Sellafield

POLFOTO

Radioactivity

The Arctic is more vulnerable than most other parts of the world to the consequences of contamination from airborne radiocesium. The higher vulnerability in the Arctic arises from the unique characteristics of food webs, the use of land, and land cover in this region.

Most radioactive contamination in Arctic lands is derived from fallout from atmospheric nuclear tests conducted during the period 1945 to 1980. In some areas, fallout from the 1986 accident at the Chernobyl nuclear power plant is also a major source of contamination. Levels from these sources are declining with time as the radionuclides decay.

A major source of radionuclides in the Arctic marine environment is releases from European plants that reprocess spent nuclear fuel. In contrast to the declining levels for other radionuclides, the levels of technetium-99 and iodine-129, which are long-lived fission products from reprocessing, are increasing in the Arctic marine environment.

The greatest radiation threats in the Arctic are associated with accidents resulting in releases of radionuclides to the environment. These include accidents involving nuclear reactors. Another environmental hazard is posed by the large stockpiles of radioactive waste in the Arctic. Efforts to reduce risks associated with these activities are ongoing, but much still remains to be done.

This chapter addresses radioactive contamination in the Arctic and its potential consequences for human and ecosystem health. The previous AMAP assessment focused on current sources, levels, and radiation doses to humans. The emphasis this time is on the behavior of radionuclides in ecosystems, the hazards associated with potential sources, and how best to address these hazards.

Closing Chernobyl

POLFOTO / KONSTANTIN DIORDIEV

A concern for human and ecosystem health

Radioactivity is a concern for human and ecosystem health because radioactive material emits ionizing radiation that has the ability to damage living cells.

Radioactivity and radiation dose

Radioactive materials contain unstable atomic nuclei. When the nuclei decay to stable forms, they emit ionizing radiation. The activity is measured as the number of disintegrations per second. The unit is the becquerel (Bq).

The health effects of radioactivity are related to the dose received. The unit of dose is the gray (Gy). A more important unit for assessing human health effects is the sievert (Sv), which measures effective dose. One sievert is equal to the effect in humans caused by one gray whole body dose of gamma radiation.

In regulating nuclear activities, 1 millisievert (0.001 sievert) is used as a yearly dose limit for exposures of members of the public to all man-made radiation. It corresponds to an increased risk of fatal cancer of 0.005%, or one additional cancer case among 20 000 exposed individuals.

The global average individual dose from natural sources of radiation is 2.4 millisieverts per year. However, this dose varies as a function of geology and other conditions.

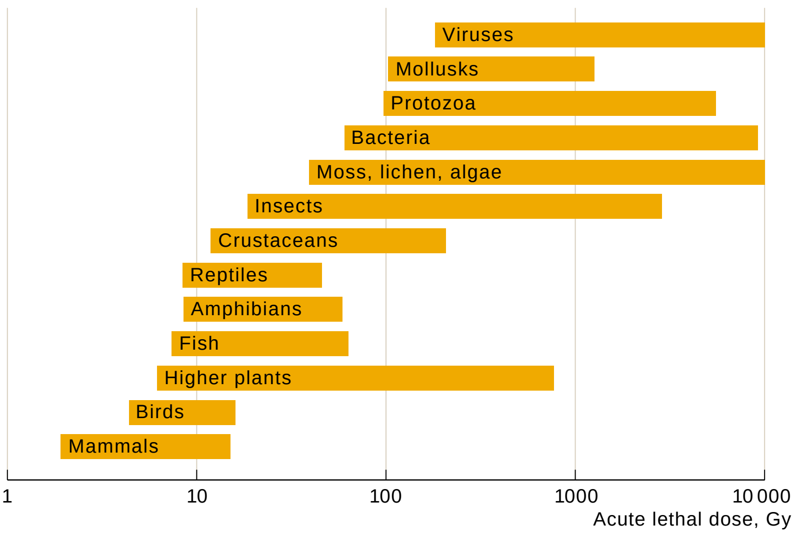
Cancer is the major human health concern

At low doses, the main human health concern is that radiation may increase the risk of cancer and/or cause genetic effects by inducing damage to the DNA. When radiation leads to genetic damage in the egg or in the early developmental stage of sperm, such damage can affect fetal development or make a person more susceptible to disease. The probability of cancer and reproductive damage increases with the dose.

For low doses, radiological protection assumes that no threshold exists below which there is no risk of damage. Thus, for low doses, the probability of adverse effects is considered to be proportional to dose.

At high doses, the effects are not a matter of probability. Radiation kills cells, causing local burns, organ damage, and radiation sickness.

Sensitivities of various organisms to acute lethal dose of ionizing radiation.



The severity of effects is directly related to dose. If the dose is high enough, the individual will die.

The goal of radiological protection efforts is to ensure that practices involving potential radiation risks are justified, dose limits are complied with, and doses are kept as low as reasonably possible.

New focus on ecosystem health

Specific consideration of radiation doses and effects on wildlife, plants, and ecosystem health is a relatively new development. Traditionally, radiological protection has focused on protecting humans with the assumption that this would also protect other components of the ecosystem. However, during the past few years an international consensus has been reached on the need to develop systems that can explicitly assess any potential harm to ecosystems and their components resulting from exposure to radionuclides.

Experience from laboratory studies and accidents has established that radiation can cause a number of detrimental effects in biota, including mortality, reduced reproduction, and genetic damage. Nevertheless, current knowledge about effects on wild plants and animals is limited and subject to large uncertainties. Moreover, there is little consensus on the relevance of these effects in the context of risk management. A better understanding of ecological effects and their uncertainties requires a framework for risk and impact assessment that can take into account the sensitivities of various species and ecosystems.

Factors that influence sensitivity include exposure pathways, the extent of uptake to biota, and dose–effect relationships. These can be ecosystem dependent and, for example, may vary with the availability of nutrients and biological productivity. They are also species dependent, examples being high bioaccumulation of technetium-99 in lobsters and the radiosensitivity of pines compared with other trees.

Acute lethal doses can vary by several orders of magnitude among and within species. However, effects on reproduction and population health may occur at much lower doses than those that would kill an organism. There is very little information about the effects of low chronic exposures.

The work of assessing the effects of radiation on ecosystems is still in its early stages, and AMAP is taking an active part in this effort (see box on opposite page). The ultimate purpose of an assessment framework is to define doses or concentrations at which effects in the environment would be expected to be minimal, with an acceptable degree of confidence and in broad harmonization with standards used to assess other hazardous substances.

International efforts

By highlighting inconsistencies among the management and regulatory approaches for radioactivity and other environmental pollutants, AMAP activities have played a key role in driving the development of a framework for assessing ecosystem effects of radiation. AMAP is also playing a part in continued efforts, for example by the International Union of Radioecology (IUR), which was one of the first international organizations to actively promote the need to focus on non-human biota and to propose a system for impact assessment. The IUR initiative has subsequently been carried forward in projects funded by the European Union, including one on environmental effects of radionuclides in the Arctic. To date, one of the main outputs of this work has been the selection of reference organisms. In this regard, the Arctic poses some special challenges because of the low number of species and high vulnerability.

POLAR PHOTOS / HENNING THING

Plankton sampling in Disko Bay, Greenland.

Proposed terrestrial reference organisms	*Proposed aquatic reference organisms*
Lichens and bryophytes	Benthic bacteria
Gymnosperms	Macroalgae (marine)
Monocotyledons	Aquatic plants (freshwater)
Dicotyledons	Phytoplankton
Soil microorganisms	Zooplankton
Soil invertebrates	Mollusks
Herbivorous mammals	Polychaetes (marine)
Carnivorous mammals	Insect larvae (freshwater-benthos)
Bird eggs	Pelagic fish (planktotrophic)
	Benthic fish
	Pelagic fish (carnivorous)
	Carnivorous mammals
	Benthos-eating birds
	Fish eggs

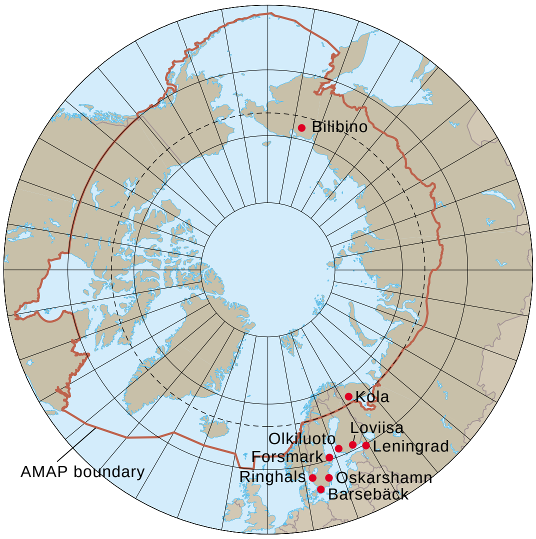
Risk management

Radiation risks can be reduced by specific measures to protect the health and safety of workers, the public, and the environment. A judgment has to be made as to what measures are feasible based on prevailing technical, social, and economic circumstances.

In this context, a risk analysis consists of the following steps: 1) Defining the facility and operation; 2) Identifying the hazards; 3) Characterizing the hazards that present the greatest risk; 4) Postulating and analyzing possible scenarios; and 5) Estimating the consequences. The results of the risk analysis process are used to consider and analyze options for prevention, preparedness, and response strategies.

The previous AMAP assessment identified a number of existing and potential sources of radioactivity in the Arctic. Some risk analyses of these sources have been included in the updated AMAP assessment. They address vulnerabilities and hazards associated with potential accidents involving nuclear power plants operating in or within 1000 kilometers of the Arctic, nuclear-powered vessels, interim storage of spent nuclear fuel, improperly stored fuel elements, and decommissioned vessels containing spent nuclear fuel.

For current radioactive contamination, the focus of the updated assessment is on new information about levels in the environment.



There are several nuclear power plants in the vicinity of the Arctic, and two plants within the AMAP area. Finland has two nuclear power plants both situated on the Baltic Sea coast: Loviisa on the Gulf of Finland, and Olkiluoto on the Gulf of Bothnia. Two reactor units are in operation at both sites. Sweden has four sites with nuclear power plants situated both on the east coast (Forsmark and Oskarshamn on the Baltic Sea) and the west coast (Ringhals on the Kattegatt and Barsebäck on Öresund). In Russia, there are two nuclear power plants in the Arctic: the Kola plant on the Kola Peninsula and the Bilibino plant in the Chukotka Region. The Leningrad nuclear power plant, situated outside the Arctic near St. Petersburg, is also of interest for the AMAP assessments.

Nuclear power plants

Two nuclear plants are located in the Arctic, at Kola and Bilibino in Russia. There are also several nuclear power plants within 1000 km of the Arctic. Under normal operating conditions, routine releases from these plants are small and contribute little to radiation levels or doses in the Arctic. The dominant radiological risks are those associated with potential accidents. AMAP has attempted to estimate the risks associated with accidents at the Kola nuclear power plant using a specific accident scenario.

Kola nuclear power plant.

Model shows health risk associated with potential Kola plant accident

The Kola nuclear power plant has four 400 megawatt pressurized-water reactors. An accident here may have graver consequences than one at Bilibino, which has four smaller reactors that are only 11 megawatts each.

Recent studies focusing on northwest Russia and northern Norway have looked at the consequences of hypothetical accidents at the Kola plant. A severe accident would obviously lead to significant doses close to the plant. Another concern is whether there would also be significant consequences farther away in adjacent Arctic areas in the short or long term. Radionuclides efficiently transfer to some Arctic ecosystems, where they can remain for a long time. An assessment therefore has to include long timescales. The scenarios that were chosen for calculating doses after a hypothetical accident represent worst-case events and their consequences.

The highest individual external doses outside the plant facility would occur in the most contaminated areas, but they are too low to result in any acute radiation damage. Doses received after eating contaminated food are initially lower than external doses, but increase and become more important with time. Doses vary spatially depending on differences in deposition, type of land cover, and associated food production. Reindeer herders and others who consume high quantities of reindeer meat would receive significantly higher annual individual doses of radiocesium from food than other inhabitants of the same region. For the high-consumption groups, reindeer meat contributes most of the internal dose during the first year after deposition. For other people, dairy products and sheep meat are the largest contributors. Doses of strontium-90 are very low for all inhabitants.

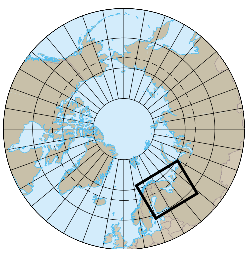
It is predicted that reindeer herders and others with high reindeer consumption would get annual ingestion doses that exceed 1 millisievert for several decades after the accident, with much higher doses in the first few years. For other population groups, the consequences vary geographically. If the deposition occurred in northern Norway (Troms (Romsa) and Finnmark (Finnmárku)), ingestion doses could exceed 1 millisievert for a few years after the accident, whereas this period would be about 10 years if the deposition occurred in Murmansk Oblast. Potential consequences in other areas were not assessed.

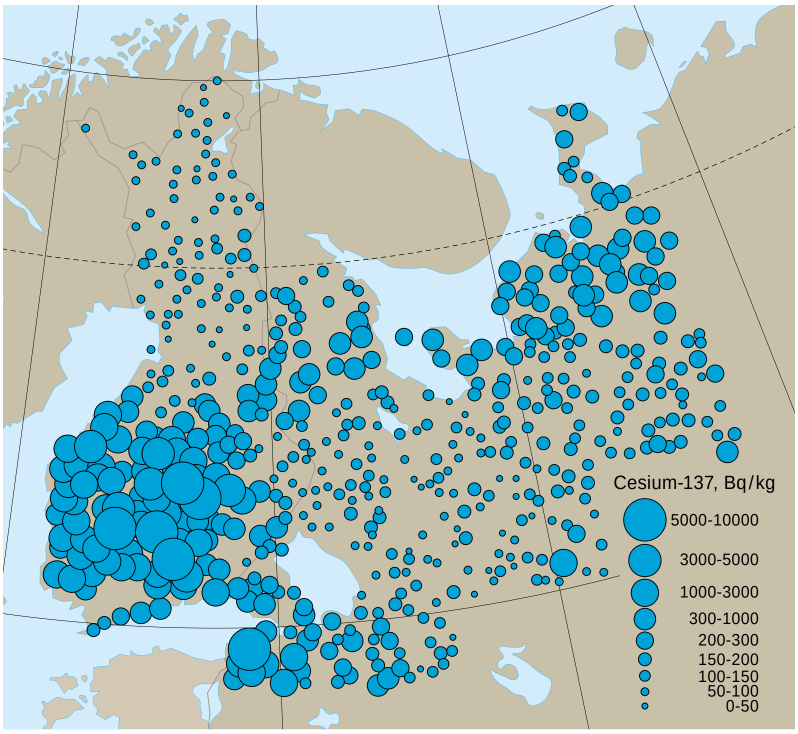
This scenario confirms that residents of Arctic ecosystems are particularly vulnerable to radiocesium contamination and that the vulnerability persists for many years after deposition. Although those who consume larger quantities of reindeer meat are particularly vulnerable, other people could potentially be exposed to high doses, especially if they consume many local products. The results clearly show the need for an effective emergency preparedness and response system, and the application of countermeasures, should a major accident ever occur at the Kola nuclear power plant.

Update on contamination from Chernobyl

One nuclear power plant accident has already had consequences for the Arctic: the explosion and fire at the Chernobyl nuclear power plant in the Ukraine in 1986. This plant was more than a thousand kilometers from the Arctic Circle. Nevertheless, radioactive material from the explosion was carried by the wind and spread over large areas, including parts of the Arctic. This source of radioactive contamination was described in the previous AMAP assessment. The major contaminated area outside the immediate vicinity of Chernobyl extends from the Leningrad region of Russia across southern Finland to parts of Sweden and Norway. A comprehensive survey of humus layers in 2000 in parts of the contaminated area in Finland and northwestern Russia provides a picture of levels of radiocesium (see

A comprehensive survey of cesium in Finland and northwest Russia was carried out in 2000. The map shows cesium-137 concentrations in the top three centimeters of the humus layer.





map). Fourteen years after the accident, the fallout from Chernobyl is still evident in the higher levels of cesium-137 in the whole southwestern part of Finland and in the area southwest of St. Petersburg in Russia.

Progress in reducing risks associated with nuclear power plants

A number of programs have been initiated to improve the safety of nuclear activities in or near the Arctic, especially at nuclear power plants in Russia. Most of the programs are based on cooperation between Russia and other Arctic countries.

Bilibino nuclear power plant consists of four small, water-cooled, graphite-moderated reactors. Efforts at Bilibino have focused on improving the safety of day-to-day operations. Projects have targeted training for plant staff, providing an analytical simulator to enhance training effectiveness, providing safety maintenance equipment and technology, and establishing improved communication links with Moscow.

Efforts at the Kola plant are also directed toward improving the safety of day-to-day operations and upgrading critical plant safety systems. The projects have focused on developing emergency operations instructions, upgrading the confinement system, and improving the engineering safety systems. Projects are also in place to perform safety assessments, to teach staff how to perform plant safety analysis, and to provide a full-scale simulator to enhance staff training.

The Leningrad nuclear power plant, located outside St. Petersburg, consists of four reactors. Safety enhancement efforts are similar to those at the Kola plant. Projects are in place for developing emergency operations instructions, providing modern safety maintenance tools and techniques, and performing in-depth safety assessments. In addition, projects are underway to provide an improved fire detection system and an emergency response program.

In the case of an emergency, it is critical that accurate information is available promptly for emergency response. Upgrading of the emergency notification system at the Leningrad and Kola nuclear power plants has been continued. There is now an automatic environmental radiation monitoring and notification system in place. These are based on satellite communication and should allow automated message transmission and direct communications with central Russian authorities as well as to the Nordic countries, independent of ground communications. Further networks have also been established, and soon all Russian nuclear power plants except Bilibino will have direct emergency communication links with central government agencies responsible for nuclear and radiation emergencies.

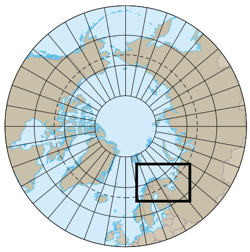
Nuclear-powered vessels

There are several locations within the Arctic where nuclear-powered vessels are being built, based, maintained and decommissioned. The size of the reactors on nuclear vessels is typically about one tenth of that of a typical nuclear power plant reactor. However, the number of operating reactors and their maintenance and decommissioning create an increased potential for accidents. The AMAP 2002 assessment contains updated information on the status of submarine decommissioning in the Russian Northern Fleet and associated waste management issues.

Since the previous AMAP assessment, the nuclear submarine *Kursk* was lost in the Barents Sea and was subsequently recovered.

The Kursk accident did not lead to environmental contamination

On August 12, 2000, the Russian submarine *Kursk* sank in international waters north of the Kola Peninsula in the Barents Sea. It was powered by two small nuclear reactors, which,



The *Kursk* accident site.

as designed, automatically shut down during the accident. The submarine was not carrying any nuclear weapons. In 2001, the *Kursk* was raised, transported, and moored on a floating dock in Roslyakov near Murmansk.

Several expeditions monitored levels of radioactivity in the water and sediment, both while the *Kursk* was at the bottom of the Barents Sea and during the recovery operation. There was no indication of radionuclide leak-

The barge *Giant-4* transporting the salvaged wreck of the *Kursk*.

POLFOTO / SEMYON MAISTERMAN

age from the submarine and the results show that the accident and subsequent recovery of the *Kursk* did not lead to any significant releases of radioactivity to the Arctic environment.

The recovery of *Kursk* has substantially reduced the risks of radionuclide releases from its reactors to the marine environment. However, until the fuel is removed and transported to proper storage, the potential for releases of radionuclides into the environment will persist.

Doses to the public are a minimal risk from a sunken submarine lying intact on the sea floor. Local seabed contamination may, however, be a concern should leakage of radionuclides occur. The major threats to humans are associated with atmospheric releases from submarine reactor accidents.

Storage of spent nuclear fuel and other wastes raise concerns

The decommissioning of nuclear submarines in the Russian Northern Fleet is continuing. As of November 2001, a total of 109 nuclear submarines had been taken out of operation. Of these, 41 have been dismantled and 68 are

PER-EINAR FISKEBECK

Andreeva Bay – the main Northern Fleet facility for storing nuclear waste.

moored awaiting dismantling. Fifty of these submarines contain spent nuclear fuel. It is expected that a further 18 to 20 submarines will be dismantled each year. During operations that involve handling of spent nuclear fuel, there is an increased risk of accidents that might cause both local and widespread atmospheric contamination.

Some of the spent fuel from refueling and decommissioning has been transported to Mayak, in the Urals, for storage and reprocessing. However, most of it is still in temporary storage on the Kola Peninsula. Although the temporary storage facilities pose a smaller threat for acute accidents with widespread atmospheric contamination than accidents in operative reactors, some of the temporary storage is causing serious local contamination, which may be spreading into the marine environment.

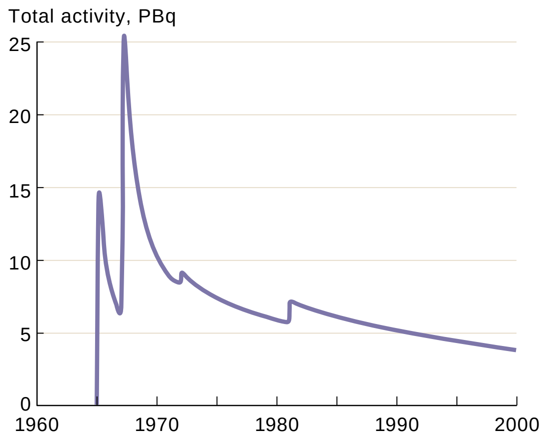
Several programs address the waste situation, which, in addition to spent fuel, includes solid and liquid radioactive wastes from submarines and other nuclear-powered vessels. An effort is also underway to launch projects related to remediation of the Andreeva Bay site that contains the largest concentration of radioactive wastes in northwest Russia. Other projects include developing a mobile processing facility for liquid nuclear wastes and new interim storage for spent nuclear fuel derived from decommissioned submarines. Large amounts of spent nuclear fuel and radioactive wastes are currently stored at the Atomflot facilities near Murmansk, including the floating storages vessels *Lepse*, *Imandra*, and *Lotta*. The *Lepse* is in a particularly poor condition and there has long been a desire to remove the spent fuel and radioactive waste from the vessel and store it elsewhere.

Since the previous AMAP assessment, the overall approach of these programs has been to adopt an integrated solution and a cooperative effort in which all the major steps from generation to disposal of the waste have to be evaluated before making any decision about options for resolving the issue. These projects represent ongoing cooperation to reduce the risks associated with radioactive wastes in the Arctic. Many other projects are being considered and may be initiated in the near future.

Amount of radioactive waste dumped at sea has been overestimated

Until 1991, the Soviet Union dumped radioactive waste in the Arctic Seas, including submarine reactor compartments containing spent nuclear fuel and part of the reactor compartment of a nuclear icebreaker. This resulted in local contamination around the dumping sites, but according to previous assessments by AMAP and by the International Atomic Energy Agency (IAEA), the major risks of releases are in the longer term, after the containment material corrodes. The IAEA study concluded that risks to members of the public from these dumped wastes are small.

There have been efforts to estimate the total content of radioactive material in the dumped

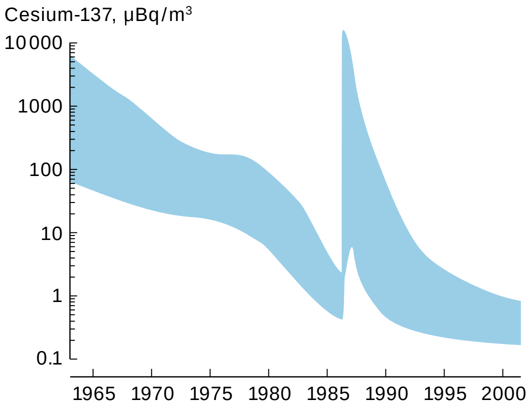


▶ Total activity of radionuclides in nuclear reactors dumped in the Kara Sea.

submarines and the icebreaker reactor, both by an international project and within Russia. Previous Russian estimates, from 1993, were published in the so-called White Book. The most recent estimates show that the White Book underestimated the activity in the reactor compartment from the *Lenin* icebreaker and overestimated the total activity of submarine reactors containing spent nuclear fuel. Recent analysis of the revised figures, also taking into account the physical decay of radionuclides present in the dumped ship reactors, shows that the White Book overestimated the total activity in all the reactors dumped near Novaya Zemlya by more than a factor of three.

Nuclear detonations and nuclear weapons accidents

The previous AMAP assessment concluded that fallout from atmospheric nuclear weapon tests conducted from the 1940s through 1980 was the major source of anthropogenic radionuclides in the Arctic environment. Radioactive contamination from these tests is declining.



The range of aerosol cesium-137 concentration from the atmospheric tests was declining in northern Finland until the Chernobyl accident in 1986.

The largest atmospheric detonation anywhere took place at the Soviet test site at Novaya Zemlya in October 1961. There have also been several underground nuclear detonations in the AMAP area. The largest of these were conducted by the Soviet Union in Novaya Zemlya in October 1973 and by the United States at Amchitka, Alaska, in November 1971.

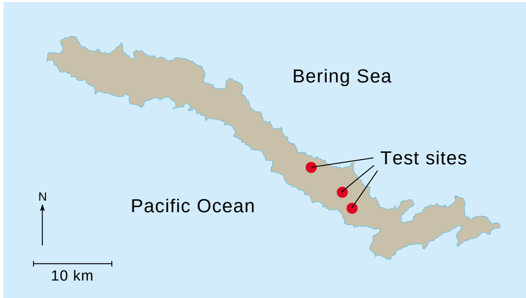
Updates on the local situations at Novaya Zemlya and Amchitka

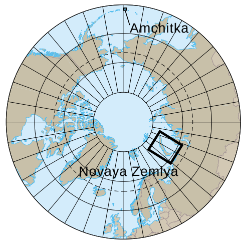
The tests at Novaya Zemlya resulted in local contamination. Since the previous AMAP assessment, two new reports on the subject have been published. Surveys have documented radioactive contamination in four areas: Chernaya Bay on the Yuzhny (South) Island, Sukhoy Nos Peninsula on Severny (North) Island, Bashmachnaya Inlet on Yuzhny Island, and the tidal area of the Matochinkin Shar Strait.

Chernaya Bay was the site of a near-surface explosion in 1957 as well as several other tests. The epicenter of the near-surface explosion is the most contaminated zone in the archipelago. In 1978, gamma radiation levels were as high as 5 microsieverts per hour. There are also traces of radioactive contamination of land areas from an above-water explosion in 1961 and from an underwater explosion in 1955.

There is also new information about the United States test site on Amchitka, where three underground tests were carried out between 1965 and 1971. When the previous AMAP assessment was written, no detailed sampling of this site had been carried out since the late 1970s. However, routine sampling and monitoring of the test site for increased radiation levels have been ongoing since the 1970s. Modeling of the movement of radionuclides in the environment of the Amchitka site had indicated that discharge from groundwater to the ocean could have started as early as 1975, ten years after the first underground tests at the site.

In 1996, leakage of radionuclides to the terrestrial and freshwater environments was reported by an environmental organization. The marine environment was not addressed in the report. In response, a federal, state, tribal, and non-governmental team conducted a freshwater and terrestrial sampling program in 1997, with additional sampling in 1998. At the Long Shot test site, where leakage of radioactive gases to the near surface occurred in 1965, elevated levels of tritium in freshwater were observed in 1997. Contrary to the claims of some environmentalists, the results of the 1997 and 1998 sampling did not pro-





Contaminated sites on Novaya Zemlya, where the Soviet Union carried out weapons tests (above), and the Amchitka test sites, where the United States conducted tests (left).

MICHAEL J. WYNNE

Amchitka.

vide any evidence of the leakage of radionuclides from the underground explosion cavities into the terrestrial and freshwater environment on Amchitka. In addition, the hydrogeological regime at Amchitka does not provide the physical means for transporting the radionuclides from the test cavities to the reported surface location.

These results do not mean that leakage from the Amchitka underground nuclear tests is not occurring or will not occur. Modeling of the movement of groundwater predicts that leakage to the marine environment could occur over timescales of 20 to 3000 years. There have also been some concerns raised about geological forces acting on Amchitka, with suggestions that stresses around a major fault could open a fracture from the island into the marine environment. These suggestions are still open to scientific debate. Assessments of the role of geological forces acting on underground island test sites to create a 'fast pathway' for radionuclide leakage could be relevant to both Amchitka and Novaya Zemlya.

MOGENS LADEGAARD / SCANPIX

Thule Airbase. Member of the American clean-up crew removing a contaminated revolver from the accident site.

Update on local contamination at Thule

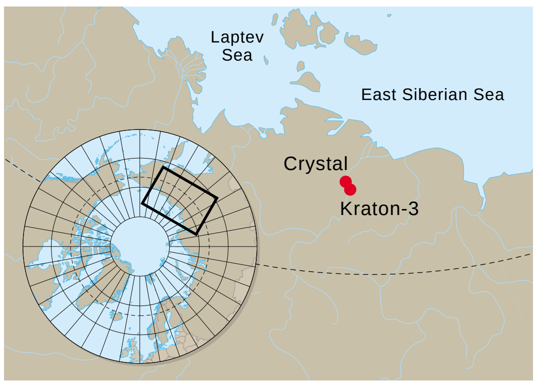
In 1968, an American strategic bomber crashed on the sea ice in Bylot Sound near the Thule Airbase in northwest Greenland. It carried four nuclear weapons, and some of the plutonium in these weapons was dispersed into the environment as a result of the aircraft explosion and subsequent fire. Most of the debris and contaminated ice was removed from the area. Some of it, however, sank through a crack in the ice or could not be recovered from the ice. The ice-embedded material was dispersed into the water column during the following summer when the ice melted.

Plutonium adheres strongly to particles. Measurements at Thule show that it is associated with particles in bottom sediment. The distribution of the contamination is uneven, and previous estimates of the amount of plutonium in the sediment did not fully take this into account. A more recent estimation method provides more accurate results. So far, only six sediment cores have been analyzed, but the results indicate that the quantity of plutonium in marine sediments at Thule is comparable to the amount that was estimated to have been lost (2.5-3 kg). Nonetheless, there remain substantial uncertainties in such estimates of the quantity of plutonium in Bylot Sound sediments.

Some animals live buried in the contaminated sediment or on the sediment surface. Plutonium concentrations in these organisms are generally one to two orders of magnitude lower than in the surface sediment, showing that the plutonium is not very bioavailable. One bivalve sample had a much higher level, which was probably due to chance ingestion of a hot particle rather than accumulation of bioavailable plutonium. Levels in most animals living in the sediment are low and the plutonium is not readily transported to surface waters.

Local contamination from civilian nuclear detonations

From 1967 to 1988, the former Soviet Union conducted a number of civilian nuclear detonations to assist in mining and construction work. At three sites in or near the Arctic, the detonations led to severe local contamination, as discussed in the previous AMAP assessment. New information from the Kraton-3 and Crystal sites in the Sakha Republic shows that local contamination of the sites remains, despite earlier clean-up efforts. In the immediate vicinity of the Kraton-3 site, the plutonium concentration in lichen in the early 1990s was 780 times higher than background. However, the contamination is highly localized: a few kilometers away from the site, the levels are much lower. Measurements of the bottom sediment of the Markha River near the explosion site show that there has been a migration of plutonium to the river, with a potential for remobilization and transport over larger areas.



▶
Kraton-3 and Crystal, two of the sites where the former Soviet Union used civilian nuclear detonations.

European reprocessing plants and the ocean pathways that carry radionuclide-contaminated water to the Arctic.

Sellafield (upper photo) and Cap de la Hague (lower photo).

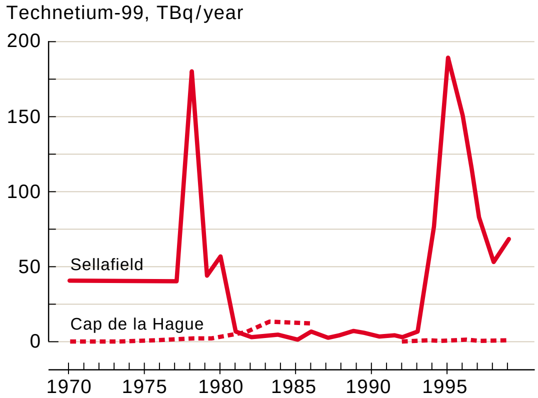
Reprocessing and transport of spent nuclear fuel

Fuel reprocessing is carried out to recover uranium and plutonium from spent nuclear fuel for reuse in reactors. Only 5-10% of spent fuel worldwide is subjected to reprocessing. Most spent fuel from reactors is instead retained on-site in interim storage. During reprocessing, the radionuclides are brought into solution. Waste solutions containing large amounts of radionuclides have been discharged to the environment during this process. There is a well-documented history of discharges of various radionuclides to the environment, with cesium-137 dominating liquid discharges. The potential for accidental releases to the environment of radionuclides in a liquid solution is greater than for all other stages of the fuel cycle. The reprocessing plants that are most relevant to the Arctic are Sellafield on the northwest coast of England and Cap de la Hague in northern France.

European plants have increased releases of some radionuclides

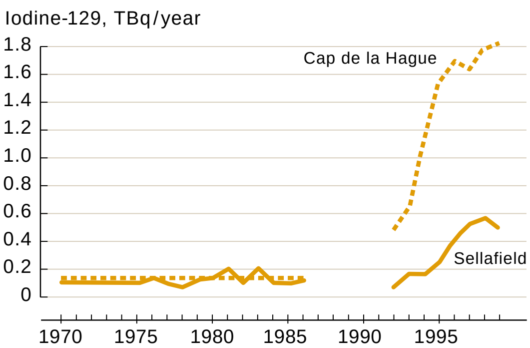
Liquid radioactive waste from the Sellafield and Cap de la Hague plants has been discharged via pipelines into the Irish Sea and the English Channel, respectively, since the 1950s. Waterborne radionuclides, including cesium-137, have been traced in northward-flowing currents and have been detected in the Arctic Basin.

In the late 1970s, there was a significant reduction in routine releases from Sellafield. In 1994, British Nuclear Fuels at Sellafield started treating a backlog of old waste in an Enhanced Actinide Removal Plant. The removal is effective for a number of radionuclides, but not for technetium-99. This treatment of old waste resulted in a considerable increase in the discharge of technetium-99, reaching levels similar to those during the previous peak releases of this element in the mid-1970s. This radionuclide is a long-lived fission product with a half-life of 213 000 years. Technetium-99 is soluble in water and can thus be transported over large distances in the marine environment.



Discharges of technetium-99 from Sellafield and Cap de la Hague, showing recent increases from Sellafield.

The discharge of iodine-129 also increased during the 1990s, especially from Cap de la Hague, where a new plant was put into operation in 1990. Iodine-129 is an extremely long-lived fission product with a half-life of 16 million years. It is water-soluble and its release has been detected and traced within the Arctic

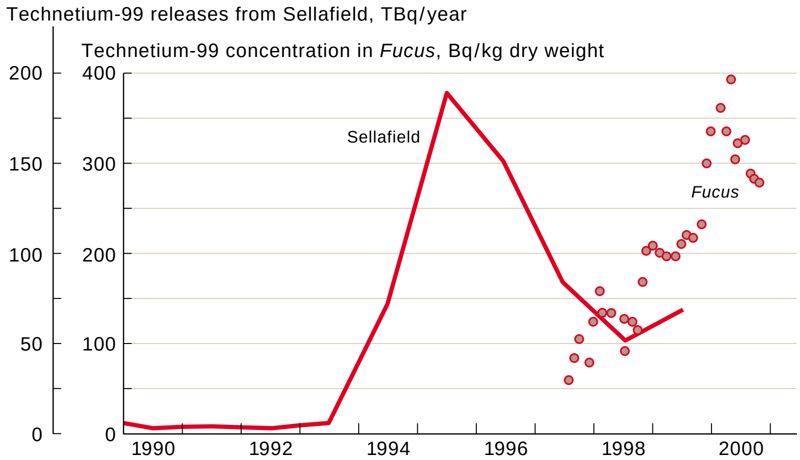


Discharges of iodine-129 from Cap de la Hague and Sellafield.

Ocean. The total discharge is ten times higher than the total amount in the ocean from natural sources and from iodine-129 generated by weapons testing.

Fuel reprocessing is a major source to the Arctic marine environment

The previous AMAP assessment showed that the input of cesium-137 from nuclear reprocessing plants is evident along the Norwegian coast and in the Arctic Ocean. Since then, the increased discharges of technetium-99 and iodine-129 have led to increasing levels of these radionuclides in the Arctic marine environment, in contrast to the declining trends for other radionuclides. A time series from Hillesøy on the northern coast of Norway shows a steep increase of technetium-99 in seaweed in the late spring and early summer of 1997.

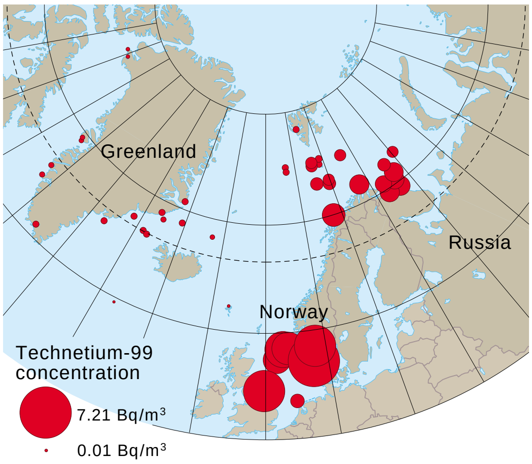


Technetium-99 releases from Sellafield and activity in *Fucus* seaweed at Hillesøy, northern Norway.

An analysis of the data suggests that the technetium-99 resulted from the rapid increase in discharges from Sellafield in the spring of 1994. Elevated levels of technetium-99 have also been detected in the southern Barents Sea. The spatial distribution, with higher activities near the coast, is consistent with current understanding of the prevailing ocean currents. At present, Sellafield is the main contributor of technetium-99 to Arctic waters.

Many radionuclides bind tightly to particles and are likely to accumulate in sediments relatively close to the source of discharge. Plutonium is one example. Several hundred kilograms of plutonium from nuclear fuel reprocessing have accumulated in the sediment of the Irish and North Seas. Measurements in seawater show that some of the plutonium in the sediment is being remobilized and transported via ocean currents into the Norwegian Sea, the Barents Sea, and eventually into the Greenland Sea and Icelandic coastal currents (see box on opposite page). Analysis of the ratios of different isotopes of radionuclides shows that the primary source of plutonium in these waters is still fallout from past nuclear testing. Through the remobilization of plutonium, however, Sellafield is indirectly the second most important contributor of man-made plutonium in Arctic seawater.

Taking into account the inventories of radionuclides from reprocessing that were presented in the previous AMAP assessment, it is clear that the reprocessing of nuclear fuel has been and still is a major source of anthropogenic radionuclides to the Arctic marine environment. The current doses to Arctic inhabitants from these sources are small. There are, however, some uncertainties about the transport to, and effects of radionuclides in the Arctic. Therefore, there is a need for further assessment of the individual and collective doses from radionuclides discharged from these and other sources. There is also a need to consider impacts on Arctic populations and the environment when evaluating discharge reduction measures.Technecium-99 discharges can be reduced using available technology, but this step has not yet been taken.



Technetium-99 distribution in seawater in 2000.

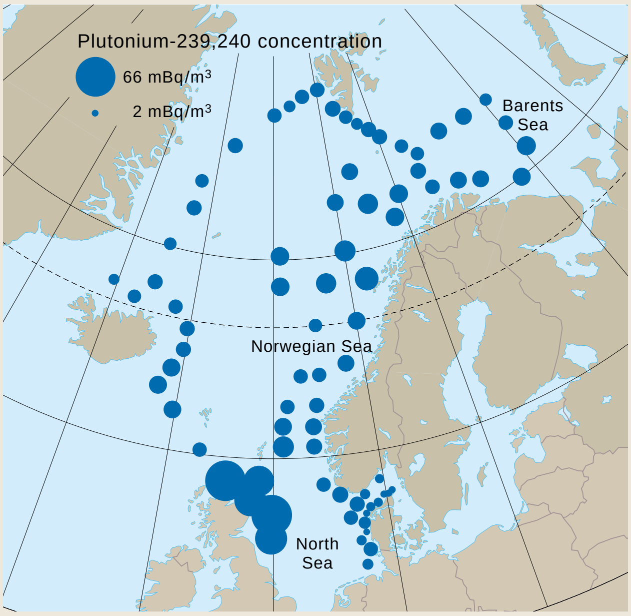
Transport of spent fuel in the Arctic is a potential risk

Spent nuclear fuel for reprocessing is sometimes transported by ships, as is the resulting reprocessed fuel. Between 1992 and 1999 there were six shipments of plutonium and high-level waste from France to Japan and one shipment of mixed oxide reactor fuel from the United Kingdom to Japan. There are suggestions that shipments in the future may use the Northern Sea Route, north of Russia. There are also ongoing discussions of shipping spent fuel from Europe to northern Russia via Murmansk for processing in Russia.

If such shipments are carried out in a manner consistent with international guidance and existing conventions, they pose only minor risks to human health. However, even if such risks are low, possible release scenarios should be considered and thorough impact assessments should be performed. The possible transfer of spent nuclear fuel in Arctic areas has caused controversy, and will continue to do so if the concerns are not addressed properly.

Old discharges still act as sources for the Arctic
The sediments of the Irish Sea accumulated large quantities of plutonium and radiocesium when discharges from Sellafield were high during the period 1970-1985. During the last decade it has become clear that these elements are not permanently deposited in marine sediments. Due to biological and chemical processes, radiocesium and plutonium are now being released in transportable forms and reaching the Arctic marine environment. The annual contribution from Irish Sea sediments has been estimated to be 50-80 trillion becquerels cesium-137 and about one trillion becquerels plutonium. This is more than the amount of these radionuclides currently being discharged by the two European nuclear fuel reprocessing plants. Plutonium and cesium-137 derived from these areas are transported to the Arctic via the Norwegian Coastal Current.

The Baltic Sea also constitutes a major source of cesium-137 to the Arctic. The Baltic was heavily contaminated by the Chernobyl explosion in 1986, and levels in the water are still high. Outflow from the Baltic in 2000 was 40 trillion becquerels of cesium-137, almost as high as the outflow from the Irish Sea sediments.



Plutonium in seawater in 1995. In the Norwegian and Barents Sea, levels are elevated above the expected fallout background levels.

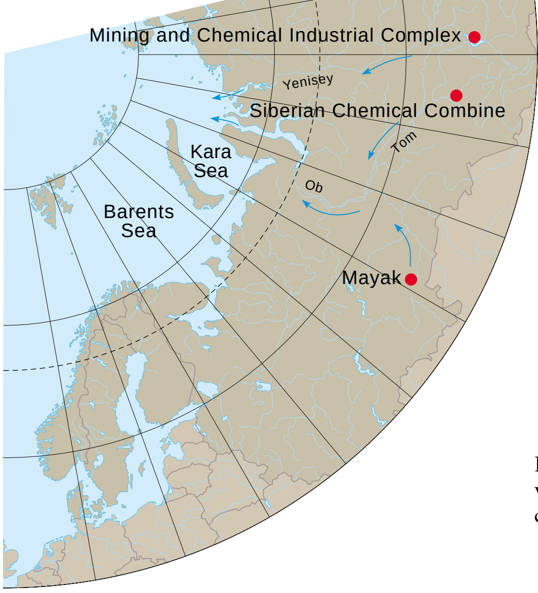
Russian nuclear facilities

Discharges from Russian nuclear facilities within the Arctic have had a minor impact on the overall radioactive contamination. However, there are three major Russian nuclear facilities located far from the Arctic that need to be considered because they discharge into river systems that eventually reach the Arctic Ocean. They are Mayak and the Siberian Chemical Combine, both in the Ob basin, and the Mining and Chemical Industrial Complex on the Yenisey River. Because discharges from these plants have historically been high, there is concern about whether they have contaminated the Arctic and whether future accidents could lead to further contamination.

Mayak was built in 1948 to produce weapons-grade plutonium. The plant and its local contamination are described in detail in the first AMAP assessment. A joint Norwegian-Russian expert group has investigated several accident scenarios and their potential to contaminate the Arctic. The scenarios included an explosion in a storage tank, a tornado at the highly contaminated Lake Karachay, dam breaks or controlled releases from storage basins that would contaminate the Techa River, a tributary to the Ob, and groundwater contamination from Lake Karachay reaching the Techa River.

Looking at worst-case scenarios, transport of strontium-90 in the river system could lead to a significant increase in contamination of the lower reaches of the Ob. For example, a dam break could lead to strontium-90 concentrations five times higher than the background level. Cesium-137 and plutonium would be much less mobile in the river system. For all scenarios, the predicted environmental concentrations of radionuclides in the Ob Bay are much lower than radiation safety standards set to protect people. Overall, the potential doses to Arctic biota and human populations associated with hypothetical accidents at Mayak involving discharge of radionuclides to water are very low. Accidents that involve discharges to air could, however, have serious consequences for the Arctic.

The Siberian Chemical Combine is located near Tomsk. Past activities produced large amounts of liquid, solid, and gas-aerosol radioactive waste, most of which is stored in warehouses and underground storage facilities. Some of the liquid waste is discharged directly into a sedi-



Russian nuclear facilities with historically high discharges.

mentation reservoir, which is connected to the Romashka River and eventually into the Ob. The major contribution to radioactivity in the wastewaters has been from reactors with single-pass core coolant systems, which were decommissioned some time ago.

In the past few years, the release of radionuclides to the open water environment has been reduced, but previous discharges led to a significant accumulation of radionuclides in bottom sediment, biota, and the floodplain. The concentration of radionuclides decreases considerably with distance from the source. It thus appears that most of the discharges from the Siberian Chemical Combine are effectively removed during transport and are not found either in the lower reaches of the Ob or in the Ob Estuary.

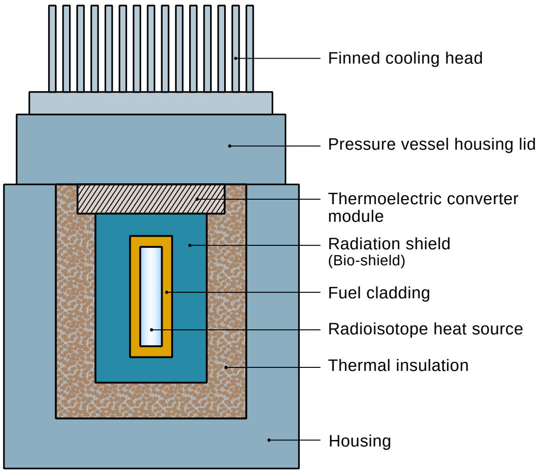
The Mining and Chemical Industrial Complex at Krasnoyarsk includes a reactor facility, a radiochemical plant, and storage for spent fuel assemblies. The releases of contaminated water have decreased considerably since the two reactors at the site were shut down in 1992. However, the bottom sediments and the floodplain are contaminated with long-lived radionuclides such as cobalt-60, cesium-137, and europium-152. Contamination from the Mining and Chemical Industrial Complex is detectable in the Arctic about 2000 kilometers downstream. The radioactivity concentrations this far away are a thousand times lower than in the zone next to the facility, but still observable. The results thus suggest that transport of long-lived radionuclides from the area near the facility is low and that the discharges from the Mining and Chemical Industrial Complex have had a minor impact on radioactive contamination of the Arctic Ocean.

Radioisotope thermoelectric generators

Radioisotope thermoelectric generators (RTGs) provide sources of power that are completely self-contained and can operate in any weather conditions. They have a long service life and are reliable, making them suitable for powering various devices in remote areas and areas with harsh climates, such as the Arctic.

The dominant radioactive material used in RTGs is strontium-90 titanate. It is a chemically stable fuel element that is not affected by extreme weather conditions or high temperatures. RTG radioactive fuel is in a leak-tight, multi-envelope container made of heat- and corrosion-resistant material. This arrangement is designed to maintain the integrity and effectiveness of the containment material during the entire service life of the generator and during possible emergencies.

Being close to an RTG is not a health hazard as the radioactive material is well contained and shielded. In terms of contamination



Schematic drawing of a radioisotope thermoelectric generator (RTG).

of the environment, the greatest threat from RTGs occurs if they are broken open during transport or as a result of malicious damage. The shields are designed to withstand accidents and natural disasters, and so the most likely cause of a breach is vandalism. If an RTG is breached, the released radioactive material can be detected and recovered. The fuel is in the form of hockey-puck sized pieces of ceramic material, selected for its strength, fire-resistance, and low water solubility. Moreover, it is in an inert form that is not easily taken up by plants and incorporated into the food web.

The United States is using ten RTGs as power sources for data collection and communications equipment at a seismic observatory on Burnt Mountain in Alaska. The observatory is run by the U.S. Air Force and is used to verify compliance with nuclear test ban treaties. In August and September 1992, a tundra fire encroached on the Burnt Mountain site, damaging some data cables. The power equip-

STAN READ

Burnt Mountain, Alaska, where RTGs have been used as power sources.

ment was not disturbed. The fire raised concern among nearby inhabitants about the safety of using a radioactive material as the power source. In response, the U.S. Air Force conducted an evaluation of the safety of RTGs and alternative power sources. While the RTGs were deemed safe, community concern resulted in a decision to remove the RTGs and replace them with a system using batteries charged by solar power and a diesel generator. Planning for this has started.

In Russia, RTGs are used to power automated meteorological stations in uninhabited polar areas. Moreover, a network of RTG-powered navigational facilities has been established for new sea routes at high latitudes. In the Arctic, no losses have been reported, but incidents outside the Arctic in connection with emergency dumps from helicopters transporting RTGs show that the risks of losing devices during transport have to be taken into account. On the coast of the Kola Peninsula, one RTG has been vandalized and the radioactive material left exposed. The fuel element itself was intact and was completely recovered. There was thus no subsequent contamination of the environment.

RTGs at lighthouses on the coast of the Barents Sea are being replaced by solar panels.

Arctic pathways and vulnerability

The effects of radioactive contamination will depend on the extent to which organisms are exposed to radionuclides. For people, a key factor in vulnerability (or sensitivity) to radioactive contamination is dietary habits and how these relate to the pathways of radionuclides in the food web. Vulnerability is a measure of how much radioactivity reaches humans through the food web for a given input to the environment. In the past few years, it has become clear that the most highly exposed people are not necessarily those in the most contaminated areas, especially some years after the initial contamination. This is because, for a given food, the transfer rate can be higher in one area than another, outweighing differences in atmospheric deposition. Understanding the physical and biological behavior of various radionuclides in the environment is as important as quantifying the extent of radioactive contamination. Combining this knowledge with information about the extent of environmental contamination provides a basis for planning emergency preparedness and response and for setting priorities for nuclear safety measures.

Terrestrial ecosystems

High transfers of radiocesium in Arctic terrestrial ecosystems are a major factor contributing to the enhanced vulnerability of the Arctic. Radiocesium transfers efficiently into many food products. One typical example is the lichen → reindeer/caribou → human food chain. Another is that mushrooms and berries can be very efficient in concentrating radiocesium.

The transfer to animals can vary seasonally, due to changes in animal diet, and can also vary spatially. For instance, radiocesium uptake from soil is greater from organic soils than from more highly mineralized soils. The type of soil can thus be important in determining vulnerability in a specific area. The type of vegetation can also have a major impact both on the transfer to food products and on how fast levels decline after initial deposition (see box below).

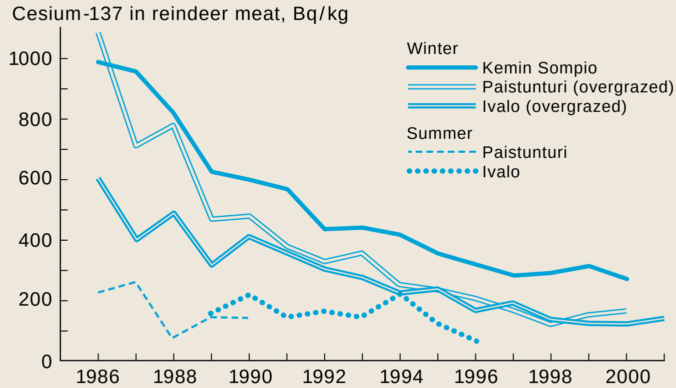
KLAZ ARVIDSSON / WINDH · JAN TÖVE / NATURFOTOGRAFERNA

Cloudberries, Taavavuoma, northern Sweden. Radiocesium transfer to some berry species is higher than to others. The highest recorded transfer rates are for cloudberries, a typical Arctic species that grows in boggy areas where radiocesium is likely to be mobile. Transfer is also high to bilberries, which are distributed more widely and grow on drier types of soil.

Focus on reindeer meat

Reindeer meat often has a high radiocesium content. In summer, when reindeer eat several hundred different species of green plants, levels are lower than during the long winter. When snow covers the ground, reindeer survive by digging for lichen and plants beneath the snow cover and by nibbling at lichen from tree branches. Lichens are efficient collectors of radiocesium from fallout.

Food availability affects the amount of time it takes radiocesium levels in reindeer meat to decline and also explains some of the spatial variation. Data from three reindeer cooperatives in northern Finland illustrate the point. Global fallout levels were similar in the three areas and two of them also had similar fallout from Chernobyl. The major difference in the trends in the concentration of cesium-137 in winter reindeer meat is probably related to the availability of lichen on the ground. The northernmost area, Paistunturi, (Báišduottar) is a rather barren reindeer-herding district. Levels here have declined faster than in the other two areas due to the limited lichen cover. The reindeer are forced to choose other foods with lower radiocesium concentrations. Currently, the levels in reindeer meat are similar to those in the Ivalo area, which received only small amounts of Chernobyl fallout, levels of which have been declining since 1986 with an effective ecological half-life of six years. In contrast, in Kemin Sompio, which contains mainly pine and spruce forest with more lichen available for the reindeer herds, levels of cesium-137 in the reindeer meat still remain fairly high 15 years after the Chernobyl accident.



Post-Chernobyl time series for cesium-137 concentration in reindeer meat in three areas of Finland. Levels are higher during winter, when no green vegetation is available.

Focus on mushrooms

The previous AMAP assessment identified mushrooms as a potentially important source of radiocesium for consumers. Mushrooms are very important food items in Russia, whereas the Saami population does not traditionally eat large quantities of mushrooms. In late summer and fall, mushrooms are also important fodder for reindeer, moose, and sheep. Where there is high radiocesium deposition, the consumption of mushrooms by animals can be a significant indirect route of radiocesium intake by people.

Mushrooms may be very contaminated in areas with high fallout, but new data from a survey of several mushroom species in Finnish Lapland shows low cesium-137 concentrations. The highest levels were found in the non-edible *Cortinarius armillatus*. Of the edible species, the highest levels were found in *Rozites caperata*, *Lactarius trivialis*, and *Suillus variegatus*. Mushrooms are an important contributor to radiocesium body burdens if consumers do not boil the mushrooms prior to consumption.

Freshwater ecosystems

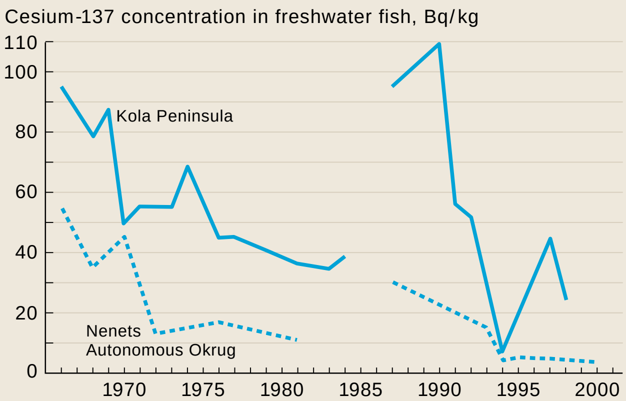
Transfers of radiocesium in Arctic freshwater ecosystems contribute to the enhanced vulnerability of the Arctic. The particular situation in a lake or river depends on how fast the water is replaced and on the characteristics of the surrounding soils. Shallow lakes with low water turnover would be more sensitive than deep lakes and rivers directly after a contamination event, simply because the contamination will not be as diluted. In the long run, the size and soil characteristics of a lake's catchment area become more important. Boggy catchments with a high content of organic matter in the soil, which is common in many Arctic areas, are efficient in transporting cesium. Snow and ice cover will affect the response of a lake, especially in the short run.

Focus on fish

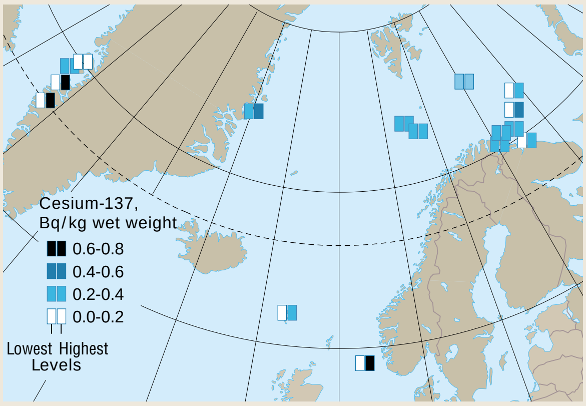
A number of fish species have been analyzed in four different lakes in northern Finland: Inarijärvi (Anárjárvi), a large regulated lake; Apukkajärvi, a small, highly eutrophic lake; and Äkäsjärvi and Jerisjärvi, which are small lakes. The feeding habits of the fish affect their cesium levels. Predatory species such as pike, perch, and burbot have the higher cesium concentrations in all the lakes compared to whitefish and vendace. The slight increase in radiocesium levels in predatory fish the first two years after the Chernobyl accident has disappeared, and levels are now lower than before the accident. Differences in the surface areas of the lakes did not seem to affect concentrations in the fish.

New data from freshwater fish in two parts of Russia show that fish caught on the Kola Peninsula, mainly in lakes, have higher levels than fish caught in the Nenets Autonomous Okrug, mainly in rivers. The explanation may be a combination of the Kola Peninsula being affected by Chernobyl fallout and the fact that levels in rivers are generally lower than those in lakes.

There are also some measurements for marine fish. The concentrations are low.



Dynamics of cesium-137 in freshwater fish from the Kola Peninsula and the Nenets Autonomous Okrug.



Cesium-137 concentration in marine fish 1995-2000.

MAGNUS ELANDER

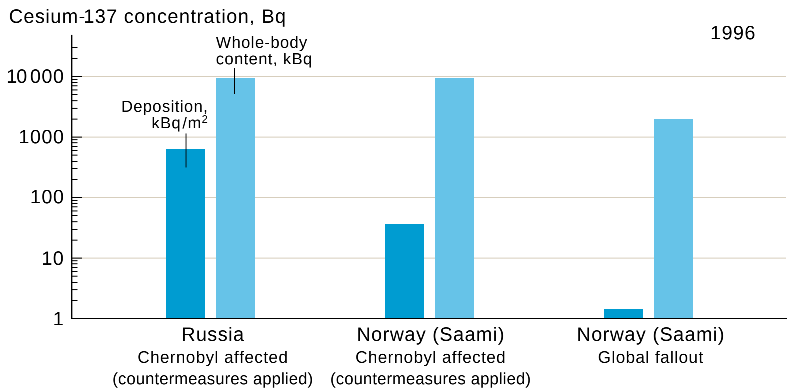
Feeding reindeer supplementary food is a way to bring down cesium levels in the meat before slaughter.

If fallout occurs in the winter, the radionuclides will not enter the water until they are released to runoff in the spring.

In fish, the concentration of cesium is affected by the amount of potassium in the water. There is a similar relationship between strontium and calcium. Lakes in natural or semi-natural areas often have low levels of nutrients such as potassium, making them more vulnerable than lakes in agricultural areas where fertilizer runoff raises the level of some nutrients. Another factor is the feeding habits of fish. Predatory fish can have levels more than a hundred times higher than those of non-predatory fish.

Radionuclides can transfer to foods long after deposition

In the Arctic, there are high transfers of radiocesium and long ecological half-lives in various food products. This means that radiocesium contamination previously deposited is still being transferred to food products. The extent of this transfer depends on the time since deposition and the type of ecosystem. In temperate areas with fertilized soils, radionuclide contamination of food products rapidly decreases in the first few months of the next growing season following deposition. In contrast, natural and semi-natural ecosystems in the Arctic often retain cesium-137 in food products for a long time. Therefore, in some Arctic areas, global fallout and Chernobyl fallout are still sources of food product contamination that need to be taken into account.



Whole body content of some populations groups of cesium-137 after Chernobyl, showing how countermeasures applied in Chernobyl affected areas effectively reduced exposure.

Implications for intervention

Actions in response to contamination can reduce exposures. Such actions include advice about what to eat, giving uncontaminated feed to semi-domesticated reindeer, and changing animal management practices. The countermeasures that were put in place in some areas after the Chernobyl accident drastically reduced the dose to people. Maintaining options to reduce human exposures depends on governments' putting effective countermeasures into place. It is more difficult to implement effective and long-lasting countermeasures in semi-natural and natural ecosystems, such as those prevailing in the Arctic.

◀
Post-Chernobyl diet-advice brochure from the Swedish National Food Administration.

Developing maps of vulnerable areas prior to an accident would provide a very useful tool in emergency response. In combination with estimates of deposition, such maps would make it possible to identify the areas where countermeasures are most needed.

Human exposure

The first AMAP assessment noted that the exposure of general populations in the Arctic to the primary radionuclides in fallout is about five times higher than in temperate areas. For smaller population groups within the Arctic, exposures could be more than 50 times higher than those of the average inhabitants.

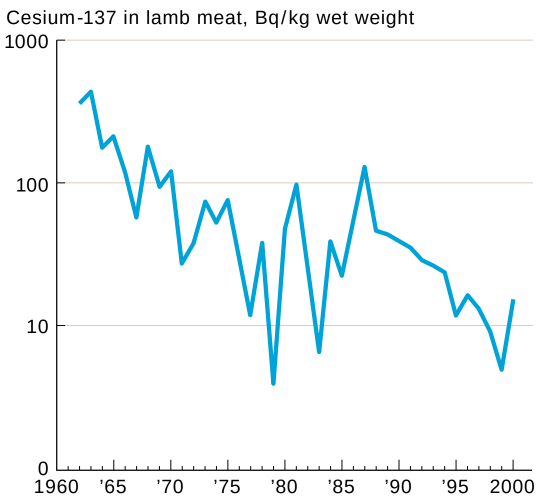
Many post-Chernobyl studies have demonstrated that the highest exposures do not necessarily occur in the most contaminated areas, especially in the mid- to long-term after the accident. The reason, as explained above, is variation in soils, vegetation types, and food webs. For people, food habits and the application of countermeasures to reduce exposure can have dramatic effects on dose. Examples of countermeasures include dietary advice and feeding uncontaminated food to reindeer to reduce radionuclide concentrations in the meat before slaughter.

The previous assessment identified several groups that receive higher doses than the average Arctic inhabitant. A common factor is that they rely heavily on terrestrial food products, such as reindeer or caribou meat. Mushrooms and freshwater fish are other important sources. The lowest anthropogenic doses were those in Greenland and Iceland, mainly because marine foods are more important in the diet.

The current assessment complements the previous picture with new data from the Faroe Islands and from an in-depth study of some communities in northwestern Russia.

The Faroe Islands

The previous AMAP assessment made dose assessments for populations in many parts of the Arctic. The Faroe Islands were not included, and therefore complementary information is provided in this report. The graph to the left depicts radiocesium concentration in lamb meat in the Faroe Islands over the period 1960-2000. There have also been several measurements in milk and drinking water. The dose to the average resident of the Faroe Islands has been estimated at 3.5 millisieverts. When compared with the doses to the average populations of other countries estimated earlier, this shows that the population of the Faroe Islands has received the second highest average dose in the Arctic. The highest doses (11.6 millisieverts) to the average residents were received by the inland population of Northern Canada.

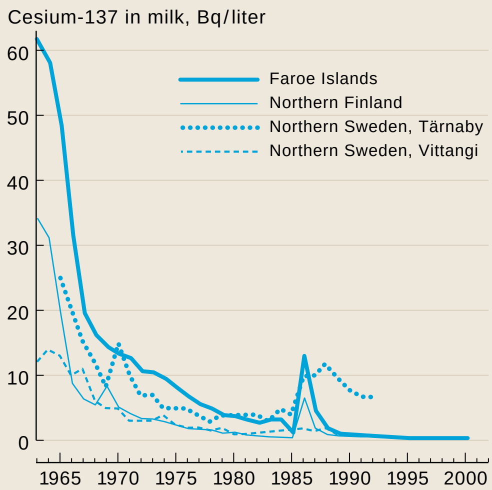


Cesium-137 levels in lamb meat in the Faroe Islands. Prior to the 1990s, samples were collected from different localities.

Focus on milk

Grazing animals in the terrestrial environment provide a major pathway of radionuclide exposures to people. It is therefore of interest to study the levels in such species. Since the previous AMAP assessment, new data have become available on cesium and strontium activity in cow's milk from Finland, the Faroe Islands, Iceland, Norway, Russia, and Sweden. All time series show a peak in the early 1960s varying from 15 becquerels per liter in Sweden to nearly 100 becquerels per liter in the Faroe Islands. After the Chernobyl accident, there was virtually no fallout detected in some parts of Sweden, whereas one Swedish location, northern Norway, and the Faroe Islands had peak values of up to 20 becquerels per liter.

The milk measurements have been used for calculating ecological half-lives. A general picture is that half-lives are short during the first year after fresh fallout and then become longer and longer, unless new fallout changes the contaminants load in the environment. For example, at a Finnish dairy in an area affected by Chernobyl fallout, the effective ecological half-life for cesium-137 was less than a year-and-a-half in the years immediately after the accident but almost ten years by the late 1990s. Another conclusion is that ecological half-lives vary geographically.



Cesium-137 concentration in cow's milk.

STAFFAN WIDSTRAND

Nenets nomads.

Northwest Russia

The new Russian data are for three different population groups living at the sites indicated on the map: indigenous people, mainly reindeer herders and their families; rural residents and inhabitants of small villages and settlements with a mixed diet; and the population of big ports and cities, whose inhabitants mainly consume food products from outside the region.

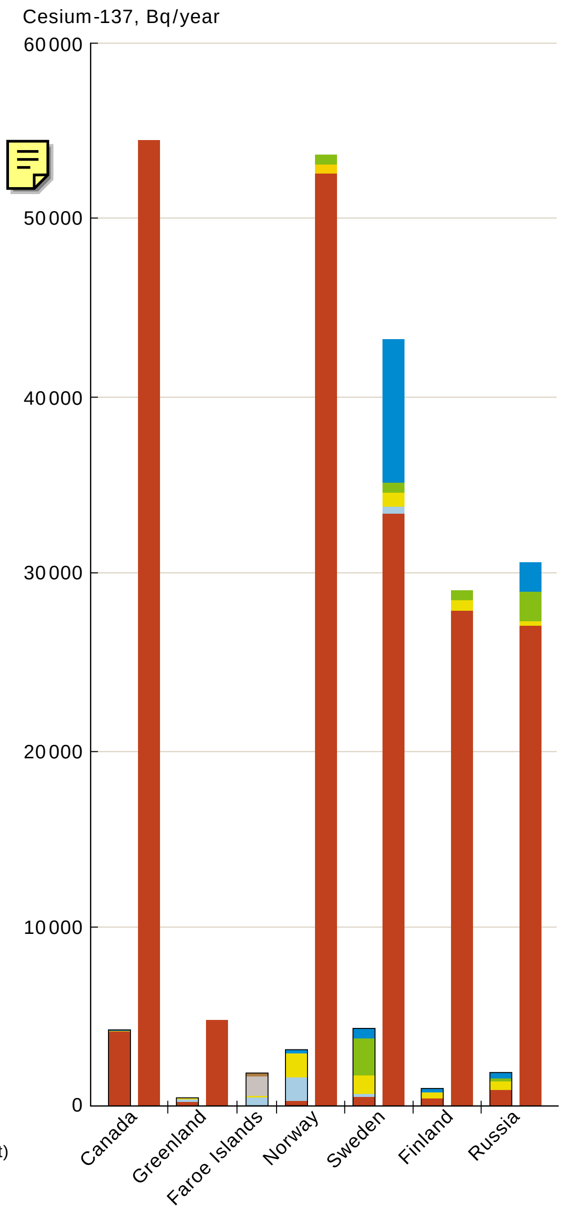
Dietary surveys showed that rural inhabitants consume, on average, two to four times less reindeer than the reindeer herders and their families. Their fish consumption is similar to that of reindeer herders. Urban inhabitants consume only small quantities of reindeer meat. The food products with the highest activity concentration are reindeer, mushrooms, and freshwater fish. The concentration of cesium-137 in these foods is two orders of magnitude higher than in locally produced agricultural food products. The activity concentrations in natural products were higher on the Kola Peninsula than in the Mezen districts and the Nenets Autonomous Okrug. The activity concentrations in agricultural products were similar in all three regions.

The dose estimates show that reindeer herders on the Kola Peninsula have an internal dose of 0.18 millisieverts per year on average. Reindeer consumption is by far the most im-

Study areas for human exposure assessment in Russia.

Intake of cesium-137 in various foodstuffs by the average Arctic populations and selected groups in Arctic countries.

The selected groups are:
Northern Canada
Old Crow diet (a community which relies heavily on caribou meat).
Greenland
A hypothetical group assumed to consume local products rather than imported, and freshwater rather than marine fish.
Northern Norway
People associated with reindeer breeding.
Arctic Sweden
Reindeer herding population.
Finland
Saami reindeer breeders.
Russia
Reindeer breeders in eastern and western Russia.



portant source of radiocesium. The rural group not associated with reindeer herding had an average internal dose of 0.07 millisieverts per year, or approximately one-third of that of the reindeer herders. Reindeer meat is the most important source of radiocesium in this group as well, but fish, mushrooms, and berries were also significant contributors. The doses for the urban group were a thousand times lower than for the herders, ranging from 15 to 25 microsieverts per year.

In summary, current doses to inhabitants in the Russian Arctic are much lower than during the 1960s when global fallout from atmospheric testing was being deposited. Individual doses on the Kola Peninsula are higher than in the other two study regions.

Summary

The major sources of radioactive contamination of the Arctic environment remains fallout from atmospheric nuclear weapons testing in the period 1945 to 1980, discharges from European spent nuclear fuel reprocessing plants, and fallout from the 1986 accident at the Chernobyl nuclear power plant in the Ukraine. Doses to humans are derived mainly from global fallout and fallout from the Chernobyl accident.

In general, levels of radionuclides in the Arctic environment continue to decline. The exceptions are seawater levels of the long-lived water-soluble fission products technetium-99 and iodine-129. These increases originate from nuclear fuel reprocessing in Western Europe. The current doses to the inhabitants of the Arctic from radionuclides originating from spent nuclear fuel reprocessing plants are small. The uncertainty surrounding the pathways to, and effects of these radionuclides in the Arctic show that further assessment is needed. Impacts on the Arctic should be considered when evaluating discharge reduction measures.

Radiation accidents are a major concern. The greatest threats posed by nuclear activities are associated with potential accidents in nuclear reactor operation and the decommissioning of nuclear-powered vessels. For example, models show that a major accident at the Kola nuclear power plant in Russia resulting in substantial releases of radioactive materials to the atmosphere would require countermeasures to avoid high radiation doses to the region's population. Major efforts are underway to reduce radiation risks connected with nuclear reactors and radioactive waste handling. However, further improvements in nuclear safety and radioactive waste management are still warranted.

Since the previous AMAP assessment, a nuclear submarine accident occurred in the Arctic, when the submarine *Kursk* of the Russian Northern Fleet was lost in the Barents Sea after an explosion on board. The *Kursk* has been recovered and monitoring shows that the accident did not result in any measurable releases of radionuclides to the Arctic environment.

To reduce the risk and to mitigate the consequences of possible future accidents, work is being done on risk management and risk analysis of nuclear activities and assessments of the vulnerability of Arctic areas. This gives a basis for improved emergency prevention, preparedness, and response for nuclear incidents.

For human health, there is increasing recognition that vulnerability and dose can vary a great deal, even over geographically limited areas. Because of high transfer and long ecological half-lives, vulnerability assessments need to take into account previous deposition.

Previously, the focus of radiation protection has been on the protection of human health. A new initiative in which AMAP has participated and that is highlighted in this report is an attempt to develop a basis for protecting the environment from the effects of radiation.