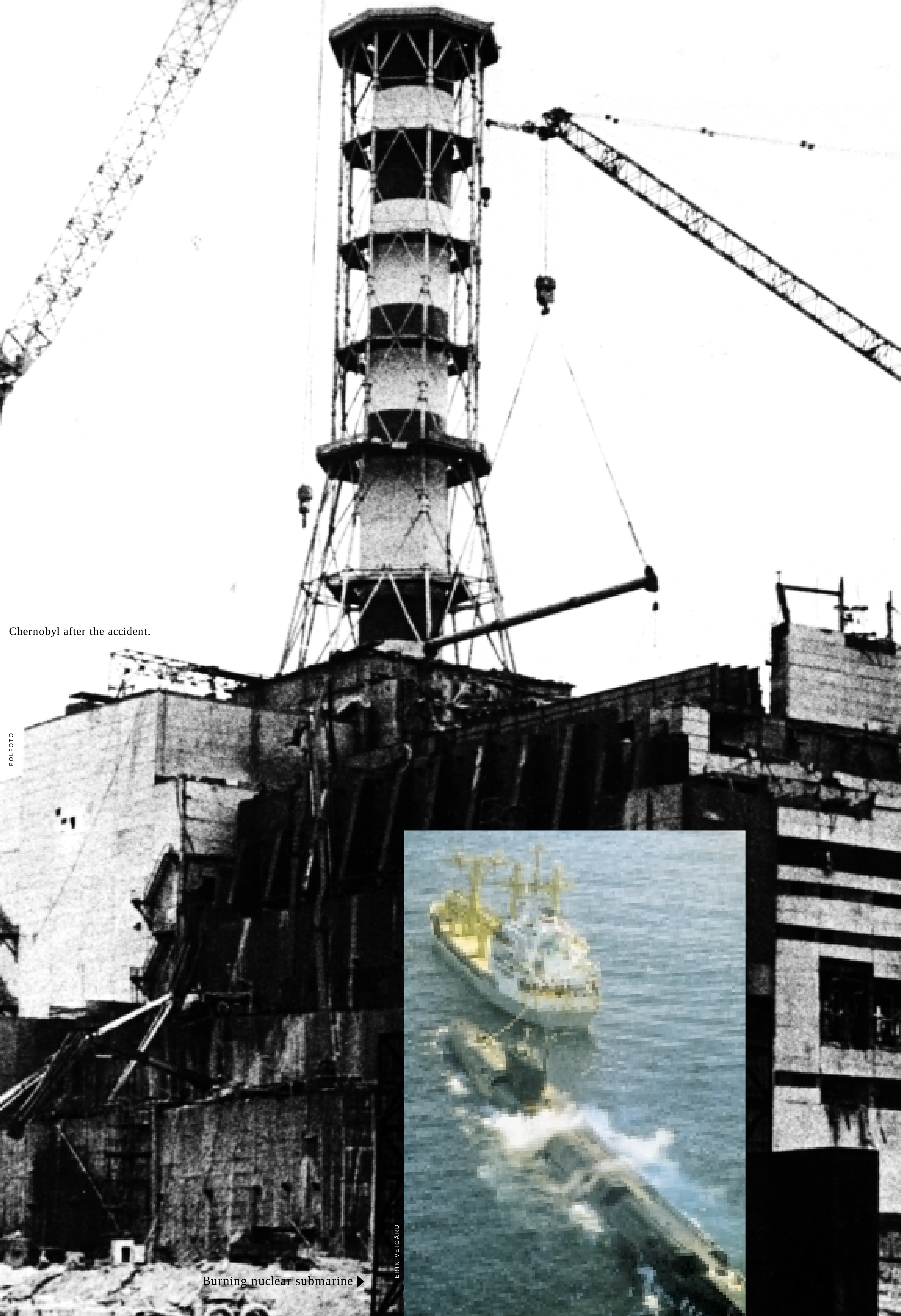


Chernobyl after the accident.

POLFOTO

ERIK VEIGÅRD

Burning nuclear submarine ▶

Radioactivity

At one o'clock in the morning on April 26, 1986, everything seemed normal in the control room of the Chernobyl Nuclear Power Plant. Half an hour later, the worst nuclear power plant accident in history began. A steam explosion in Reactor 4 started the chain of events, and further explosions caused the collapse of the core. During ten days of fire, 9000 kilograms of radioactive material and 700 000 kilograms of radioactive graphite escaped from the building. The heavy material fell to the ground close to the power plant, but the lighter material followed the winds.

The accident was devastating to people nearby, but it also changed the lives of people over a thousand kilometers away. The winds were southeasterly, those spring days in April, bringing rain to parts of Sweden, Norway, and Finland. It seemed like any other spring rain, but more than a decade after the accident some Saami villages still give their reindeer special fodder to get rid of radioactive cesium that the animals accumulate from eating contaminated lichen.

Many people think of Chernobyl as the worst-ever large-scale release of radionuclides. It was not. Atmospheric tests of nuclear bombs, which went on until 1980, spread much more radioactive material and over a wider area than Chernobyl. But Chernobyl added to the radionuclides in the northern polar area, especially in Fennoscandia, and the question remains: What are the long-term consequences of this for people living off the land? It was also a reminder that accidents can spread radioactive material over large areas. What future accidents, military and civilian, could affect the Arctic? This region may be particularly vulnerable because of the high density of nuclear sources and because of its special natural conditions and food chains.

This chapter describes sources of radionuclides and levels in the environment in an attempt to assess how past and present activities might affect the health of Arctic people. Emphasis is placed on the ecology and food consumption patterns that effectively carry radionuclides from their source to people. It also discusses risks of future releases from nuclear operations and activities, including nuclear reactors, nuclear waste storage and processing, spent nuclear fuel, and other nuclear production and reprocessing operations. What would happen if there were an accident in or near the Arctic? Such events cannot be ruled out, especially considering the current lack of effective safety provisions in some nuclear installations.

Radioactivity and health

Radioactivity is accompanied by the emission of ionizing radiation, which can damage living cells. Whereas estimates of radioactivity are useful for making inventories of sources and for tracing radionuclides in the environment, health effects are connected to the dose received by organisms, including people. The table below describes some units used to measure radioactivity and dose.

Units and abbreviations

Unit		Describes	Older unit
Becquerel	Bq	*Radioactivity* (the spontaneous decay of atomic nuclei). Number of disintegrations per second	Curie = 3.7×10^{10} Bq
Gray	Gy	*Dose.* One gray equals an energy uptake of one joule per kilogram	Rad = 0.01 gray
Sievert	Sv	*Effective dose.* One sievert has the same biological effect in humans as one gray of gamma radiation. In this chapter effective dose is usually expressed in millisievert (mSv). 1 mSv = 10^{-3} Sv	Rem = 10 millisievert
man-Sievert	man-Sv	*Collective dose* (the sum of doses to a group of people). *Collective dose-commitment* (the sum of doses to a group of people over a specified time period)	

The relationship between levels of radioactivity and the dose that can affect people's health is complex. It depends first on whether exposure is external or internal, the latter from inhaling or ingesting radionuclides. Other factors include the mobility of different radionuclides in the environment and whether they accumulate in important foodstuffs. The dose therefore depends on how we live and what we eat.

At low doses, the main concern is an increased risk of cancer, which can develop if an irradiated cell is modified rather than killed. The probability of cancer increases with the dose. There is no evidence of a threshold dose, a lower limit below which there is no risk. The table below gives some examples of the increases in cancer incidence associated with certain doses.

Radiation doses – a comparison.

0.1 millisievert: Dental x-ray or a return flight across the Atlantic
1 millisievert: The average yearly dose from natural radiation (from the ground, cosmic radiation, and naturally radioactive substances within the body), excluding radon. In regulating nuclear activities, 1 millisievert is used as the yearly dose limit for all man-made radioactivity to which the general public can be exposed. It corresponds to an increased risk of fatal cancer for 1 person out of 20 000.
20 millisieverts: In many countries, the highest allowable yearly dose for people working with radioactivity.
A few hundred millisieverts per year: the lower limit for deterministic effects from chronic exposure.
One thousand to a few thousand millisieverts: thresholds for different deterministic effects at acute exposures.
10 000 millisieverts: will kill most people and higher animals after acute exposure.

Radiation can also affect germ cells, the egg and an early developmental stage of sperm, which transmit genetic information from generation to generation. This increased risk of genetic damage might inhibit development in the womb or make a child more susceptible to disease after birth. As is the case with cancer, the probability of such effects increases with dose.

At higher doses, radiation above a certain threshold dose kills cells, causing radiation sickness. Most people exposed to such high doses have been in the near vicinity of severe accidents with radioactive material, such as the fire fighters at the Chernobyl nuclear power plant in 1986, or near nuclear bomb explosions, such as the residents of Hiroshima and Nagasaki in 1945. The first symptoms of radiation sickness are nausea, vomiting, and reddening of the skin. Radiation sickness can lead to death if the doses are high enough or if the person does not get medical treatment. The severity of this radiation damage increases with dose, and the effects are often called deterministic (certain to occur). Below the threshold, there will be no deterministic effects.

Sources

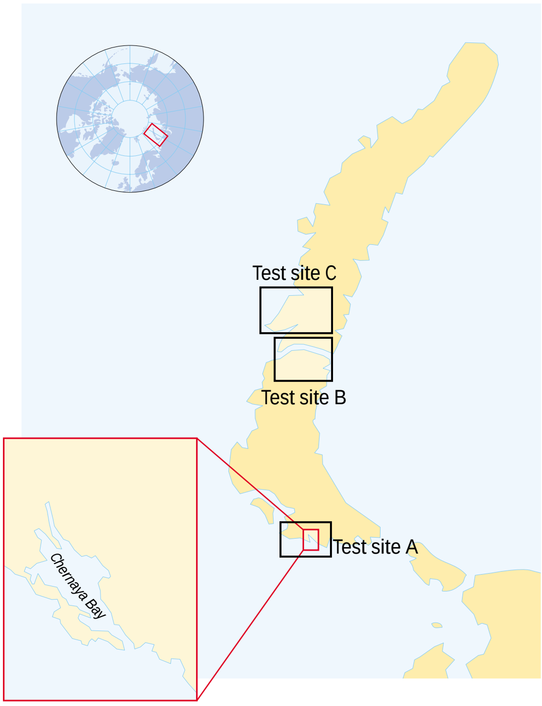
Radioactivity has both natural and anthropogenic sources. The natural radiation stems from the decay of nuclei in the Earth's crust and from cosmic radiation. The levels vary geographically, depending on local rock formations. Concerns in the Arctic are similar to those in other areas. For example, many countries have guidelines limiting the concentration of radon gas in buildings.

In addition to this natural radiation, human activities have added radionuclides to the Arctic environment. Fallout from atmospheric testing of nuclear weapons is the major source, followed by routine releases from European nuclear fuel reprocessing plants and the Chernobyl accident. Several accidents within the Arctic have added local contamination. There may also be some local contamination from dumping of nuclear waste, storage of radioactive waste, and spent nuclear fuel.

Nuclear weapons are the major source of radionuclides

Past atmospheric tests of nuclear weapons remain by far the largest global source of radioactive contamination. Most of the atmospheric tests were done before 1962, and atmospheric testing ceased entirely in 1980. Novaya Zemlya, Russia was the only site for atmospheric nuclear weapons tests in the Arctic. No tests have been conducted there since 1962. Some underground nuclear tests also took place in the Arctic, at Novaya Zemlya, Russia (see the map in the left column of opposite page) and at Amchitka Island, Alaska.

About 12 percent of the fallout from the tests has normally been deposited close to the test site, and about 10 percent has ended up in a band around the same latitude as the test site. The remaining 78 percent is global fallout, most of which has ended up in the same hemisphere as the tests. The map at top right shows the distribution of radiocesium as calculated by AMAP.

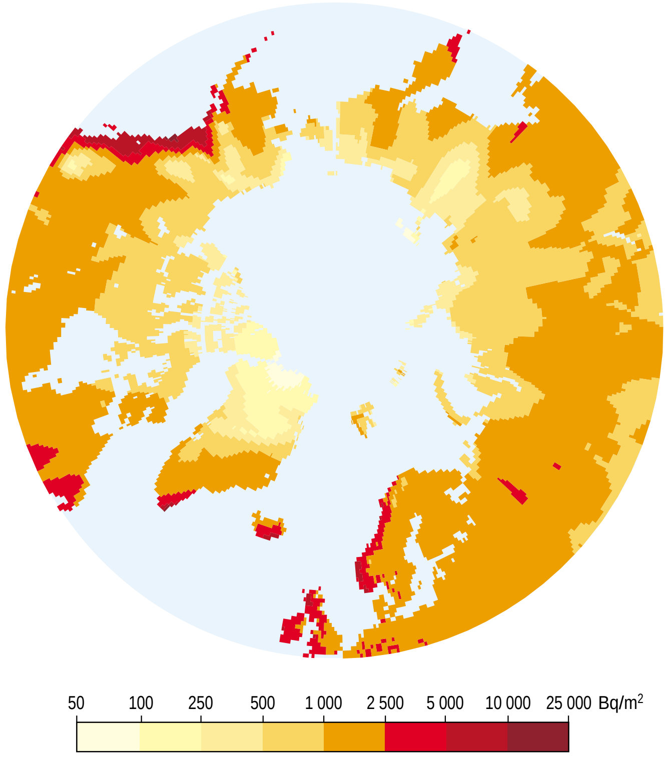


Areas of testing nuclear weapons on Novaya Zemlya, Russia.

Based on the transfer of radionuclides in the food chain, AMAP has tried to estimate the average dose to the members of Arctic population as well as the collective dose to the Arctic population as a whole. The calculations show that bomb fallout will contribute, in total, to about 750 additional cases of fatal cancer. The internal dose is very dependent on food habits. People living wholly on local products such as reindeer/caribou have received much higher doses than those mostly eating food imported from temperate regions. People living off marine fish and marine mammals have received the lowest doses.

Reprocessing plants have added radionuclides to the sea

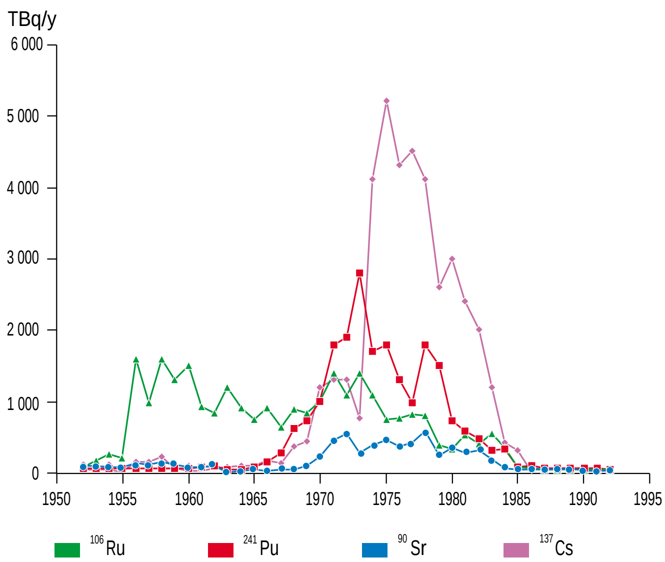
Spent nuclear fuel is often processed to recover plutonium. Water used in reprocessing contains a soup of different radionuclides, and some of this contaminated water has been released routinely into the sea. In Europe, three reprocessing plants are relevant to the Arctic because of transport of radionuclides by ocean currents: Sellafield (formerly Windscale) in Cumbria on the northwest coast of England, La Hague near Cherbourg, France, and Dounreay in northeast Scotland. Sellafield has been the most important source of radionuclides to the Arctic marine environment, because of the scale of its discharge. The effluent has been released into



Estimated ground deposition of cesium-137 from nuclear-weapon fallout, decay converted for 1995.

the sea and carried north by ocean currents. The releases, which started in 1952, are well documented. The graph below indicates the rates of liquid discharges from 1952 to 1992. Cesium-137 dominates. The peak of the release for most radionuclides was in the mid-to-late 1970s.

The people most exposed to radioactivity from Sellafield are those eating fish and seaweed from the coastal region near the plant



Discharges of beta-emitters from Sellafield nuclear reprocessing plant, 10^{12} bequerels per year.

and those working along the shoreline close to the plant. Even for them, doses are well below the recommended maximum. Individual doses to people in the Arctic will be much lower.

The reprocessing facility at Cap de la Hague has operated since 1965. The total discharges are much less than for Sellafield, as is also the case for Dounreay. The major peak for Dounreay was in the 1960s and early 1970s, with small peaks in 1968 and 1973 from plant cleaning and decontamination procedures.

AMAP has estimated the collective dose commitment for the Arctic to be 50 mansieverts from European reprocessing plants. This indicates that there would be approximately one to two additional cancer deaths in total within the Arctic area.

The Chernobyl accident spread radiocesium across the European Arctic

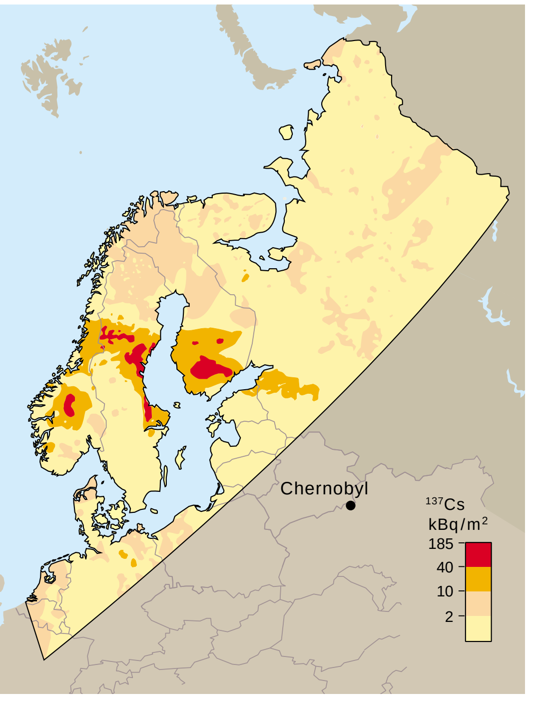
On April 26, 1986, two explosions in quick succession blew the roof off one of the four reactors in the Chernobyl nuclear power plant in the Ukraine. Concrete, graphite, and debris were ejected into the air, leaving a gaping hole that exposed the reactor core. During a ten-day fire, smoke and gases rose more than one kilometer into the atmosphere, followed by fragments of uranium fuel. The heat from the fire released radioiodine, a substantial fraction of volatile metallic elements including radiocesium, and somewhat lesser amounts of other radionuclides normally found in a reactor.

Estimated total releases from Chernobyl

iodine-131	1500×10^{15} becquerels
cesium-137	85×10^{15} becquerels
cesium-134	46×10^{15} becquerels
strontium-90	8×10^{15} becquerels*
alpha-emitting plutonium nuclides	0.1×10^{15} becquerels*

*most of these radionuclides were deposited in the vicinity of Chernobyl.

The radioactive material spread over more than 140 000 square kilometers of the territory of Ukraine, Belarus, and Russia. At first, the most important route of exposure was via milk, not via air as many expected. In the following years, other local foodstuffs became important sources, such as mushrooms and berries, in which contaminant levels have declined much more slowly.



Cesium-137 contamination after the Chernobyl accident, 10^3 bequerels per square meter.

The radioactive cloud from Chernobyl also reached the Arctic. The winds carried the material first to the Baltic states, then to Sweden, Norway, and southern Finland, and in Russia to the Arkhangelsk region, the southern part of the Kola Peninsula, and Salekhard in the estuary of the Ob River. In contrast to the European and western Russian Arctic, the radioactive deposition in the north of eastern Siberia was relatively insignificant.

The map on this page shows the most significantly contaminated area, which extends in from east to west across the Leningrad region of Russia, southern Finland, and Scandinavia. No large regions north of the Arctic circle were severely contaminated. The levels in northern Scandinavia are about 2000 becquerels per square meter, which is close to the level of global fallout. Most of the European part of the Russian Arctic also has levels of less than 10 000 becquerels per square meter.

The most important ecological pathway for radiocesium in the Arctic is the lichen-reindeer-human food chain. The cesium-137 in lichen peaked in 1986-1987 at levels that are comparable to the peak in fallout from nuclear weapons tests. After that, the concentrations have decreased with an environmental half-life of three to four years. Measurements in reindeer also show a peak similar to that associated with global fallout.

In several countries, the human body burden of radiocesium has also been monitored. After the Chernobyl accident, there was a significant increase of radioactivity in Arctic indigenous people who consume foods that concentrate radiocesium, such as reindeer meat, freshwater fish, mushrooms, and berries. A typical value for Finnish Saami in the Inari region in the early 1980s was 4000 becquerels. In 1986-1989, it rose to 9000 becquerels. It has now decreased to its earlier level. In Norwegian Saami, the pre-accident level was 3000 becquerels, peaking at 40 000 becquerels in 1989 in the Chernobyl-affected areas, and gradually decreasing since then. Reindeer-breeding Saami in northern Sweden accumulated an average of 40 000 becquerels of cesium-137 in 1987-1988 compared with 5000 in previous years. In the Murmansk region of the Kola Peninsula, body burdens in the indigenous population before the accident were 20 000 to 30 000 becquerels. By July 1991 these had increased to 33 000 becquerels. The range of peak values in whole body content reflects the level of soil contamination, meteorological conditions, the duration of the snow cover in 1986, and individual food habits. The high pre-accident body burden in Russia may reflect a relatively higher intake of reindeer there than in the other countries.

Based on whole body measurements, it has been possible to estimate the radiation dose before and after the accident. The individual committed effective internal dose ranges from

0.5 to 10 millisieverts. Based on the collective dose for the population of the European Arctic, the Chernobyl accident will probably cause about 25 additional cases of fatal cancer.

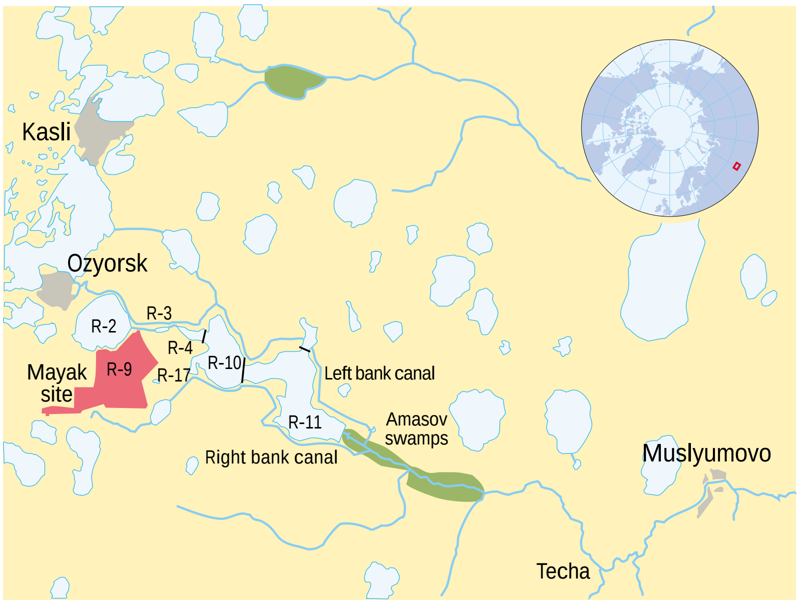
Weapons production has contaminated Russian rivers

Russia has three fuel reprocessing plants, at Mayak, Krasnoyarsk, and Tomsk, which are all situated south of the Arctic. Radioactive releases from the Mayak and Tomsk installations enter the drainage area of the Ob River and those from Krasnoyarsk go directly into the Yenisey River. They can eventually be transported to the Kara Sea.

The Mayak plant was built in 1948 to produce plutonium-239 for nuclear weapons. From 1949 to 1956, the plant discharged large quantities of radioactive waste into the nearby Techa River, and, since 1951, also into a lake with no outlet, Lake Karachay; see the map right.

Spring flooding has contaminated large parts of the Asanow Swamp along the bank of upper Techa River. Some of the radionuclides, especially mobile isotopes such as strontium-90, have also been carried downstream via the river system and into the Kara Sea. Current releases from the Mayak plant are considerably reduced, since the last of the reactors producing weapons-grade plutonium was shut down in 1990. In addition to intentional discharges, the area around Mayak (about 20 000 square kilometers) has been contaminated by the Kyshtim accident in 1957, when a storage tank of highly radioactive material exploded.

Between 1951 and 1966, a system of dams along the upper parts of the Techa was constructed in an attempt to retain the radioactive material, creating several artificial lakes along the river course. The concern for the Arctic is that the storage ponds might fail to contain the waste. One scenario is a total dam failure, which could empty the radionuclides into the Asanow Swamp below the dam and into the Techa River and eventually into the Ob. Another large-scale release could occur if the Asanow swamp were to dry out, after which floods could wash radionuclides into the Ob. One of the dams also leaks radioactive contamination through the bottom into groundwater.



The system of dams and drainage channels at Mayak, Russia. Lake Karachay (R9) is located within the Mayak site.

Lake Karachay has no outlet but caused contamination of the surroundings during a dry period in 1967, when lake sediments were exposed and spread by winds. The lake bottom is now covered with blocks of concrete to prevent further resuspension. However, radionuclides can leach from the sediments into the groundwater, from where they might spread farther into the Techa River.

The Siberian Chemical Combine at Seversk near Tomsk is one of the largest nuclear weapons production facilities in the world. It came to international attention in April 1993, when a chemical reaction caused an explosion in a tank containing fission products and uranium nitrate solution, contaminating an area of about 90 square kilometers. A recent report from the Russian Federation Security Council has stated that large amounts of radioactive wastes were stored within the industrial zone, some of which are retained in reservoirs.

Since 1956, the plant has released contaminated cooling water into the river Tom, which ultimately drains into the Ob. Storage ponds at the site are also severely contaminated. The major concern is contamination of the groundwater. In addition to surface discharges, Tomsk-7 is one of two sites in Russia

Activities of waste discharge by Russian reprocessing plants.

Russian reprocessing plants	Environmental discharge	Storage in the environment
Mayak	10^{17} Bq to Techa River. 7×10^{16} in the Kyshtym accident, 1957	About 4×10^{18} Bq in Lake Karachay 8×10^{16} Bq accumulation in reservoirs and surrounding areas
Siberian Chemical Combine Tomsk-7	4×10^{13} Bq in 1993 explosion. Discharge of cooling water to River Tom (1995 inventory in river was 1.4×10^{15} Bq)	1.5×10^{19} Bq underground 5×10^{18} Bq surface storage
Krasnoyarsk Mining and Chemical Combine	Cooling water discharge to River Yenisey; leaking pipeline.	8×10^{18} Bq in cooling water stored in stainless steel tanks 4×10^{18} Bq injected into the ground 2×10^{5} Bq liquid waste in reservoirs

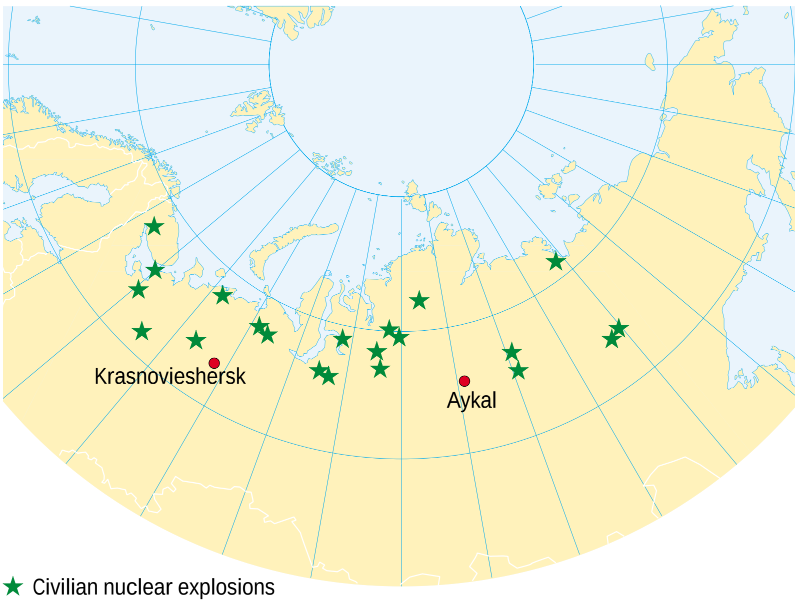
that has used underground injection as a way of disposing of large volumes of liquid waste.

The Krasnoyarsk Mining and Chemical Combine, recently renamed Zheleznogorsk, reprocesses spent nuclear fuel for the production of plutonium and is also a storage site. It routinely discharges cooling water into the Yenisey River and stores waste in ponds, some of which might contaminate groundwater migrating into the Yenisey.

Most of the radioactive waste on the site stems from reprocessing and much of it has been injected into the ground. The liquid waste was transported to the injection site via a reportedly leaky pipeline, which has spilled unknown amounts of radioactive waste along its route. The plant has also stored liquid waste in reservoirs.

How contaminated are the Russian river basins, and how much radioactivity have they supplied to the Arctic? It is difficult to estimate the total flux of radionuclides, especially before 1961. Recent investigations indicate that most of the contamination in Ob estuary sediments comes from global fallout of cesium-137. However, little information on strontium-90 and other mobile radionuclides is available.

From 1961 to 1990, annual mean concentrations in the water show that the rivers have transported about 1.4×10^{15} Bq of strontium-90 to the Kara Sea. Several recent investigations of the tributary rivers and the reservoirs confirm that most of the radioactivity is deposited in the upper Techa River, in the reservoirs, in the Asanow swamp, and in areas contaminated by the storage-tank explosion. Therefore, the Russian reprocessing plants are mainly a local source of radioactivity. The concern for the Arctic is that the storage ponds might fail to contain the waste. A broken dam or an accident at the site could create a sudden large release, while seepage into groundwater would make the ponds a long-term continuous source.



Locations of civilian nuclear explosions in the Russian Arctic.

Underwater weapon tests have contaminated Chernaya Bay

Chernaya Bay (see the map in left column of page 113) is a fjord inlet, connected to the Barents Sea, on the southwestern coast of Novaya Zemlya. The former Soviet Union used the bay to conduct underwater tests of nuclear bombs in 1955 and 1957, and in the vicinity of the bay in 1961. As a result of these detonations, the bottom sediments of the bay are contaminated with elevated levels of radioactive plutonium and cesium, as well as other radioactive isotopes. However, the mobility of radionuclides in sediment is low and may at present only cause insignificant exposure for people. Exposure of biota is unknown.

Today, the inventory of plutonium in Chernaya Bay is similar to other sites of major plutonium contamination, such as the most contaminated areas of Bylot Sound (where a B-52 bomber crashed), and the Irish Sea in the vicinity of the Sellafield reprocessing plant.

Three underground nuclear detonations were carried out by the United States on Amchitka Island in the Aleutian Islands in 1965, 1969, and 1971. These detonations caused radioactive contamination of deep groundwater and rock around the shot cavities. Long-term monitoring activity is planned for this site to 2025. In 1996, above-ground radioactive contamination was detected at the site.

Civilian use of nuclear explosives has led to local contamination

The former Soviet Union used nuclear explosives to carry out mining and construction work. From 1967 to 1988, several such civilian nuclear explosions were carried out underground in the Arctic or close to the Arctic. At three of the sites, accidents led to significant local contamination; see map left.

The nuclear explosion 'Taiga' in March 1971 was the first of 250 planned underground charges to create a canal in an attempt to redirect some northern Russian rivers. The explosion contaminated a 700-meter-long trench 100 kilometers from Krasnovieshersk. Fifteen years after the explosion, the radiation levels were still 0.01 mSv per hour in the most contaminated areas.

On October 2, 1974, an explosive was detonated to construct a dam about 90 kilometers from Aykhal. The 'Crystal' detonation did not go according to plan, and an array of radionuclides was released into the nearby environment. The contamination was not measured until 1990-1993 and there is not enough information to estimate the amount of radioactivity that was released. The report mentions a dead forest but not whether this was the result of radioactive fallout.

'Kraton-3' took place on August 24, 1978, about 120 kilometers from Aykhal at a depth of 577 meters. Its purpose was seismic sounding of the Earth's crust. A few seconds after the explosion, instruments recorded a radioactive release, probably from an incompletely sealed well. The cloud came over a camp and exposed about 80 people. In 1981, there was a large-scale attempt to decontaminate the area. The table below presents some measurements from 1990-92. The reports mention a dead forest at this site, too.

Local contamination from nuclear explosions.

Chernaya Bay underwater bomb tests	3×10^{12} Bq integrated inventory in sediment measured in 1995
Aykhal Crystal detonation in 1974	2×10^4 Bq Cs-137 and 3.5×10^4 plutonium per kilogram soil as measured in 1990-1993
Kraton-3, 1978	Soil samples in 1990-92: strontium-90 less than 10^3 Bq per kg soil, plutonium-239 and 240 less than 2×10^3 Bq/kg soil, cesium-137 less than 10^4 Bq/kg soil up to 4.4×10^4 Bq per kilogram reindeer moss

American aircraft crash spread plutonium at Thule

In January 1968, an American B-52 aircraft carrying four nuclear weapons crashed on the ice in Bylot Sound near Thule, Greenland. The impact triggered conventional explosives, which led to fragmentation of the nuclear weapons on board. The plutonium spread over the ice.

Clean-up crews removed the debris from the crash and the upper layer of contaminated snow. However, it was agreed that not all the plutonium was recovered and some unknown amount fell to the bottom of Bylot Sound. Subsequent environmental studies carried out by Denmark have concluded that approximately half a kilogram of plutonium sank to the underlying sediments. (The Danish study results have not been officially endorsed by the U.S. government.)

Immediately after the accident, the seawater in Bylot Sound had slightly higher levels of plutonium than other places along the Greenland coast. By 1970, the levels were down to background, the most likely explanation being that the plutonium adhered tightly to sediment particles. The map right shows the activity in the sediment.

Cosmos-954 satellite spread radioactive material over Canada

On January 24, 1978, the nuclear-powered satellite Cosmos 954 burned up in the atmosphere over the Northwest Territories of Canada. Early search-and-recovery operations showed that radioactive debris spread over a thousand-kilometer path northeast from Great Slave Lake.

Aerial surveys indicate that about one quarter of the radionuclide inventory the satellite reactor was deposited in the form of millimeter-sized particles over an area of 124 000 square kilometers. The remaining three-quarters probably volatized or dispersed as fine particles in the upper atmosphere. The strontium and cesium on the particles deposited to the surface over a period of several years.

The most exposed people were the recovery personnel, some of whom had individual doses of up to 5 mSv. A member of the public spending several hours near an unrecovered core fragment could have received an effective external dose of about 5 mSv. Handling a millimeter-size particle for several hours would have given a skin dose of 1 mSv. Eating a core particle one month after the accident could give an effective dose of up to 12 mSv to the stomach and intestines. This is more than half the allowable yearly dose for people working with radiation.

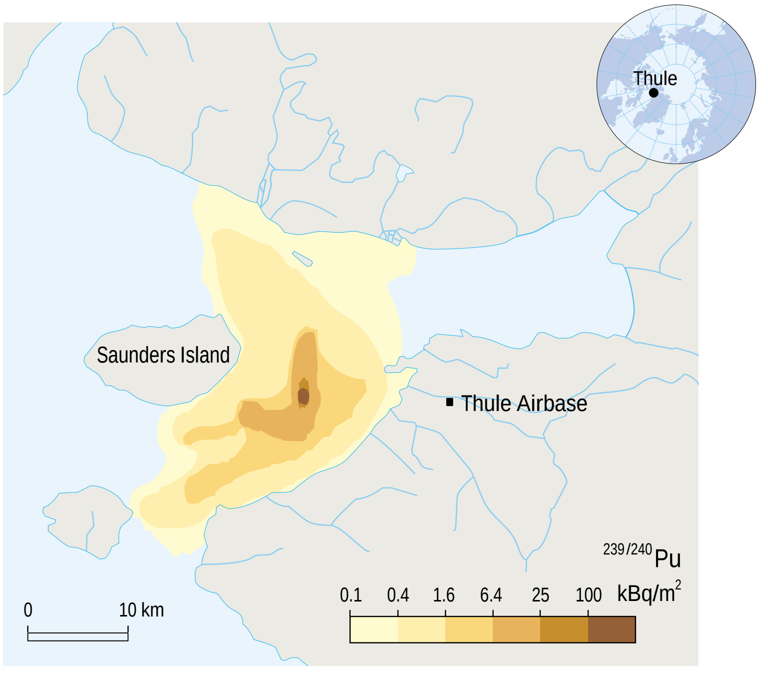
Nuclear power plants have minor routine releases

There are two nuclear power plants within the Arctic: the Kola plant near Polyarny Zori on the Kola Peninsula and the Bilibino plant in the Chukchi region of eastern Russia. In addition, there are nuclear power plants within 1000 kilometers of the Arctic in Sweden, Finland, and Russia.

Measurements and reports from the Swedish and Finnish plants show that routine discharges from nuclear power plants are usually small and that they have not contributed measurable amounts to the current levels of contamination in the Arctic region. Releases from the Russian plants are higher than from Swedish and Finnish plants but within limits that have been set on the basis of international safety standards.

The main concern with nuclear power is the risk of accidents, which is further discussed under *Potential Releases*.

Contamination of sediment after the Thule accident, mean value 1979-91, 10^3 bequerels per square meter.



Ship reactors are poorly documented

Russia has eight nuclear-powered civilian vessels operated by the Murmansk Shipping Company. Their base, Atomflot, is situated two kilometers north of Murmansk. Seven of the ships are icebreakers, used mainly for shipping along the northern coast of Siberia, but also for scientific expeditions and for tourism. The other vessel is a container ship.

Several countries, including the United States, the United Kingdom, France, and China also have nuclear-powered military vessels that can transit the Arctic. Ships in the Northern Fleet of Russia, stationed at bases on the Kola Peninsula, contain approximately 150 nuclear reactors, most of them in submarines.

The routine, operational releases of radioactive material from nuclear-powered vessels are probably small, but documentation is not available.

Levels of radionuclides

The nuclear weapons tests in the 1950s led to increased interest in measuring levels of radionuclides in the environment. Along with studies of the fate of radionuclides from the reprocessing of spent nuclear fuel, these measurements allow the study of time-trends and geographical variations in radioactivity. The levels reflect the input and the rate of radioactive decay, but also the physical and ecological pathways that move radionuclides in the environment.

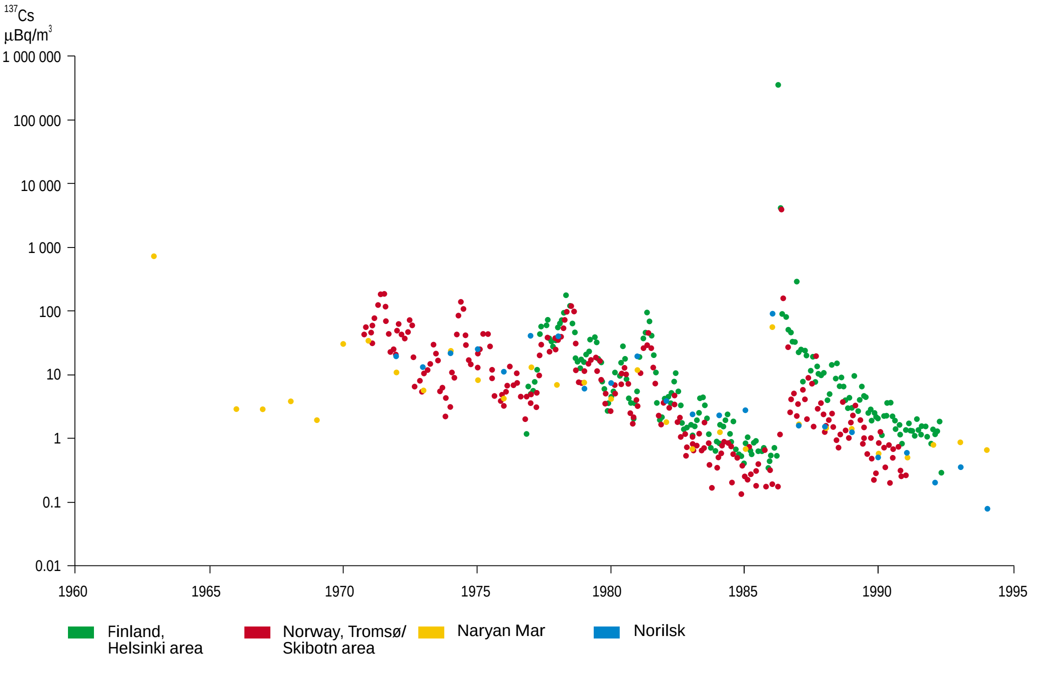
Air concentrations have dropped since the bomb tests ceased

The Arctic atmosphere has traces of radionuclides from bomb tests and from nuclear power plants. The atmospheric tests of nuclear weapons spread contamination mostly in the upper stratosphere. Slowly, the material moves to the lower layer, the troposphere, especially in the spring. The mean residence time for radionuclides in the Arctic stratosphere is approximately one year. Radionuclides from smaller nuclear bombs and from accidents are usually injected into the troposphere, where they stay for only a few weeks.

Measurements of cesium-137 from Tromsø and Skibotn in northern Norway show that concentrations in Arctic air were lower than at nearby non-Arctic locations in Finland; see the graph below. The levels of cesium-137 have dropped rapidly since 1980, when the last atmospheric test was carried out. The Chernobyl accident in 1986, however, again increased the air concentration by several orders of magnitude for a few months. In recent years, the decline in air concentration of cesium-137 has slowed down. The explanation could be resuspension, that winds pick up the radionuclides from the ground.

Deposition peaked in 1963

Long-lived radionuclides in the air will eventually fall to the ground, or be washed out by rain and snow. Deposition levels therefore follow the same trends as the air measurements. Data from Arctic Finland, Greenland, and Arctic Russia all show that deposition peaked in 1963. Until 1980, atmospheric bomb tests kept adding new material, which slowed down the decline in deposition rates. After 1980, resuspension of radionuclides from the ground has also made the decline less rapid than one would expect from a purely stratospheric source. AMAP has made an estimate of the deposition from nuclear weapons fallout, and the relationship between precipitation and deposition. The deposition for 1995 is shown in the map on the top right column of page 113.



Monthly mean concentrations of cesium-137 in air.

Fallout has contaminated terrestrial plants and animals

Radionuclides captured by rain or snow contaminate vegetation and the ground, as does dry deposition. Lichens and mosses, with large surface areas that gather moisture directly from the air, are particularly effective in gathering radionuclides from atmospheric fallout. Lichens are also fodder for reindeer and caribou and thus one of the major routes through which radionuclides reach people.

The levels of strontium-90 and cesium-137 in lichen in Greenland and in Arctic Finland and Russia peaked in 1965-1969; see the graphs at bottom of this page. The Chernobyl accident clearly shows up in Fennoscandian lichen, but is less evident in northeast Russia and hardly detectable in Greenland, Iceland, Canada, and Alaska.

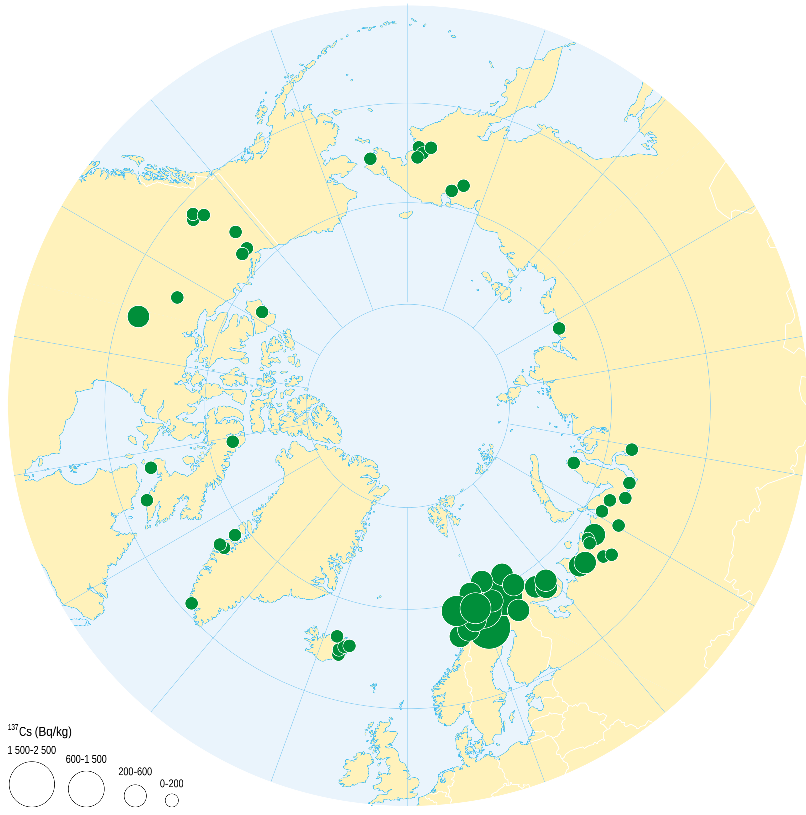
Other plants also take up radionuclides from the soil through their roots. Mushrooms have a propensity for concentrating some radionuclides. People eating mushrooms and berries from contaminated land will ingest some of the material that the plants have gathered from the soil. In some areas, mushrooms are an important component of the local diet.

Grazing animals concentrate radionuclides

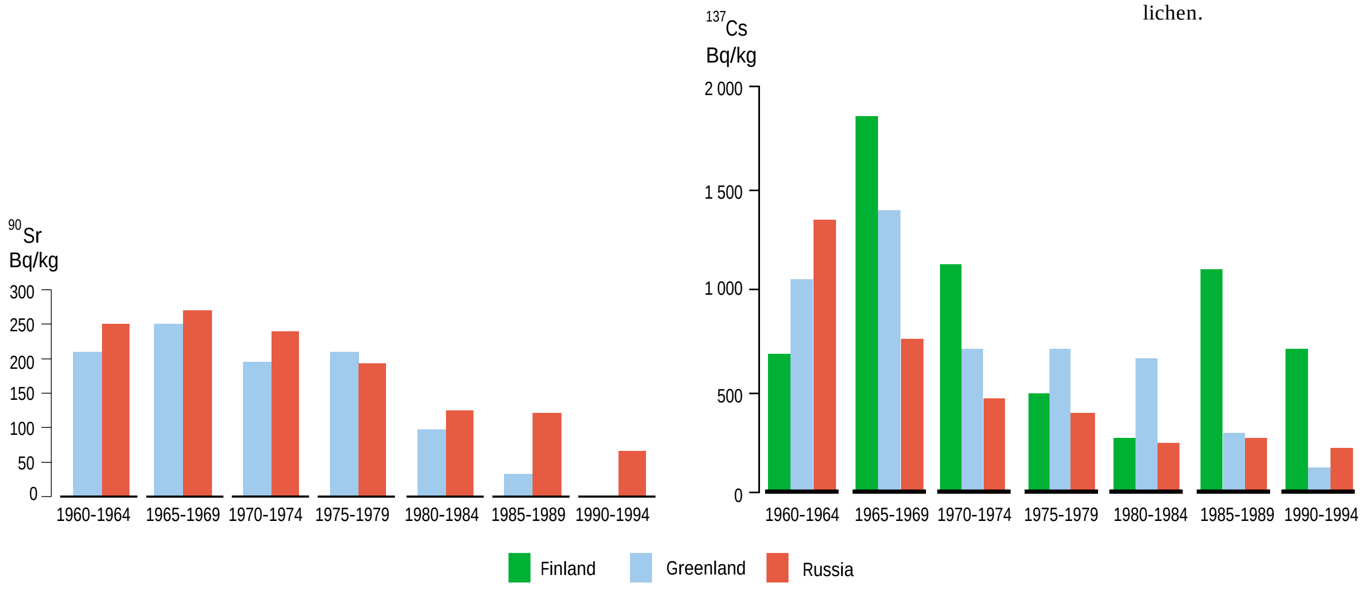
Concentrations of radionuclides in grazing animals reflect their food habits. This is especially evident in the high levels of cesium-137 in caribou/reindeer that feed on contaminated lichen. In the summer, they prefer herbs, which are less contaminated than their winter fodder of lichen.

The concentrations of cesium-137 in caribou/reindeer meat peaked in the mid-1960s. After that, the levels decreased until the Chernobyl accident in 1986, when there was a significant increase in Sweden, Norway, and northwest Russia. The levels have now stabilized again and the future decrease will probably be slow. The geographic variation mirrors precipitation rates, wind direction, and distance from the source, with much higher levels in Norway, Sweden, and the Kola Peninsula than in the rest of the Arctic; see the map above.

Reindeer/caribou meat is an important food source for many indigenous people, and some groups might consume as much as a kilogram per day. The high levels in reindeer/caribou have made their meat the major source of cesium-137 for Arctic people. Sheep and cows feeding on contaminated grass and mushrooms can also pass radionuclides to people via meat, milk, and cheese.



Average activity concentrations of cesium-137 in reindeer/caribou meat 1990-1995.



Five-year average of strontium-90 (left) and cesium-137 (right) in lichen.

Ecological pathways in the Arctic environment

The highest levels of cesium-137 and strontium-90 in the Arctic environment appear in terrestrial animals that graze on long-lived plants. The prime example is reindeer/caribou feeding on lichen. This biological pathway can be contrasted to an agricultural system, where the plants usually grow for less than a year before they are harvested and thus have a much shorter time to accumulate radionuclides. Plowing and fertilizer use also lead to reduced uptake in agricultural systems. Moreover, agricultural plants rely more on their roots to take up moisture and nutrients than on the parts that are exposed to the air, and root uptake of radionuclides is usually less efficient than air uptake. However, in forests, bogs, and mountain pastures, root uptake may be very important for radioactive contamination of berries and indirectly of animals through fodder. Mushrooms often have relatively high uptake of radiocesium through their root systems.

Efficient transport of radionuclides from fallout to lichen to reindeer/caribou, along with uptake in other natural food products such as mushrooms, freshwater fish, and berries, leads to Arctic people receiving higher doses of cesium-137 from fallout than people almost anywhere else in the world. The doses from naturally-occurring radionuclides are also higher for people who rely heavily on caribou or reindeer in their diet.

The transport of radionuclides in the marine food web is very inefficient. One explanation is that they are diluted in huge water masses, another that the high content of salt and stable isotopes of cesium and strontium compete for the same sites of uptake as the radionuclides. Marine animals and people living off marine food sources have the lowest levels of cesium and strontium in the Arctic.

Lakes and rivers provide route to fish and people

Freshwater systems such as lakes and rivers accumulate contaminants from the air and from the soil. Strontium-90, in particular, ends up in the water, since it does not adhere strongly to soil particles or to sediment. Some Russian rivers are also contaminated directly by discharges from nuclear facilities. There is a lack of data from Russian rivers before 1960. It is possible that the highest levels in the Ob River occurred prior to 1960 because of the releases from Mayak between 1949 and 1956. The levels in most other rivers peaked in the mid-1960s. The graph below shows levels in freshwater at some sites in Russia and Finland.

The radionuclide levels in fish depend on many factors. For example, nutrient levels, size of the catchment area of the lake or river, and water volume play a major role in the uptake of cesium-137. In lakes with high biological productivity, the radionuclides are diluted, and the concentration in each fish is lower than in nutrient-poor lakes. The levels also depend on the feeding habits of the fish. After Chernobyl, the peak came first in plankton-eating fish, low in the food chain, and later in predatory fish such as pike. Levels in fish can be similar to those in sheep and wild animals, but normally lower than reindeer meat and some mushroom species.

Glaciers are reservoirs of old fallout

Measurements of strontium-90 in drinking water in Greenland show that storage in ice can slow down cleansing from the environment. In northern Greenland, most drinking water comes from ice and snow. Here, the levels of strontium have gone down much more slowly than in southern Greenland, which relies more on surface water. However, even the highest levels today are lower than in the 1960s.

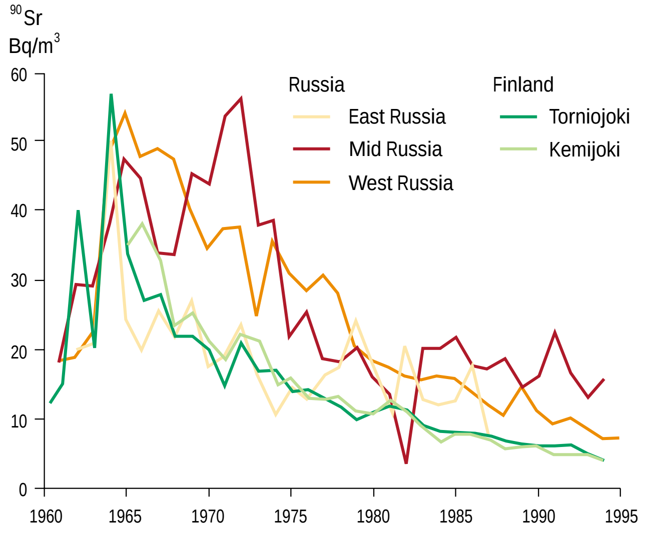
Currents transport radionuclides around the Arctic Ocean

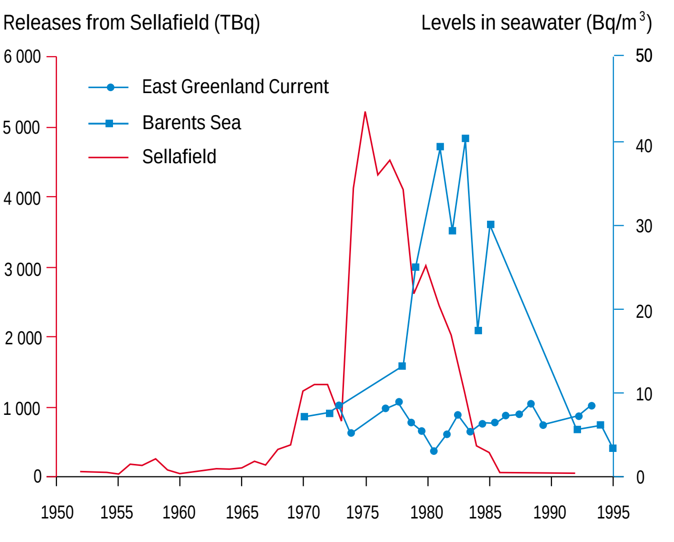
A major direct input of radionuclides into the marine environment has been from European nuclear reprocessing plants, particularly Sellafield on the shore of the Irish Sea. Currents transport the material along the Norwegian coast and into the Arctic Ocean. After six to eight years, some of the contamination leaves the Arctic by way of the East Greenland Current, but much of it stays in the Arctic Basin much longer.

Environmental radiocesium levels have been measured since the early 1970s. As can be seen in the graph below, the releases of cesium-137 from Sellafield are virtually mirrored in the levels found in the Barents Sea after a transport time of four to five years. The peak in concentration in the early 1980s is probably the highest level that has ever occurred in that area of the ocean. The Chernobyl accident in 1986 added cesium to the Arctic Ocean and continues to do so via outflow from the Baltic Sea.

▶ Releases of cesium-137 from Sellafield nuclear reprocessing plant (10^{12} bequerels per cubic meter) compared to activity in the Barents Sea and East Greenland Current (bequerels per cubic meter).

▼ Yearly average concentrations of strontium-90 in Russian and Finnish rivers.

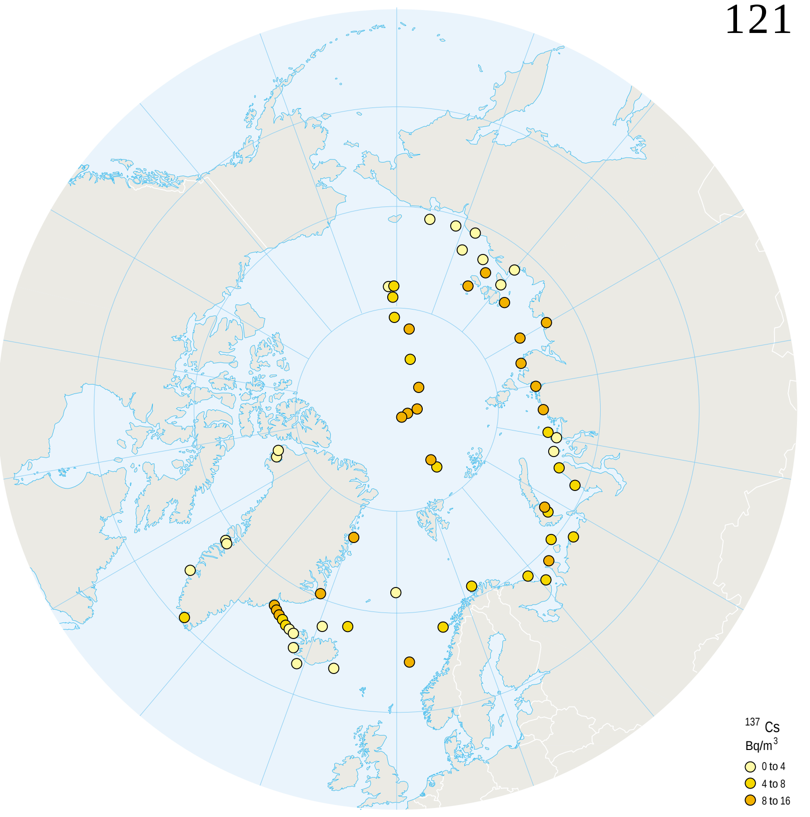




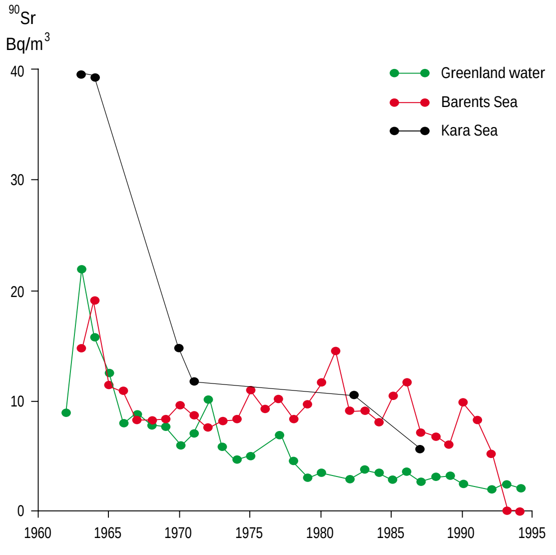
The map to the right shows the recent levels of cesium-137 in seawater around the Arctic.

Strontium-90 has been measured in surface seawater collected around Greenland and the Barents Sea; see the graph below. Over the past 35 years, levels in the waters around Greenland have decreased, with approximately half removed or decayed every 13.5 years. This value is probably representative for the Arctic Ocean as a whole.

The levels in fish, seals, and whales collected in Greenland waters and in the Barents Sea since the early 1960s are very low, especially compared with levels in caribou and reindeer. The reasons are that salts in the seawater prevent plants and animals from taking up the radionuclides and that the oceans are so vast that the material is diluted. Consequently, Arctic people living off the sea have low body burdens of cesium-137.



Activity concentration of cesium-137 in seawater in 1994.



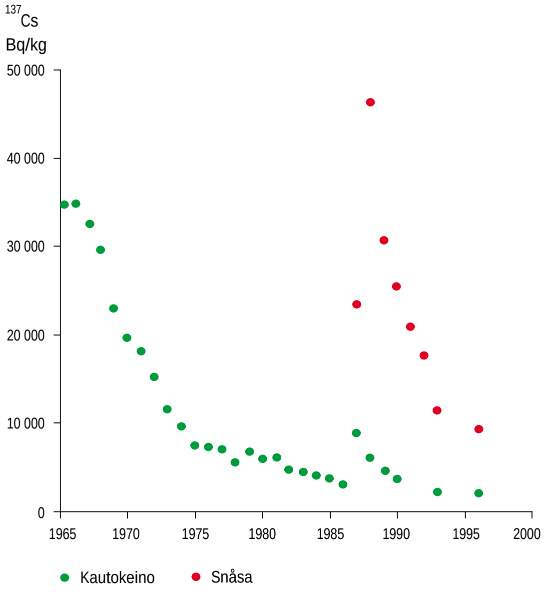
Time trends of activity concentrations of strontium-90 in seawater.

The body burden in people has decreased

People are exposed to atmospheric fallout directly by breathing the air, but also by eating plants and animals that have gathered contaminants and by drinking water that has been contaminated by fallout.

How much of the radionuclide contamination in the environment ends up in people? The answer depends to a large extent on what we eat. Reindeer meat, mushrooms, and fish from nutrient-poor lakes are some of the foodstuffs that contribute most to human body burdens.

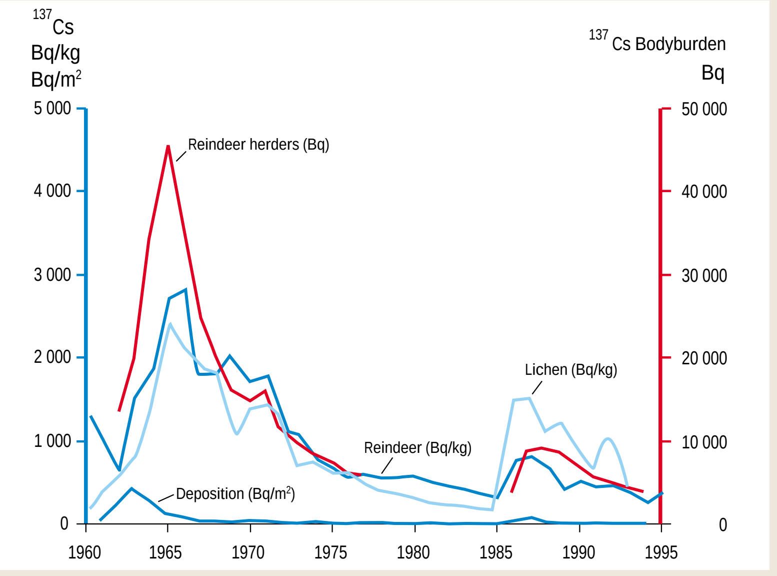
The highest levels of cesium-137 in people were recorded in the mid-1960s; see the figure bottom left. For the following 20 years, the human body burden decreased by a factor of three to seven. However, in 1986, the Chernobyl fallout changed the trend in areas directly affected by the accident, and in small areas mainly in Norway and Sweden, higher levels than in the 1960s have been observed.



Time trends of body burden of cesium-137 in two groups of Norwegian reindeer herders.

ERIK ANDERS WESTERLUND

Measuring body burden of radionuclides by keeping a detector on the knees and bending over with the body. Kautokeio, Norway.



Do radionuclides behave differently in the Arctic?

Information about radioactive contamination in air, water, plants, animals, and people can be used to calculate how effectively radionuclides are transferred within the food chain in the Arctic environment. Such calculations have previously been made mostly for non-Arctic areas, and there have been questions about how well they apply to northern vegetation patterns and eating habits. For example, what happens if people or animals rely heavily on mushrooms one year and hardly eat any the next, because the crop is poor? This could easily change the body burden of radionuclides without any changes in deposition rates. It is also possible that reindeer one year might be fed with hay because of a shortage of lichen, which would reduce their intake of cesium-137.

AMAP has compared a non-Arctic-based assessment of radiocesium transfer to people with an assessment where specific Arctic conditions are taken into account. The comparison shows that for the general population the transfer in the Arctic is five times higher than in temperate areas. However, for special groups of the population consuming a large proportion natural food products, the transfer could be more than 100 times higher than in temperate areas. The Arctic is thus more vulnerable to radioactive contamination than temperate areas.

The graph summarizes the relationships between cesium-137 in deposition, lichen, reindeer meat, and the human body for northern Finland, as an example of real rather than calculated transfer. The AMAP assessment has provided similar data for Arctic Norway and Arctic Russia and, partially, for Greenland. The main conclusion is that there is a geographic variation in the land-based food chain deposition–lichen–reindeer–human. The efficiency of radionuclide transfer depends on the density of lichen growth and on the food habits of reindeer and people.

Individual exposure and food habits

Information about levels of radioactivity in the Arctic environment can be used to assess doses of radiation and the consequent risks to human health. If the deposition levels are representative, if all pathways are taken into account, and if the assumptions about food habits and lifestyle are correct, this dose should reflect the body burden for people.

Natural radiation dominates the external exposure

External exposure refers to radiation that is emitted outside the body. The external exposure from natural radiation varies little over time and is about 0.85 mSv per year for cosmic rays and terrestrial gamma rays combined. In areas with high natural radiation, the dose can be higher.

Anthropogenic sources add to the load. For the 60-70° N latitude belt, where the majority of the Arctic population lives, the additional lifetime dose is about 0.6 mSv. This includes fallout from nuclear weapon tests and Chernobyl. The levels decrease from south to north because of decreasing amounts of precipitation. People in areas with high levels of fallout from Chernobyl will have higher doses. The estimated external dose commitments over a lifetime for the Norwegian, Swedish, and Finnish average populations are 1.0, 0.6, and 1.7 millisieverts respectively, but Arctic populations were generally less exposed to the Chernobyl fallout because of the fallout pattern. The range in total lifetime external dose for Arctic populations will be 0.6 to 1 millisieverts from all man-made radioactivity.

The internal dose varies with diet

The internal dose comes from radionuclides we breathe in or take up from food and water. Natural radioactivity gives an internal dose via potassium-40 in the body and from radon gas and its decay products. For Arctic regions, the average is 1.5 mSv per year but may be higher in areas with a high release of radon from the ground into dwellings. The annual dose from radon is 0.5 to 4 millisieverts. However, exposure to radon is generally lower in the Arctic than in temperate areas. Caribou/reindeer meat that has gathered naturally-occurring radioactive polonium can also add to the load, giving a dose as high as 10 mSv per year for some groups.

The most important man-made radionuclides for internal exposure are strontium-90 and cesium-137. The dose depends primarily on what we eat. AMAP has therefore divided the risk assessment among different groups of people according to food habits. In the AMAP assessment, caribou hunters in Canada have the highest intake of radionuclides from both natural and anthropogenic sources. The high intake stems from the fact that people in the selected community used in the calculation are projected to eat as much as one kilogram of caribou meat per day. This may also be accurate for other indigenous communities in the Arctic countries.

The exposure from man-made radionuclides is calculated as a dose commitment from 1950 to infinity. The dose commitment for cesium-137 is about 150 mSv for the Canadian community that relies most heavily on caribou meat in its diet. This is four to five times higher than the average dose commitment for all Arctic indigenous people during the same time period. The Arctic indigenous people who rely heavily on terrestrial food products (especially reindeer meat) have about 50 times higher exposure than average members of the general population.

Most of the dose commitment stems from fallout passed on to people via lichen and reindeer between 1960 and 1994. The future dose will only make a minor contribution to the total dose.

The lowest anthropogenic doses are those in Greenland and Iceland, mainly because marine foods are more important components of the diet.

Cultural differences reflect importance of various foods

Which foods are important with respect to radiation dose? The answer varies depending on what we prefer to eat and on how local ecology governs the transfer of radionuclides in the food web. Knowing the major sources in different cultures is an important base for making risk assessments and giving dietary advice.

In Canada, caribou meat is the predominant source of cesium-137. In contrast, the Swedish intake of cesium also comes from freshwater fish, mushrooms, and other products. Mushrooms are also an important source in Finland and Russia. A unique source in Norway is goat cheese.

In temperate areas, radioiodine in milk is a significant source of radioactivity immediately after an accident. This source is not as important in the Arctic because of relatively low milk production.

The left panel of the graph below gives a picture of the relative importance of different foodstuffs for the average population and the right panel for selected high-risk groups in different regions. The table on top of this page gives a brief description of the selected groups.

Caribou/reindeer is the dominant source for all the selected groups.

Selected groups used for dose estimates.

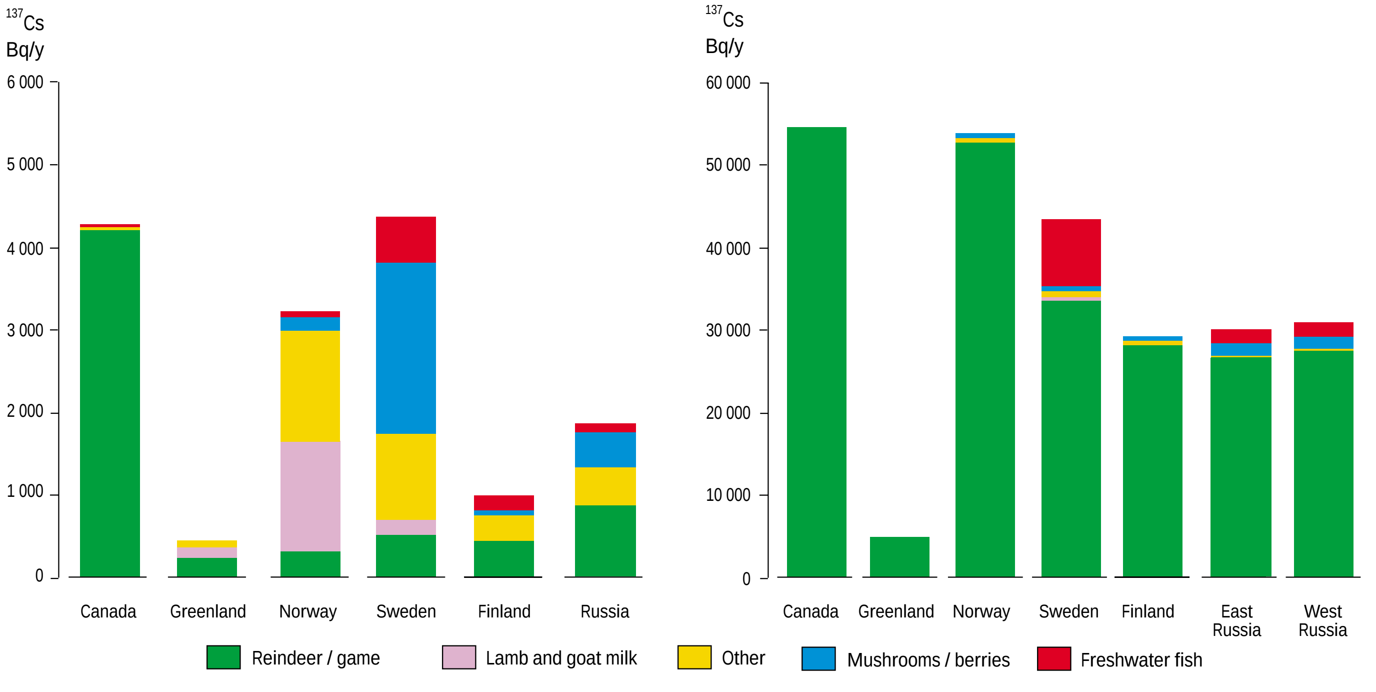
Finland	Adult Saami reindeer breeders
Greenland	A hypothetical group assumed to consume only reindeer meat rather than imported meat and lamb; only freshwater fish rather than marine fish; only local berries rather than imported fruit
Northern Canada selected group	Diet characteristic of Old Crow. This community relies heavily on caribou meat
Russia group 1	Reindeer breeders (east and west Russia, selected populations)
Russia group 2	Rural populations and urban populations not involved in reindeer breeding (average population)
Northern Norway	People associated with reindeer breeding
Arctic Sweden	Reindeer herding population with relatively high consumption of reindeer meat and freshwater fish

Future accidents and potential releases

Large amounts of radioactive material are contained in nuclear power plants, in deposits for spent fuel, in weapons, and in nuclear-powered vessels. Reactors and containers dumped on the seabed are another potential source of radionuclides. What are the risks that accidents will spread some of this material in the Arctic environment?

Power plant accidents can have severe consequences

Preventing accidents in nuclear reactors has been the main objective of nuclear safety since the beginning of the nuclear era. However, the Chernobyl accident in 1986 showed that safe-



Left. Intake of cesium-137 in various foodstuffs by the average populations in the Arctic countries, bequerels per year.

Right. Intake of cesium-137 in various food stuffs by selected groups in the Arctic countries, bequerels per year. Note that the intakes are approximately tenfold greater than for the average population.

ty standards were not stringent enough in all countries to prevent large-scale releases of radioactive material, and that nuclear power can indeed threaten the health of thousands or millions of people. Since the accident, safety has been tightened in most countries, but the regulations, as well as their implementation, differ from country to country.

The primary risk in reactor accidents is associated with releases of the large amounts of fission products that the plants generate. Safety precautions aim at creating barriers between the fuel and the environment, even if something goes wrong in the reactor. Moreover, the nuclear process should be self-controlling, so that it shuts down automatically. For example, technical guidelines in some countries stipulate that even if there is an accident, no one in the surrounding population should receive a dose of radioactivity greater than 5 mSv from external sources.

The Nordic Nuclear Safety Research Programme has compared how well western European plants and reactors in the former Soviet Union fulfill the demands of modern safety requirements. One of the conclusions is that many eastern reactors built before the 1980s lack the necessary containment capability. This is further emphasized by information AMAP has received about the Kola Nuclear Power Plant, where the present technical and protection devices are not adequate to retain the radioactive products inside the plant in case of a severe accident. The consequences of an accident that damages the core could thus be worse than those stipulated in the safety standards.

The probability of severe accidents is difficult to estimate. AMAP has only attempted to look at some of the consequences of potential accidents, not the probability of an accident occurring. The first scenario is a serious accident in one of the reactors in the Leningrad Nuclear Power Plant, about 1000 kilometers south of the Arctic Circle. The plant is of the same type as Chernobyl, but with some improvements. The release of radioactive material is therefore assumed to be somewhat smaller.

The conclusion is that there is probably no risk in the Arctic area of acute, deterministic health effects (radiation sickness) from nuclear power plants situated farther than 1000 kilometers from the Arctic Circle. The dose from deposited gamma emitters in the first year would be on the order of 0.01 to 1 millisieverts. Nevertheless, it is possible that contamination of the food pathways (lichen, reindeer, mushroom, freshwater fish, etc.) would call for protective actions to reduce the health consequences of the accident. The food pathway depends on the season in which the accident occurs and on local habits, but doses from local foods in the first year would be higher than from deposited gamma emitters. It has not been possible to do an assessment that includes internal dose to the Arctic population but this would clearly be of great importance in future studies.

The second scenario is an accident in the Kola Nuclear Power Plant. Calculations show a high likelihood that the doses would be less than 1000 millisieverts at distances greater than 5 kilometers from the plant during the first 24 hours, and less than 100 millisieverts at distances greater than 30 kilometers. The external and inhalation doses contributing to long-term health risks would be similar to those at other sites. However, the contamination of the terrestrial environment would have much more severe consequences than at lower latitudes because some plants and animals are highly effective at gathering radioactive contaminants and concentrating them in the food web. Again, the present assessments have not included the long-term internal dose, which may be significant. This is a priority in future studies.

There is no information about the probability of an accident of this severity occurring. If it does, however, there will be a need for protective measures against acute health effects for people living close to the reactor. There will also be a need to protect people in an area of several thousand square kilometers around the plant against delayed health effects, such as increased risks of cancer. Acute health effects are probably not expected at distances of more than 5 to 10 kilometers from the plant, even without protective measures.

Nuclear vessel accidents pose a risk for the personnel

There are many nuclear-powered vessels in the Arctic and these pose a significant risk for accidents. Several accidents with releases of radioactivity have already occurred. The experience from these shows that the acute threat is specifically to the personnel involved, who can receive radiation doses high enough to cause radiation sickness. Environmental contamination has been limited to the local area, and the radioactivity in water, sediment, and bottom-dwelling organisms is now down to background levels.

A major problem for the future is the disposal of old nuclear submarines. As of 1996, about 90 nuclear submarines had been taken out of service from the Northern Fleet of Russia, of which only one fourth have been defueled. The rest are stationed at military bases at different places on the Kola Peninsula, waiting to be defueled and dismantled. An additional number of submarines will be decommissioned by 2010. At the same time, it is known that the storage sites for spent nuclear fuel are overfilled and in some cases in poor condition.

Almost all the radioactive material aboard a submarine is in its reactor, and the safety

Decommissioning of nuclear submarines creates serious technical and ecological challenges.

assessment focuses on the defueling process. An analysis made for AMAP by the Russian Federation shows that accidents anticipated in the design of the defueling process do not lead to any contamination beyond the zones that are designated for defueling operations. The risks to the public relate to accidents that have not been taken into account in designing containment and safety procedures. The largest design accident involves two or more control rods being ejected from the core of the submarine reactor, which could lead to a nuclear reaction that would melt the core of the reactor. People within the defueling zone could suffer severely, and some might die from the high immediate exposure. There will be a need for protective measures, especially against the effects of radioactive iodine releases.

In spite of the severity of this design accident, the conclusion given along with the Russian estimates is that the public beyond the containment zone would probably not be at great risk. The dose would not exceed 5 mSv, though under certain wind conditions it might be necessary to evacuate nearby towns because of higher doses. There is a need for further work on such assessments.

Sunken nuclear submarine is no immediate threat

On April 7, 1989, the Russian nuclear submarine *Komsomolets* caught fire and sank southwest of Bear Island in the Norwegian Sea. The wreck rests at a depth of about 1650 meters.

This submarine contains a nuclear reactor and two torpedoes with mixed uranium-plutonium warheads. Small amounts of radionuclides have already leaked out of the reactor compartment, but the likelihood of a large-scale release from the *Komsomolets* is small. Even if the containment material corrodes with time, most of the activation products will have decayed before they are released. Studies in the surrounding area show only minor contamination from the submarine.

The uranium and plutonium from the warheads will also be released with time as the casing is breached. However, the contribution of uranium to the surrounding water will be insignificant in the context of the natural uranium content of seawater. Plutonium has high affinity for particles and will most likely be retained in the sediments close to the wreck.

Russian, NATO, and Norwegian authorities each have made independent assessments of the threat posed by the Komsomolets accident. The conclusion from these studies is that the maximum levels of contamination in the water will not exceed 2.7 Bq per liter. The zone of contamination will be largest if the radioactive material is released rapidly, and will be more than 600 square kilometers. If the material is released slowly, the zone will not exceed 200 square kilometers. If the release is rapid, the contamination will persist no longer than half-a-year, whereas a slow release will contaminate the area for four to five years. The concentration of radionuclides in the bottom sediment will increase as the activity in the water decreases.

One of the concerns is that animals feeding on the bottom sediments will transport radionuclides to the surface and thus into the food web. Calculations show that the edible parts of fish might accumulate a plutonium content of 0.1 to 6 becquerels per kilogram.

Making some assumptions about how long the fish stay in the area and how much fish people eat, the most critical population group should receive no more than 0.03 mSv per year. The threat posed by radionuclides from the wreckage of the *Komsomolets* submarine is therefore minor. The studies also show that releases of radionuclides into the marine environment give rise to much smaller human exposures than similar releases into the terrestrial environment.

Dumped nuclear waste

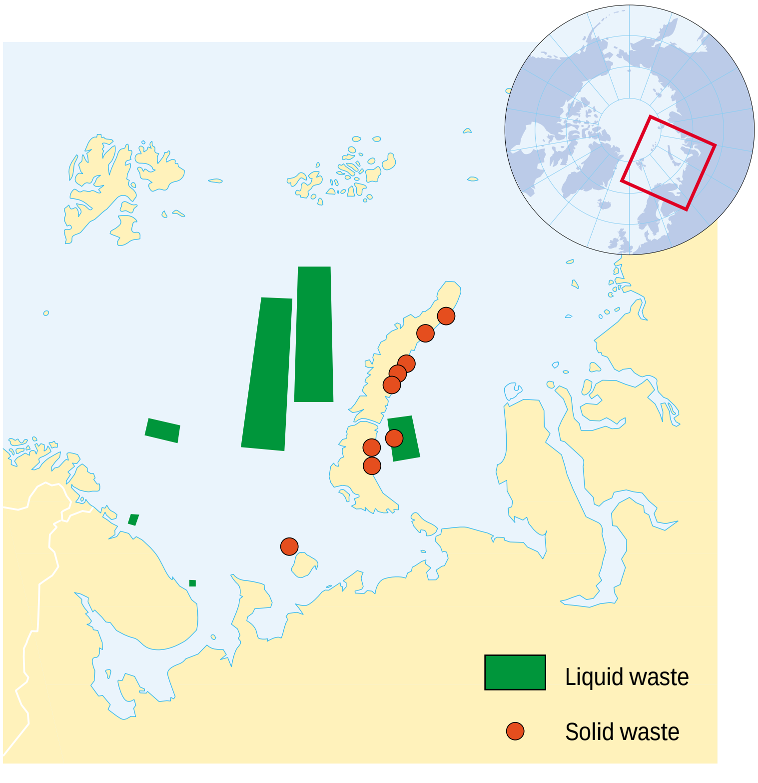
The Soviet Union dumped high, intermediate, and low level radioactive waste in the Arctic Seas during the years 1959-91, including six nuclear submarine reactors and a shielding assembly from an icebreaker reactor containing spent fuel.

The solid waste and the nuclear reactors were dumped in the Kara Sea and in the fjords of Novaya Zemlya at depths of 12-135 meters, and in the Novaya Zemlya trough at a depth of 300 meters; see map below. The liquid, low-level waste was dumped into the open Barents and Kara Seas. At the time of dumping, experts estimated that the spent nuclear fuels represented a total activity of 8.5×10^{16} becquerels.

From 1992 to 1994, a joint Norwegian-Russian expert group has used sonar and a remotely operated vehicle in an attempt to find and examine the waste. The exploratory cruises also took samples of water, sediments, and biota in the area. The results show that there is no significant contamination of the Kara Sea. In fact, the levels of radionuclides in the water are lower than in many other marine areas, such as the Irish, Baltic, and North Seas. However, higher levels of radioactivity in the immediate vicinity of the waste show that there is local contamination at the dump sites.

The major risks are for the long term, after the containment corrodes. To evaluate the amounts of radioactivity that could be released and the risks to people, the International Atomic Energy Agency has established a special project, the International Arctic Seas Assessment Program. Its conclusion is that, on radiological grounds, remediation is not warranted. Controls on the occupation of beaches and the use of coastal marine resources and amenities in the fjords of Novaya Zemlya must, however, be maintained.

Sites in the Arctic used by the former Soviet Union for dumping radioactive waste.



Accidents with nuclear weapons pose the greatest threat

Platforms that carry nuclear weapons may have accidents. Although many weapons are designed not to explode even if there is an airplane crash or a fire in a submarine, not all weapons construction adheres to 'safe design' practices, and a recent report reveals that only good fortune has prevented serious accidents in the past.

If a nuclear weapon explodes accidentally, it will probably not lead to a full-scale detonation. The releases will be predominantly localized. The world-wide release may vary from almost zero to a maximum of 10^{15} becquerels of cesium-137 and strontium-90.

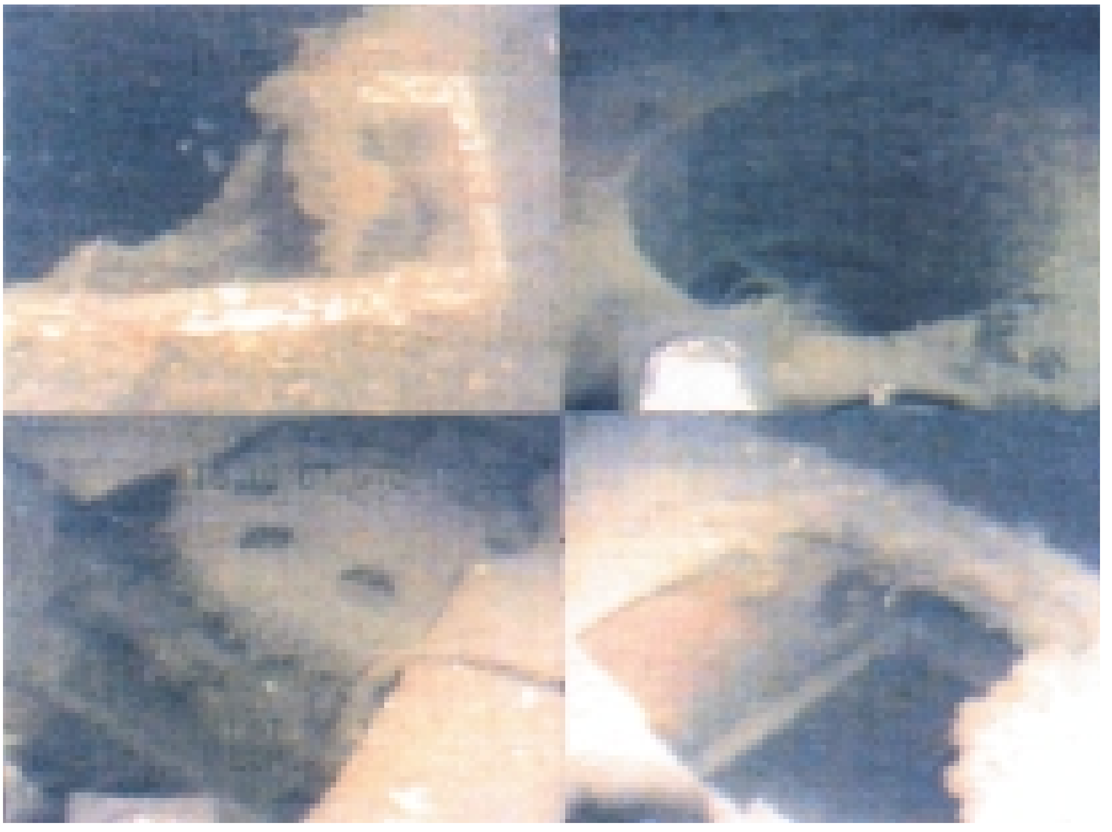
A more dangerous situation occurs if nuclear proliferation is not prevented. New nuclear nations may not be able to make 'safe' designs. The worldwide exposure from an accident could amount to 10^{16} becquerels of long-lived isotopes.

Summary

The risks connected with radionuclides in the Arctic are best described by dividing the assessment into two parts: past and present contamination, and potential releases from stores and accidents.

Past and present contamination

The Arctic terrestrial system is more vulnerable to radioactive contamination than temperate areas. The exposure of people in the Arctic and subarctic is, for the general population, about five times higher that what would be expected in a temperate area. However, for part of the population the exposure could be more than 100 times higher than expected for similar fallout in temperate areas. The major sources of anthropogenic radionuclides in the Arctic are global fallout from nuclear bomb tests, releases from European nuclear fuel



JOINT NORWEGIAN-RUSSIAN E. G.

Some of the radioactive-waste containers dumped in Stepovogo Bay.

reprocessing plants, and fallout from the Chernobyl accident.

In addition, discharges from Russian reprocessing plants, underground and underwater nuclear detonations, stores of spent fuel, and dumped waste have contaminated local areas. These latter sources are currently only of minor importance in relation to health risks associated with radioactivity in the Arctic.

The levels of radionuclides in the Arctic attained their peak values in the 1960s, primarily as a consequence of atmospheric nuclear weapons tests.

Arctic people receive their major radiation dose from previous weapons explosions, the fallout from which is ingested through terrestrial and freshwater pathways. However, in some areas of Fennoscandia and western Russia, Chernobyl fallout contributes a comparable dose to that of weapons fallout.

People with a diet high in terrestrial and freshwater foodstuffs receive the highest radiation exposures, from both natural and anthropogenic radionuclides. These foodstuffs include caribou/reindeer, freshwater fish, goat cheese, berries, mushrooms, and lamb. People who eat mostly marine foodstuffs have the lowest doses.

Polonium from caribou/reindeer dominates the natural radiation dose, whereas cesium-137 from an array of terrestrial food sources is the most important anthropogenic radionuclide.

The highest average exposures to individuals in indigenous Arctic populations are in Canada and the lowest in Greenland. Consumers of large amounts of caribou/reindeer can have radiation exposures 50 times higher than the average members of their national population.

Potential releases

A large number of radioactive sources are present in the Arctic: storage of spent nuclear fuel, decommissioned nuclear submarines, nuclear reactors on land and on board ships, and contained sources in the environment. This concentration of potential sources and the risks for releases cause concern, especially together with the fact that the uptake and transfer of radionuclides, and thereby the potential exposure of people and biota, is much higher in the Arctic terrestrial environment than other areas.

Therefore, international guidelines on radiation protection, nuclear safety, and nuclear waste management must be rigorously observed by all Arctic states. Moreover, there is a need for high-standard risk assessments, including long-term dose estimates for potential releases of radionuclides from all potential sources within the Arctic.