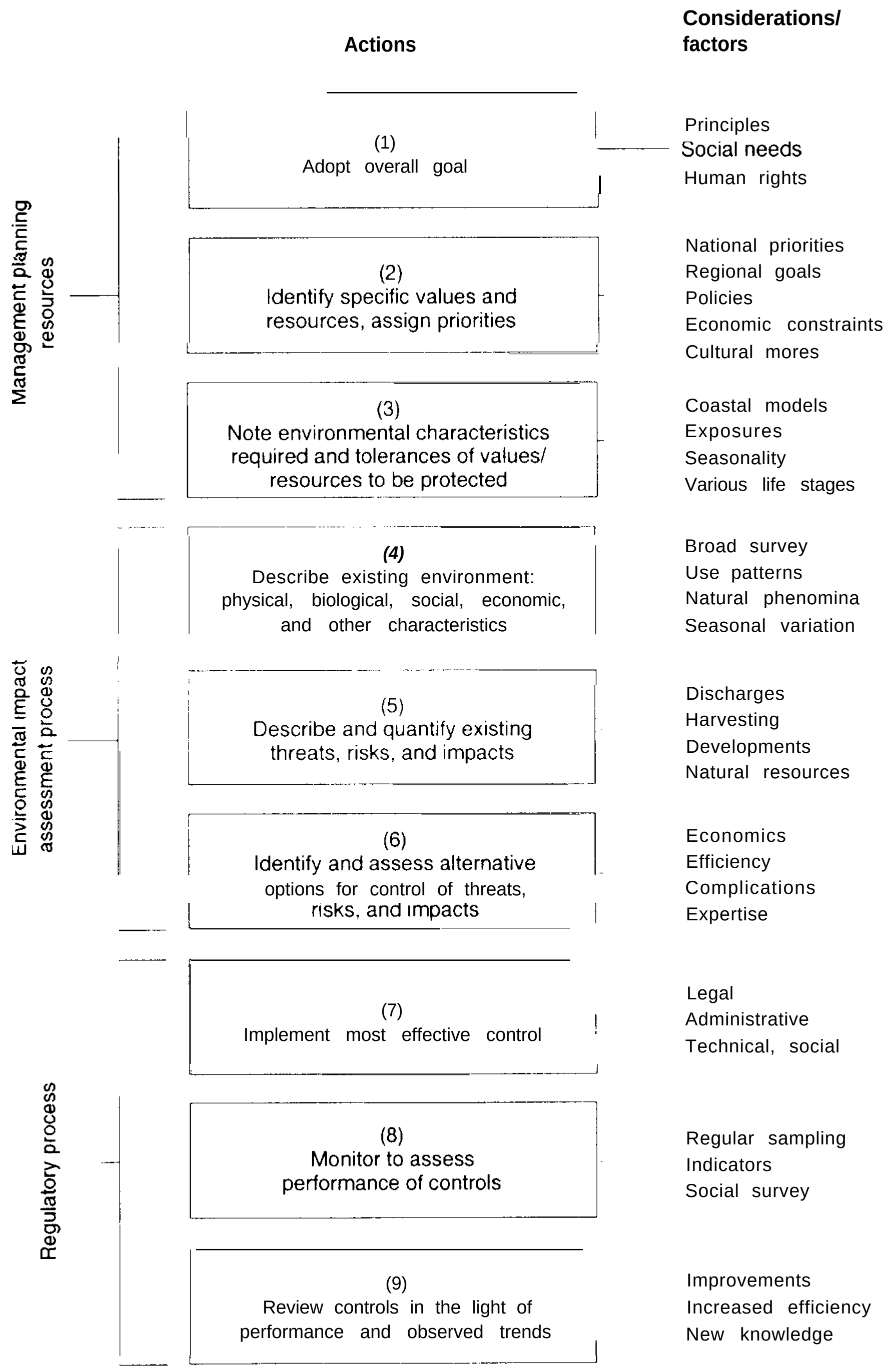
An Integrated Framework for Evaluating Mitigation Options

The Group of Experts on the Scientific Aspects of Marine Pollution issued a report on the possibility of a common framework for managing radioactive and non-radioactive substances to protect the marine environment. This report was written in response to questions posed by the Inter-Governmental Panel of Experts on Radioactive Waste Disposal at Sea (IGPRAD). In its report, GESAMP finds that "a frequent problem in environmental monitoring and with assessments of the quality of the environment is that the information gathered is hard to interpret in a management (i.e., nonscientific) context. Thus, it is difficult to decide whether a particular set of environmental conditions is acceptable unless the aspirations of society are explicitly defined" (30). GESAMP recommends that goals be established for protecting the environment and that tolerances or regulatory standards be established to support these goals. With this framework in hand, environmental impact assessments can be used to provide a basis for designing measures to reduce or prevent damage. The framework can then help to identify where intervention might be used to mitigate adverse effects. The regulatory process, in turn, can be designed by using control measures and performance monitoring to identify the need for any revision of decisions made earlier in the framework (30).

Figure 2-6 depicts the overarching management framework developed by GESAMP for protecting the environment. The framework contains a hierarchical sequence of planning, assessment, and regulatory activities that are critical for environmental protection. Although the framework was designed as a general tool for use in the marine environment, in its modified form it is a relevant tool for decisionmaking concerning the management of radioactive material dumped in the Russian Arctic. Decisionmakers may wish to work their way through the various steps in figure 2-6 to help them decide what remedial action(s), if any, are necessary. Steps 1 through 5 are the basis for making the decision in step 6.

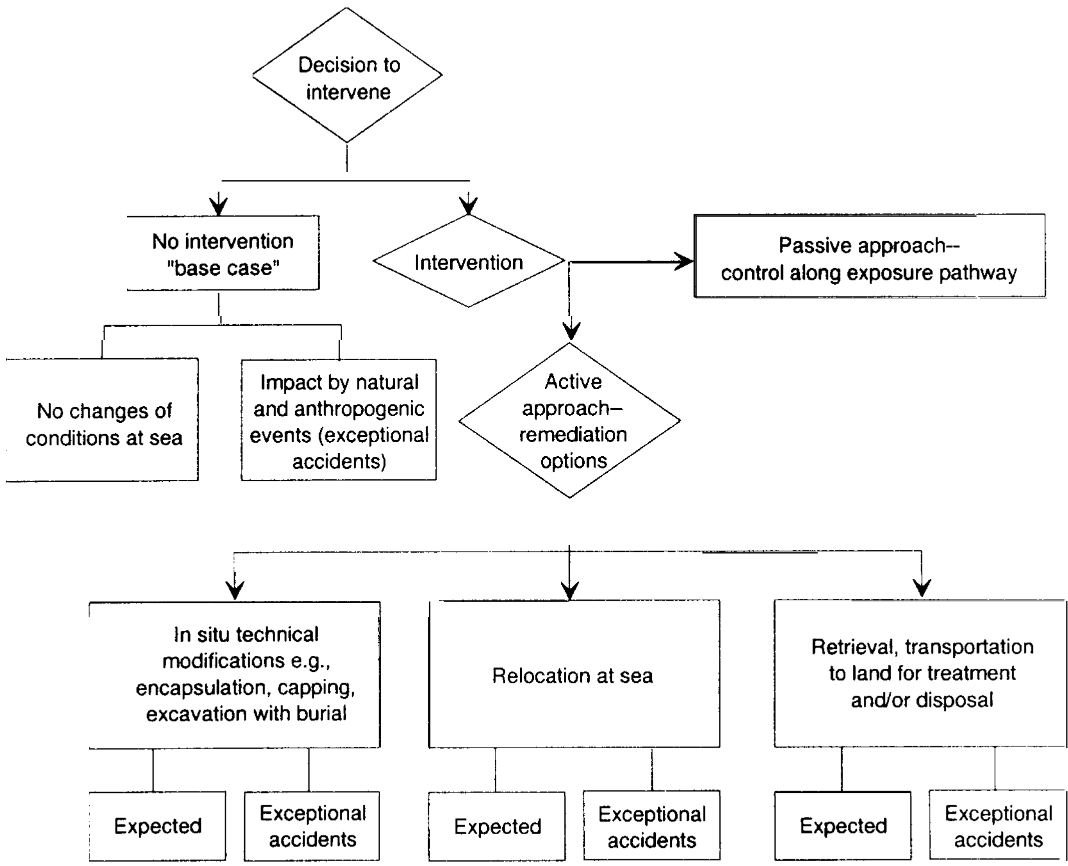
One issue that adds to the difficulty of selecting an appropriate mitigation option is the lack of any internationally agreed-upon mechanisms or values for determining when it is necessary to intervene and remediate a site (29). In other words, steps 2 and 3 of figure 2-6 have not been completed. Nonetheless, one objective of the IASAP project as defined in the Report of Work-

FIGURE 2-6: Management Framework for Protecting Marine and Other Environments



SOURCE: Office of Technology Assessment, adapted from Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP), *Can There Be a Common Framework for Managing Radioactive and Nonradioactive Substances 10 Protect the Marine Environment?* GESAMP Reports and Studies No. 45, Addendum 1 (London, England: 1992).

FIGURE 2-7: Framework for Evaluating Mitigation Options to Remediate Radioactive Dump Sites at Sea



SOURCE: Office of Technology Assessment, adapted from International Atomic Energy Agency (IAEA), "Report of Working Party 3," materials given to members of the International Arctic Seas Assessment Project's Working Group on Remediation Measures in preparation for the initial meeting, Vienna, Austria, January 23-27, 1995

ing Party 3 is to examine possible remedial actions related "to the dumped wastes and to advise on whether they are necessary and justified" (29).

Steps 4 and 5 are accomplished by collecting necessary information on the condition of the dump sites and status of the dumped material. This information is used in step 6 as decisionmakers select an appropriate mitigation option. Figure 2-7, which is adapted from a figure developed by the IAEA (29) for its Remedial Measures Working Group, illustrates a framework for evaluating options that would likely be available to decisionmakers.

Mitigation Options

It is very possible that decisionmakers would choose different options, depending on the conditions present at a particular dump site. For example, one may choose an option (e.g., no intervention) for sites containing low levels of contamination and another option (e. g., a technical measure to contain waste in situ) for those containing higher-activity waste in structurally unsound containers. No attempt is made here to identify or recommend the most appropriate option for particular conditions at a dump site. Instead, this section describes both the series of steps or framework that a decisionmaker would use in selecting mitigation options and the factors that must be considered in assessing each option.

The first choice that a decisionmaker must face is whether or not to intervene. In making this initial decision, it is critical to understand the consequences of taking no action—leaving the dumped material on the sea bottom. IAEA refers to this as the "base case" against which intervention measures can be judged, and efforts to complete this assessment are being actively pursued by the other IASAP working groups (29). Even the no-action option has two possible outcomes—an expected situation, in which forecasted consequences occur and no accidental situations arise, and exceptional situations in which a low-probability event occurs. Such low-probability events can be accidents (e.g., icebergs colliding with dumped material or fishing vessels inadvertently dropping objects on containers and rupturing them) or non-accidental rare events (e.g., people deliberately disturbing dumped material or seismic events rupturing containers). Calculating this base case is a critical first step in defining outcomes against which all other options can be compared.

In analyzing intervention options, there are two broad choices—a passive approach and an active approach. Under the passive approach, options are available that do not cure the root cause (i.e., take some action at the dump site) but that address some exposure pathway emanating from the root cause. Examples of such actions include restricting the local population from using or consuming resources from the region in which the material was dumped. Another action may involve relocating the local population away from a region of radiological concern.

Under the active approach, several remediation options are available, all of which deal with managing the dumped material in some way. These can be divided into three generic options: 1) in situ technical modification of the material (e.g., encapsulating the material, capping over the material, excavating underneath the material and burying it); 2) relocation of the material from all sea sites to a common location; and 3) retrieval of the material and its transportation to land for storage, treatment, and/or disposal.

It should be noted that any of these options would require very specialized equipment to maneuver or deploy heavy loads and otherwise manipulate materials underwater in potentially rough weather. Such equipment exists or could be developed by modifying existing vessels (20), but the procedures would be costly.

In situ technical modification of the material

1. *Encapsulate the material*: Dumped radioactive material can be encapsulated by several methods. It is possible to coat the material or cover it with some type of cement. Various kinds of cement are available. Cement density, setting time, and strength can be altered by adjusting its composition. The dumped material can also be surrounded by a structure of steel that can be filled with cement or some other material. The Kurchatov Institute has studied the durability of another encapsulation material, furfural, in seawater. Furfural is a compound derived from oats that polymerizes to form a solid. It was used by Russians to fill some of their sunken reactor compartments and act as a barrier to radionuclide release. Some Russians have attributed a 500-year lifetime to furfural (25), but this requires confirmation (46).

   In the case of building a structure around the dumped material (which could include a submarine) prior to encapsulating it, a cofferdam could be built, constructed of blocks bolted or welded together above the center well. These blocks may be made from prefabricated pieces of steel to ease storage and handling issues aboard the workship. The internal volume of the blocks could be either open to the sea or filled with heavy drilling mud if greater weight were required. Once the cofferdam is in place, the seawater from within could be displaced by mud or cement pumped from the drill string. Cement may be preferable because it would set in place and be more permanent than mud (20).

2. *Cap the material:* The dumped material can be covered with sedimentary material or capped. This is a common practice used in managing contaminated areas of dumped dredge spoils. It is important to monitor and maintain the integrity of the cap.
3. *Excavate underneath the material and bury it:* The seabed underneath the dumped material can be excavated, allowing the material to fall into the depression created. The material can then be covered with sediment, leaving no hummocky features on the seabed. This is an option under consideration by the Sanctuary Manager of the Gulf of the Farallons off the California coast for remediating radioactive waste barrels dumped to depths of 1,000 fathoms (79). This option is of particular interest to the Farallon Islands because of the great depths of the dump site; the barrels' lack of structural integrity, which makes recovery difficult; and the artificial reef that the barrels have produced, which attracts fish and other organisms to the site as a habitat. If the material is buried underneath the seabed, this latter problem is addressed.

Relocation of the material from all sea sites to a common location

Two types of sites are being considered in the relocation option (46). First, the material could be moved inside a small fjord that has a shallow inlet to the open sea. The inlet could be dammed, cutting off circulation to the open sea. As with any of the options, there are significant risks and costs associated with this option that would have to be weighed against possible benefits. Risks, not only to human health but also to the environment, are associated with cutting off a water body from adjacent open waters. The factors of greatest relevance that must be considered are listed in figure 2-8 and table 2-8.

A second possible location may be the region of underwater caves along the Novaya Zemlya coast. The material from all existing dump sites could be collected and placed in the caves. The caves could be sealed off to prevent any water flow. The same calculation of risks and costs versus benefits would have to be conducted.

Retrieval of the material and transportation to land for storage, treatment, and/or disposal

The material could be recovered and transported to a shore-based facility for storage, treatment, and temporary or ultimate disposal. The first step in treatment could include sorting the material to segregate it into different categories or sizes appropriate for containment or disposal.

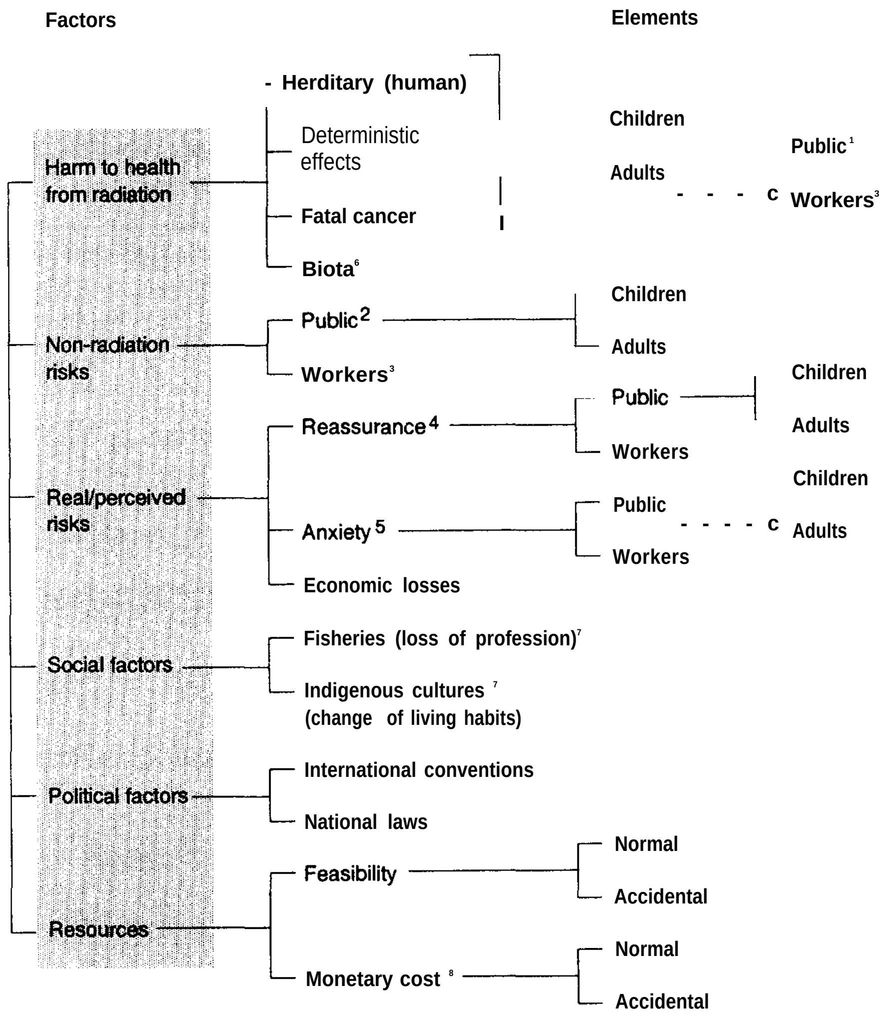
The IAEA Remedial Measures Working Group meeting in late January 1995 reviewed several underwater retrieval technologies, including videos of actual operations in retrieving hazardous materials. Several types of platforms are being used to service or retrieve underwater objects. Of particular concern to most experts is anticipating how these technologies may perform or operate under sea ice conditions (6). Until the actual conditions of the dumped wastes and their environments are better understood, however, the specific retrieval needs—if any—will not be clear.

Factors to Consider in Choosing the Most Appropriate Mitigation Option

Before any intervention measure is initiated, it is important to know whether the measure is justified (i.e., will do more good than harm) and whether the approach selected maximizes protection of human health and the environment. Several factors need to be considered at each juncture of the decision framework (figure 2-7) for evaluating mitigation options. Figure 2-8 lists factors recommended by the IAEA for consideration and to the right of each factor, the various elements associated with it. More detailed explanations of these elements can be found in table 2-8 which describes the specifics that must be considered and why they are important.

All of the elements and their associated comments must be considered and calculated to determine the impact that a particular factor can have in influencing the choice among all applicable mitigation options. Once these factors have

FIGURE 2-8: Factors to Consider in Selecting an Appropriate Mitigation Option



NOTE: Superscript numbers correspond to the elements listed in Table 2-6.

SOURCE: Office of Technology Assessment, adapted from International Atomic Energy Agency (IAEA), "Report of Working Party 3," materials given to members of the International Arctic Seas Assessment Project's Working Group on Remediation Measures in preparation for the initial meeting, Vienna, Austria, January 23-27, 1995

TABLE 2-8: Elements to Consider in Assessing Intervention Measures

Element	Comment
1. The avoidable individual and collective doses from exposure to radiation and risks of potential exposure situations for members of the public	Dose reductions and risk reductions from potential doses that would be achieved through intervention are estimated here. The assessments must consider critical group doses and population doses.
2. Individual and collective physical (non-radiological) risks to the public caused by the intervention measure	
3. Individual and collective risks to workers in carrying out the intervention measure	These risks can be both radiological and nonradiological, and can involve both normal risks and those due to accidents.
4. Reassurance of the public and the workers provided by implementation of the intervention measutre	Removal of stress caused by situations of real or perceived hazard.
5. Anxiety caused by implementation of the intervention measure	Note that the intervention measure may transfer anxiety from one population group to another (e.g., if the waste is moved from the sea to land).
6. Impact of intervention measures on the environment, live, and other natural resources	
7. Individual and social disruption caused by implementation of the intervention measure	Note that individual and social disruption may also occur if no intervention takes place. This could happen if living habits of the population are changed or fishing grounds must be moved.
8. Monetary cost of the intervention measure	

SOURCE: Office of Technology Assessment, adapted from International Atomic Energy Agency, "Report of Working Party 3," materials given to members of the International Arctic Seas Assessment Project's Working Group on Remediation Measures in preparation for its initial meeting, Vienna, Austria, January 23–27, 1995.

been calculated or assessed, decisionmakers can work their way through the decision framework described in figure 2-7 to decide which option or set of options is appropriate for addressing the contamination at a particular dump site. Decisions on these sites not only must be considered in terms of the costs and benefits of different interventions at a particular site, but must be integrated into a larger plan for the prevention or mitigation of nuclear waste problems in the wider region. In other words, prevention of future dumping or of releases of nuclear wastes must also be considered an option competing with remediation for limited resources.

As mentioned, there are areas in which data are either lacking or uncertain. Consequently, it is difficult to calculate factors and their elements precisely, a difficulty that affects risk assessment and inhibits accurate decisionmaking. This problem is the primary driver for devising and maintaining an accurate system to monitor the dump sites.

CONCLUSIONS

Progress has been made in assessing the extent of current contamination in the Arctic and North Pacific, and available information suggests that the anthropogenic radionuclide contamination measurable in the Arctic comes primarily from nuclear weapons testing, from European nuclear waste reprocessing discharges, and from the Chernobyl accident. Nuclear wastes dumped by the former Soviet Union, listed in the Yablokov report, seem to have led to only very local contamination near the dump sites so far, but a thorough inspection has not yet been done at each site.

Questions about potential future contamination remain, and further information is required to address them. Data about source terms, containment, and transport factors are needed for ongoing modeling efforts and for a thorough risk assessment. Inspections of the dump sites are necessary complements to expert assessments of the size of the source terms. A system of monitoring can provide some of the needed information as well as early warning of releases.

Decisions about remediation will require consideration of many different factors in addition to the potential impacts from the dumped wastes if no remediation action is taken (ongoing risk assessment efforts through ONR and IASAP). Note that there are currently no internationally agreed upon values for what constitutes too much radiation at an ocean dump site. Information about the conditions around the sites and the current disposition of the wastes will be critical in considering the feasibility and cost of remediation or mitigation options. The management framework developed by the IAEA (figure 2-7) can be used to organize these and other factors (social, political) that must be weighed in decisionmaking. Such factors must ultimately include other potential sources of nuclear waste contamination of the environment, such as land-based sources of high-level wastes awaiting disposal or disposition elsewhere (see chapter 4).

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