Chapter 7

Potential Accident Scenarios

7.1. Introduction

This chapter considers the nature and scale of consequences arising from potential accidental releases of radioactivity into the Arctic environment from sources under human control. The sources considered to warrant accident assessment are those described in Chapter 2. All scenarios are described in more detail in the relevant literature. Relevant accidents and subsequent impact assessments are reviewed and, where possible, extrapolated to provide perspectives on the consequences of accidents associated with other sources. The chapter concludes with recommendations for further impact assessments.

Scenario analysis begins with a consideration of the different possibilities for sequences of events and processes (such as containment failure mechanisms) that can lead to radionuclide release. These depend upon the specific management and engineering features of the facilities under consideration. The release mechanisms and characteristics are important determinants of the environmental and human health impacts. Relevant variables might include: isotopic composition; amounts of each isotope released; physical-chemical form of release (gas, solution, aerosol, etc.); time development of the release; release point and plume height; and the energy content of the release.

The scenarios discussed here were not necessarily developed for the same purposes as the AMAP assessment. They are illustrative of selected aspects of the possible consequences of radionuclide release rather than representative of comprehensive risk or scenario analyses for the Arctic.

The radionuclide release information provides input to a radionuclide transport model that is used to predict the subsequent environmental distribution of contamination. For accident scenarios resulting in releases to the atmosphere, the assumed (or actual, if assessing the consequences of past accidents) meteorological data are very important as they can radically affect the degree of atmospheric dispersion. Similarly, for releases to the aquatic environment, the hydrodynamic characteristics of the receiving environment are equally important. Distribution following releases to the ground are strongly dependent upon surface geology and hydrology. The radiation characteristics of the radionuclides and their environmental mobility are also important determinants of the magnitude of the consequences following release. The receiving environments themselves also influence the scale of the consequences, since some are more susceptible to incorporating radionuclides into human exposure chains than others, as discussed in Chapter 4 (NRPA, 1999; Skuterud *et al.*, 1999). Radiation doses to humans and other biota are assessed using assumptions about the ways in which they interact with contaminated media. Finally, the impact on human and environmental health is assessed using assumptions relating radiation doses to health impacts. Such information is essential for risk management.

7.1.1. Risk management

Risk management includes the analysis of accident scenarios and consequences and, where possible, an assessment of the probabilities of accidents and their consequences. Sources may occur within the Arctic, in which case these ‘point sources’ require analysis, and outside the Arctic. The potential for accidents occurring outside the Arctic to contaminate the Arctic environment depends on the dispersal characteristics.

Generally, the larger the inventory of radionuclides, the greater the hazard. In most cases, the inventory in Becquerels (Bq) is well established owing to the application of well-proven technology and associated regulatory requirements. However, in some cases, the information may be less complete, as for example, in the case of old waste storage facilities for which information is limited.

The risks associated with hazardous sources may also be modified by measures to control the source term. That is, consideration of the risks must address both the scale of the consequences and the likelihood of their occurrence. Thus, while a very large source term may present the greatest hazard (potential for harm), measures to reduce the chances of release may reduce the risks to a tolerable level (HSE, 1988). Nuclear safety initiatives to reduce the likelihood of accidents are discussed in Chapter 6. Other ways of reducing risk include measures to reduce the consequences of potential accidents. Risk management must account for both. A simple example is the case of spent nuclear fuel, which is a significant radioactive source term. Left on the surface with limited containment, the chance of releases into the environment, before radioactive decay has reduced the hazard significantly, whether as a result of waste container degradation or by human sabotage, is relatively high. Deep disposal is considered to reduce the risks by reducing the likelihood of gross and acute environmental releases. See, for example, discussions concerning high level waste disposal in Japan (JNC, 2000).

Another aspect of risk management is the introduction of measures to mitigate the impact of accidental release. International guidance concerning countermeasures is provided by the International Commission on Radiological Protection (ICRP, 1992). Examples include evacuation, advice to remain indoors, and the distribution of iodine tablets. Interventions should be based upon evaluations of their benefit, expressed as averted doses, and disbenefits, especially those of an economic or social nature. Assessments of the consequences of accidents should take account of the planned emergency response in the early and latter phases of the accident; in the long-term the effects of clean-up measures may be important, see Brown *et al.* (2000).

7.1.2. First AMAP assessment

The first AMAP assessment concluded that of greatest concern were the possible accidents associated with: nuclear power plant (NPP) operation; nuclear weapons handling and storage; decommissioning of nuclear submarines; and the management of spent fuel from nuclear-powered vessels.

Consideration is given to the consequences of each of these types of accident. Also, to additional or modified potential accident sources, particularly reactors in sunken submarines such as the *Kursk* (Amundsen *et al.*, 2002a) and the management of damaged spent fuel, as stored on the *Lepse* (NRPA, 2001).

7.2. Land-based nuclear power plants

Operational land-based NPPs in the Arctic include the Kola and Bilibino NPPs. The Kola plant comprises four VVER-440 pressurized water reactors each with a design output of 1375 MW(th) and 411 MW(e). The Bilibino NPP is located in the Chukotka region in eastern Russia and comprises four light-water cooled, graphite-moderated reactors each of output 62 MW(th) and 12 MW(e).

Owing to design differences, a direct comparison of the risks posed by the Kola and Bilibino NPPs is not straightforward. Risk assessments need to include a consideration of the engineered features and management at the respective plants, but for assessing significant releases, there are obvious differences owing to the reactors at the Kola NPP being more than 20 times larger.

The power plants on the Kola Peninsula clearly represent the major potential reactor accident source within the Arctic.

7.2.1. Accident scenarios and consequences for the Kola NPP

The Kola NPP is located in Murmansk Oblast in northwest Russia and severe accidents at the site have the potential to substantially contaminate both northwest Russia and northern Fennoscandia. Studies by Stokke (1997), including a review of the Kola reactor safety systems, have provided detailed information on the Kola plant and its reactor inventories.

7.2.1.1. Initiating events

Initiating events that may lead to core melt sequences in pressurized water reactors are generally grouped into three classes: loss of coolant accidents (LOCAs), transients, and common cause initiators (CCIs).

LOCAs may be initiated by large leaks or breaks in the primary circuit, which in turn may be caused by mechanical failure (such as pipe breaks, fire, and corrosion) resulting from poor maintenance. The loss of cooling may take place early in the sequence or at a later stage. Early loss of cooling is potentially the most dangerous as it gives little time to re-establish cooling and because significant decay of short-lived radioisotopes will not have occurred.

Transients can be failures in power supply, reactivity transients (sudden increases in reactivity), failures in control systems (e.g., control rod ejection), and loss of flow.

CCIs (e.g., power transients and earthquakes) lead to multiple failures and may affect several components in the system.

According to Stokke (1997), loss of coolant in pressurized water reactors does not immediately signify a large radioactive release. The vessel should be able to contain an overheated core for a period that may be sufficient to allow restoration of adequate core cooling. If there is extensive core damage, it is unavoidable that radioactivity leaks occur. A core melt by itself, however, does not create an explosive situation unless reactor containment fails. A source term for the Kola NPP having a very high radioactive plume rise and thus exposure of core and fuel to the open air has therefore a low probability. Nevertheless, releases of noble gases and volatile radioactive compounds should be expected in a severe core damage accident.

There are differences between the two older and the two newer plants. For the older Model 230 reactors, the effectiveness of the confinement structure in containing the radioactive steam–gas mixture after a LOCA is uncertain. The airtightness of the confining structure is not assured and there may be considerable leakage even without open valves or other penetrations. Breaks in the largest coolant pipes may generate a steam pressure that could crack or rupture the confinement structure and create an open passage from the core to the environment, although the reactor vessel would still be intact (Stokke, 1997).

7.2.1.2. Probabilities

The probability that a severe accident may occur is dependent on many factors such as design features, construction quality, and human performance. The probability that an event may lead to an unintentional core melt can be assessed on the basis of engineering judgment or by performing a Probabilistic Safety Assessment where, in principle, all realistic chains of events leading to core melt are analyzed and their probabilities of occurrence calculated. The sum of all probabilities for all possible initiating events to cause a core melt is the Core Melt Frequency (CMF), given as the probability per reactor operating year. The CMF does not include the probability of human failure, sabotage, or terrorist attack (Stokke, 1997). For modern NPPs, the CMF is considered to be within the range 10^{-4} to 10^{-5}. At present, there is no CMF for the Kola NPP for use in accident consequence analysis. However, the International Atomic Energy Agency (IAEA) has reported a preliminary estimate of 5.5×10^{-3} per year for the oldest Kola reactors (Stokke, 1997).

7.2.1.3. Accident source terms

Accident source terms depend on the initiating events, which may result in different accident scenarios. Examples of scenario development are provided by Stokke (1997). Worst case scenarios concern situations in which the reactor core contains the maximum number of products and maximum activity concentrations of radionuclides at the end of the normal fuel burn-up cycle.

Table 7·1. Combined inventory of radionuclide groups with release potential in a VVER-440 Kola NPP (Stokke, 1997).

		Total activity in core, Bq
Noble gases	^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{89}Kr, ^{90}Kr, ^{133}Xe, ^{135}Xe, ^{138}Xe	1.21×10^{19}
Halogens	^{84}Br, ^{87}Br, ^{131}I, ^{133}I, ^{134}I, ^{135}I	1.48×10^{19}
Alkaline metals	^{86}Rb, ^{88}Rb, ^{89}Rb, ^{90}Rb, ^{134}Cs, ^{136}Cs, ^{137}Cs, ^{138}Cs	7.53×10^{18}
Tellurium group	^{127m}Te, ^{127}Te, ^{129}Te, ^{129m}Te, ^{131m}Te, ^{132}Te, ^{127}Sb, ^{129}Sb	3.90×10^{18}
Alkaline earth metals	^{89}Sr, ^{90}Sr, ^{91}Sr, ^{140}Ba	6.42×10^{18}
Transition metals	^{90}Y, ^{91}Y, ^{95}Zr, ^{97}Zr, ^{95}Nb, ^{99}Mo, ^{99m}Tc, ^{103}Ru, ^{105}Ru, ^{106}Ru, ^{105}Rh	2.14×10^{19}
Lanthanides	^{140}La, ^{141}Ce, ^{143}Ce, ^{144}Ce	9.57×10^{18}

Table 7·1 summarizes information on the relatively mobile radionuclides present at the end of the fuel burn-up cycle that are most likely to be released in the event of an accident.

There is currently no information on the inventory of actinides for the Kola NPP and so the consequences of actinide release have not been assessed. Stokke (1997) has estimated the highest release fractions for various potential accidents from the Kola reactors (Table 7.2).

Table 7.2. Highest release fractions (%) from the core inventory for different initiating events (Stokke, 1997).

	VVER-440/213			VVER-440/230
	Transient	Small LOCA	Large LOCA	Large LOCA
Noble gases	100	20	50	100
Iodine	2.5	0.05	1	15
Cesium	2.5	0.05	1	12
Tellurium	0.1	0.05	0.2	10
Strontium	1	0.1	1	2
Barium	0.5	0.05	0.5	2

For a given event, the estimated release for a single nuclide is calculated by multiplying the amount of the nuclide in the core by the release fraction. The source term suggested for the VVER-440 230 model (Stokke, 1997) is based on source terms applied in earlier consequence assessments of accidents at the Kola NPP. The source term for the VVER-440 213 model is based on the IAEA Technical Co-operation Project on Evaluation of Safety Aspects for VVER-440 model 213. Because all aspects of a potential accident are not yet completely understood, a conservative approach should be taken so as not to underestimate the risk. The source terms for model 230 reflect a conservative approach that results in source terms that are larger than most other source terms previously applied for VVER-440 reactors.

Releases of noble gases, radioiodine, and radiocesium are the most important, as these are assigned the highest release level (level 7) on the International Nuclear Event Scale (INES) for this reactor type. Releases of radioiodine, radiocesium, and radiostrontium are important from a radiological hazard point of view, while the long-term consequences of much smaller releases of actinides are also significant. The inventory estimates in Table 7·1 and fractions released in Table 7·2 are assumed to be valid for both VVER reactor types. Various accidental release scenarios have been considered, examples of which are given in Sections 7.2.1.4 to 7.2.1.7, for an unintentional 'worst case' scenario (i.e., where the accident that is not a result of malicious intent, e.g. terrorism) with a large LOCA and a less severe transient scenario. Table 7·3 shows the inventory, fraction released, and consequent activity emitted to atmosphere for the two scenarios. A major fraction of the radionuclides, including Cs- and Sr-isotopes will be present as particles. Since the air dispersion and transfer model does not currently include radioactive particles, these are not considered in the estimated ecosystem transfer and doses to humans.

7.2.1.4. **Initial dispersion**

The dispersion of radionuclides from a source depends on the release height and meteorological conditions at the release site and along the transport route, in addition to the properties of the released material such as size distribution and the degree of volatilization. Buildings and other structures near the release point can also affect the initial dispersion, especially in the case of releases at low height. This effect, however, becomes insignificant at distances over a few kilometers from the source, and is negligible for releases with a high effective release height. Scenarios for a hypothetical release from the Kola NPP are based on data from the Norwegian and Danish Meteorological Institutes.

Table 7·3. Calculated release fractions for selected radionuclides under a large LOCA and a transient scenario (Larsen *et al.*, 1999; Stokke, 1997).

	Inventory, PBq	Fraction released, %		Activity released, PBq	
		LOCA	Transient	LOCA	Transient
^{137}Cs	117	12	2.5	14.0	2.9
^{134}Cs	156	12	2.5	18.7	3.9
^{90}Sr	85	2	1	1.7	0.9
^{132}Te	2240	10	0.1	224	2.2
^{132}I	2330	15	2.5	233	57.5
^{131}I	1570	15	2.5	236	39.3
^{103}Ru	2350	1	0.1	23.5	2.4
^{140}Ba	2790	2	0.5	55.8	55.8
^{140}La	2860	0.2	0.1	5.7	2.9

The information was supplemented by a study of the meteorology and transport of radioactive contamination from the Kola NPP (Bartnicki and Saltbones, 1997; Saltbones *et al.*, 1997). The Norwegian Meteorological Institute defined the meteorology in the area, calculated the transport times, and investigated the likelihood of nuclear contamination at specific locations. Three scenarios were selected as initial conditions for the dispersion model (Saltbones *et al.*, 1995). The scenarios used three sets of weather situations that would provide particularly unfavorable consequences for Norway. Two of the three situations were relevant to Arctic Norway.

Scenario A, with a rapid transit time to northern Norway, where one-eighth of the released material was deposited within 72 hr.

Scenario B, with precipitation during the passage of the plume over northern Norway, with wet deposition such that nine-tenths of the release was deposited over Norwegian territory.

7.2.1.5. **Consequences**

There have been recent assessments of both the short-term and long-term doses from hypothetical accidents at the Kola NPP. The analysis of short-term doses was confined to Norway and to external and inhalation doses. The short-term analysis did not include ingestion doses based on the assumption that the accident occurred outside the short growing period, when dairy animals would be housed; a situation which prevails for most of the year in the Arctic. The long-term doses were estimated for northern Norway and for various regions of northwest Russia and considered external and ingestion doses arising from the mobile, long-lived radionuclides, radiocesium and radiostrontium only. For both assessments, the unintentional worst-case accident was selected for an assessment of radiation levels and doses.

7.2.1.6. **Short-term assessment**

The assessment included more than 50 radionuclides. The dispersion model results were based on the release of particles with a given mathematical mass and must therefore be combined with information about the radioactive emission in order to calculate the atmospheric and ground levels of the various radionuclides. Activity concentrations and ground deposited activity were used as a starting point for calculating doses from the various exposure pathways associated with inhalation and external irradiation from radionuclide deposits on the ground and in the air.

Although foodstuffs are the major contributor to the total long-term dose, the focus of the short-term consequence assessment was on external exposure and inhalation. There is a very short growing season in the Arctic and the implicit assumption is that the accident occurred outside this period.

For an adult, the effective dose was calculated at about 1 mSv for Scenarios A and B. In both cases, the contribution from radionuclides deposited on the ground predominates, especially where precipitation is high and wet deposition considerable.

Throughout the first year, external irradiation from the ground is the most important exposure pathway: calculated effective doses are 3.5 mSv and 5.1 mSv for Scenarios A and B, respectively, with ^{134}Cs and ^{137}Cs the most important contributors (60 to 70%). High activity of deposited radiocesium is the main reason for the higher annual dose in Scenario B, the precipitation scenario.

External irradiation from airborne radionuclides is a relatively insignificant exposure pathway a week or more after the hypothetical accident. However, during cloud passage, airborne radionuclides, such as noble gases with very short half-lives (e.g., ^{133}Xe), could be of some significance for the dose rate.

Owing to large quantities of short-lived radionuclides emitted during the hypothetical accident, a considerable fraction of the external dose will occur during the first few days after contamination. In Scenario A, where the atmospheric transport of radioactivity occurs rapidly, about 20% of the effective external dose will result from irradiation during the first week after deposition. In Scenario B, where the transport is considerably slower, the corresponding value was estimated at about 10%. Furthermore, if radionuclide migration through soil profiles, and the subsequent radioactive shielding by overlying soil, is considered, then the external dose received from the first few days may be of even greater relative importance than that estimated.

Of the 50 radionuclides considered, only a few are significant contributors to the total external dose. Over a short time-scale (days or weeks) the dominant nuclides are ^{132}Te/^{132}I, ^{131}I, ^{103}Ru, and ^{140}Ba/^{140}La. After these decay the external dose is dominated by ^{134}Cs and ^{137}Cs.

The effective dose from inhaled radionuclides is predicted to be <1 mSv for both scenarios and is generally highest for young individuals. The dominant nuclide is ^{131}I, which contributes 50 to 70% to the total inhaled dose, depending on the scenario and age group. Equivalent doses to the thyroid gland were calculated at 4.6 to 10.6 mSv (Scenario A) and 1.6 to 3.6 mSv (Scenario B).

The doses calculated for the two scenarios are assumed to represent the worst possible consequences of a severe nuclear accident at the Kola NPP. Nevertheless, the received doses are much too low to result in any acute radiation injuries.

International guidance concerning countermeasures (e.g., ICRP, 1992), such as evacuation, staying indoors, or the distribution of iodine tablets is based on evaluations of the benefits and disadvantages of implementation, expressed as saved (averted) doses. This assessment indicates that the saving potential is too low to justify the direct implementation of countermeasures; however, this must be investigated further. The uncertainties in the calculations are large, and an evaluation of the pros and cons for an actual situation can result in the use of different countermeasures, e.g., for special groups.

7.2.1.7. **Long-term assessment**

The first AMAP assessment concluded that the vulnerability of the Arctic (defined as the relationship between dose and atmospheric deposition of nuclides) is higher than in most other areas of the world, particularly for ^{137}Cs. This reflects the transfer of radionuclides deposited from the atmosphere through terrestrial food chains to human radiation exposure. The long-term assessment estimated the long-term impact of radioactive contamination from a hypothetical LOCA at the Kola NPP on the two northernmost counties of Norway (Troms and Finnmark), and on the Murmansk Oblast in Russia. The weather pattern for the Russian scenario was based on predicted ground deposition provided by the Danish Meteorological Institute, with most deposition occurring on the Kola Peninsula.

The study considered radionuclide deposition, transfer to and contamination of locally produced foodstuffs, and external and ingestion doses for reindeer herders and other inhabitants. A spatial model was developed within a geographical information system to predict the long-term consequences of radionuclide deposition on northern Norway and northwest Russia. As no site specific data were available, general transfer factors were used in the model (JNREG, 2002a,b,c).

External doses

The highest individual external γ-doses occur in those areas receiving most accident deposition, but are negligible compared to ingestion doses. Individual external γ-doses for reindeer herders are twice those of the other inhabitants owing to the tendency of the latter to occupy areas with higher shielding (i.e., buildings).

Internal doses

Radionuclide transfer to foodstuffs was modelled using aggregated transfer coefficients (T_{ag}; Box 3·2) and effective ecological half-lives (T_{eff}; Box 3·1). Long-term predictions were made for the spatial variation in activity concentrations in foodstuffs, individual external and ingestion doses for reindeer herders and other inhabitants, and radionuclide fluxes (total Bq output from contaminated land areas over specified time periods).

Data were collated for each study area to derive area-specific T_{ag} and T_{eff} values for radiocesium and ^{90}Sr (JNREG, 2002a). The biggest difference was the 3-fold higher T_{ag} value for ^{137}Cs transfer to reindeer meat for the Murmansk Oblast compared to Norway, and the longer associated half-life. Together, these were responsible for the greater intakes predicted for radiocesium in reindeer meat per unit deposition, and the greater persistence in reindeer meat and thus Russian reindeer herders. In addition, the T_{ag} value for ^{137}Cs transfer to potato and to a lesser extent berries, was lower for Norway than Russia. T_{eff} values for freshwater fish were lower for Norway than Russia. The T_{eff} value used for ^{90}Sr in milk was much greater for Russia than that assumed for Norway. For ^{90}Sr, T_{ag} values for Russian dairy products and potatoes were lower than for Norway, while those for most other products were higher.

The most obvious difference between the diets of the Norwegian and Russian inhabitants is in the consumption of dairy products; these are important in Norway but much less so in the Murmansk Oblast. Reindeer meat consumption is highest in the male reindeer herders in Lovozero in Russia. Sheep and goat meat is only consumed in Norway. Potato and freshwater fish consumption is also greater in Russia.

Under the scenarios considered, high activity concentrations persist in foodstuffs owing to the high T_{eff} values. Activity concentrations for ^{90}Sr in foodstuffs are much lower than for radiocesium. In the first year after accident deposition, the highest radiocesium activity concentrations were predicted to occur in reindeer meat, sheep meat, mushrooms, and berries, and the highest ^{90}Sr activity concentrations in berries and potatoes. After fifty years, the highest activity concentrations predicted for foodstuffs were for ^{137}Cs in mushrooms, reindeer meat, and berries.

As for foodstuffs, predicted annual individual ingestion doses for reindeer herders and other inhabitants vary spatially according to differences in deposition and land cover. Annual ingestion doses for all population groups in the first year after deposition were predicted to exceed 1 mSv. Annual individual radiocesium ingestion doses for reindeer herders are significantly greater than for other inhabitants. In the first year after deposition, the most significant contributor to annual individual radiocesium ingestion dose is reindeer meat for all population groups, with the exception of other Norwegian inhabitants for whom dairy products and mutton are important contributors. Potatoes and dairy products are the largest contributors to the much lower annual individual ^{90}Sr ingestion doses for all population groups. Berries are another important ^{90}Sr contributor to the two Russian population groups, while reindeer meat is also a source of ^{90}Sr for Russian reindeer herders.

Under all accident scenarios, reindeer herder annual ingestion doses are predicted to exceed 1 mSv for many decades after accident deposition (and are much higher in the first few years); for the other population group, ingestion doses exceed 1 mSv for a few years after accident deposition in northern Norway and for a decade in Murmansk Oblast. Fifty years after accident deposition, individual ^{137}Cs ingestion doses for reindeer herders are over two orders of magnitude lower than during the first year; those for the other population group are more than 30 times lower. The largest contributors to annual individual ^{137}Cs ingestion doses for Norwegian reindeer herders fifty years after accident deposition are reindeer meat, freshwater fish, and dairy products, with dairy products, freshwater fish, mushrooms, and reindeer meat the most important contributors to the other Norwegian population group. Reindeer meat and mushrooms are the largest contributors to annual individual ^{137}Cs ingestion doses to the Russian population groups 50 years after accident deposition.

Sr-90 is a much less important contributor to ingestion dose and the predicted consequences of the accident scenarios are much less certain owing to the paucity of relevant data for the Arctic, in particular for milk. For reindeer herders, freshwater fish, potatoes, berries, and reindeer meat, provide the largest contribution to annual individual ^{90}Sr doses, while potatoes, freshwater fish, and berries, are the most significant contributors for the other inhabitants.

The most significant contributor to total doses for all population groups is radiocesium ingestion. Vulnerability to ^{90}Sr contamination is much lower than to radiocesium for both reindeer herders and other inhabitants.

There are substantial differences in agricultural production within the various areas of northern Norway. Production of almost all agricultural products in Troms is 2- to 5-fold higher than in Finnmark, whereas reindeer production is 20-fold higher in Finnmark where most of reindeer herders live. Detailed production data were not available for Murmansk Oblast. Annual radionuclide fluxes have been predicted for all locally grown foodstuffs (production of mushrooms, berries, and freshwater fish was estimated by multiplying diet and population). In the first year after deposition, the highest radionuclide fluxes are predicted to coincide with the areas receiving the highest accident deposition. The largest contributors to radiocesium fluxes are reindeer meat and dairy products, while dairy products and potatoes are the largest contributors to annual ^{90}Sr fluxes. The contribution of different foodstuffs to radionuclide fluxes changes with time. Fifty years after accident deposition, the highest radionuclide fluxes do not necessarily occur in those areas receiving the greatest accident deposition. High radionuclide fluxes can occur in areas with high food production. In general, reindeer meat and dairy products remain the significant contributors to ^{137}Cs fluxes in the fiftieth year, while berries, potatoes, and freshwater fish are the largest contributors to the lower annual ^{90}Sr fluxes.

This study confirms the outcome of the first AMAP assessment, i.e., that Arctic residents are particularly vulnerable to radiocesium contamination and that the vulnerability would persist for many years after deposition. Reindeer herders are particularly vulnerable due to their higher levels of reindeer meat consumption. Nevertheless, other inhabitants of northern Norway and Russia would also be potentially exposed to high doses, especially if consuming many local products. While reindeer production is the most vulnerable pathway, freshwater fish, lamb meat, dairy products, mushrooms, and berries are also vulnerable foodstuffs. Although game was not included in this study, post-Chernobyl studies show high and persistent contamination of some game animals.

The location of communities and their types of agricultural production are important variables determining vulnerability; if high deposition occurred in the major reindeer production areas (Finnmark in Norway and Lovozero in the Murmansk Oblast) the impact would be much higher than if deposition occurred in areas where other types of agriculture predominated. Conversely, because dairy cattle are inside for much of the year, vulnerability increases if an accident occurs during the short summer grazing period, especially for ^{90}Sr.

Major factors contributing to the uncertainties in the estimates of doses and fluxes are the limited number of nuclides being considered, as well as the use of general rather than site specific transfer factors. Also, the scenarios address releases of gaseous and aerosol components but potential releases of radioactive particles are not taken into account. The effects of countermeasures were not evaluated in this assessment. Doses and fluxes were predicted assuming no mitigating actions having been taken. However, the results clearly indicate the need for an effective emergency response, including the application of countermeasures, should an accident of the scale considered in this assessment ever occur at the Kola NPP.

7.2.2. Barents region environmental center study of atmospheric transport pathways from the Kola NPP

An assessment of atmospheric transport pathways from the Kola NPP was undertaken for four geographical regions: Scandinavia, Europe, the central former Soviet Union (CFSU), and the Taymir Peninsula. Several approaches were used to determine the probability that air would be transported from the Kola NPP to each of these regions, transport times, and seasonal variations in atmospheric transport.

The assessment indicated that Scandinavia would be affected by a release for 44.5% of days between 1991 and 1995, Europe for 8.1%, the CFSU for 43.2%, and the Taymir Peninsula for 55.5%. The airflow probability field had a similar pattern to that for the one available assessment of the consequences of hypothetical accidents at the Kola NPP, where the released materials were distributed in an almost circular pattern extending slightly in a northeasterly direction (Baklanov *et al.*, 2002). Seasonal variations influenced the transport pattern.

Two cases of rapid transport from the Kola NPP to Scandinavia were selected for more detailed study. In both scenarios, 60 PBq of ^{137}Cs were released over a period of 20 hr in a plume rising 400 to 600 m. The areas contaminated by ^{137}Cs to a level exceeding 30 kBq were 190 000 and 250 000 km^2.

Mean individual doses, collective doses, and collective risks were calculated for one of the two scenarios, based on assumptions of the relative importance of various nuclides and exposure pathways to the total dose resulting from the effects of the Chernobyl accident on Scandinavia. The highest mean individual doses, 1.15 mSv, occurred in northern Norway. The collective dose for the area affected was calculated as 1100 manSv, corresponding to a collective risk of 54 cases of additional cancer.

7.3. Nuclear-powered vessels

The reactors of nuclear-powered vessels located around the Kola Peninsula represent the greatest density of nuclear reactors in the world. Several types of release have been registered from these vessels, particularly from those operating at sea. However, releases have also occurred at bases on shore, for example in Andreyeva Bay and Gremikha Bay. Limited effort has been made regarding impact assessments for accident scenarios related to operating vessels, decommissioned vessels, or vessel components after dismantling, owing to the traditional secrecy surrounding these vessels, their reactors, and the composition of their fuel. There is a need to standardize the existing studies comparing Russian and western efforts and to complete the assessments. Nevertheless, some significant contributions have already been made, such as the IAEA assessment of the risks from the dumped reactors close to Novaya Zemlya (IAEA, 1998a). Other more recent efforts include the pilot study by the NATO Committee on the Challenges of the Modern Society concerning an environmental risk assessment for decommissioned Russian nuclear submarines still containing fuel, and an evaluation of the potential impact of large releases from the *Kursk* at the time of sinking and during subsequent recovery operations (Baklanov *et al.*, 2003).

The operation, maintenance, decommissioning, and dismantling of a nuclear vessel fleet is a complex process involving a large number of smaller operations. The activities include: different modes of operation (training, patrolling, tracking, etc.); assignments in port, changes of crew; docking for maintenance and repair; refuelling and defuelling; storage onboard of fuelled reactors; on- and off-loading of fresh and spent fuel from vessels and transport ships; mode of fuel transport; and storage of damaged reactors/damaged fuel.

To date, some of these operations have been covered by risk assessments. Hopefully, the most serious scenarios involving potential releases have been covered; however, as this work and international efforts to assist Russia in these tasks are reaching new levels of advancement and maturity, new facts and scenarios are being identified. The most recent and relevant efforts toward comprehensive impact assessments are presented in the rest of this section. These have been subdivided into vessels in operation (Sections 7.3.1. and 7.3.2.), decommissioned vessels still containing spent fuel on board (Section 7.3.3.), and accident scenarios involving spent fuel and radioactive waste after dismantling of the vessel (Section 7.3.4.). The focus is on the presence of spent fuel because 90 to 99% of the radioactivity resides within the fuel. However, the reactor compartments, and the solid and liquid high-level, medium-level, and low-level radioactive waste also constitute formidable problems, mainly in the remediation of the bases and sites. The latter requires further evaluation as remedial work involving international participation is to begin shortly.

7.3.1. Military vessels

There are around 33 operative nuclear submarines within the Russian North Fleet. According to Ølgaard (2001), these comprise 12 ballistic missile submarines (Typhoon and Delta Classes), 4 cruise missile submarines (Oscar Class), 12 attack submarines (Akula, Sierra, Yankee, and Victor Classes), 1 cruiser (Kirov Class), and 4 other submarines (Yankee, Uniform, and X-ray Classes). These regularly patrol the nearby oceans as part of their contribution to the Russian defense force. During service, four Russian nuclear submarines have sunk, 36 accidents have occurred, and there have been 378 associated fatalities (Ølgaard, 2001).

The first AMAP assessment made reference to design and beyond-design accident scenarios prepared in relation to Russian nuclear-powered submarine refuelling. No new assessments of this type were available for the present assessment and so that in AMAP (1998) remains the most appropriate. A submarine incident in a ship repair yard in Chazhma Bay on the Russian Pacific coast on 10 August 1985 (Sarkisov, 1999; Sivintsev *et al.*, 1994) involved inadvertent criticality in a reactor core. This can be used to illustrate the potential circumstances and the nature, scale, and consequences of such accidents. The accident claimed ten lives and gave rise to 39 cases of acute radiation effects. Subsequent on-site observations and radioecological investigations showed that the accident did not have a measurable radiological impact on Vladivostok or the nearby Shkotovo-22 village. Residual long-lived radioactive contamination in the Chazhma Bay region is localized and does not give rise to serious radioecological concern.

Risk estimates of criticality events during refuelling have been performed by NATO (NATO, 1998). The probability of a severe accident in the Russian navy is estimated to be 2×10^{-3} per refuelling.

7.3.1.1. *Kursk*

The latest accident involving a Russian submarine was that of the *Kursk* in August 2000. The sinking, and subsequent recovery operation, raised considerable concern about possible consequences. The accident represented a significant challenge for the nuclear emergency preparedness organization; from the day of the accident until the larger part of the submarine was brought into dock at Roslyakovo in October 2001.

Owing to considerable concern in Norway, the Norwegian Radiation Protection Authority undertook an environmental risk assessment for four scenarios; combining two inventory calculations and two release scenarios. The *Kursk* inventory calculations were based on information for the Russian cargo ship *Sevmorput* with some adjustment of the technical input data. The hypothetical release rate for radionuclides depends strongly on release conditions. These range from instantaneous release owing to the explosion of torpedoes or cruise missiles within the submarine, to the slow long-term corrosion of fuel material. The latter may occur when seawater has penetrated the fuel cladding. If the cladding is zirconium, penetration may take several hundred years. However, if conditions for galvanic corrosion are present, the cladding could be fully corroded in less than a year.

Two radionuclide release scenarios were considered.

1. An abnormal event one year after the accident, i.e., during the salvage operation, in which 100% of the inventory in both reactors is released instantaneously.

2. The assumption that all barriers, for all practical purposes, have been removed after 100 years, and that 100% of the inventory of both reactors is then released.

Two versions of operational history, resulting in burnups of 12 000 (Version 1) and 24 000 (Version 2) MW-days respectively, were considered for each scenario. Both versions were based on the submarine being operational for an average of 50 days per year for each year since commissioning at the end of 1994. Version 2 includes extensive operation of the reactors for electrical power in port, as has been reported to occur by several sources in recent years. An estimated release of 100% of the inventory, a very pessimistic approach, was chosen to demonstrate the consequences of a simple scenario, even if not realistic, to the public concerned. There is a lack of comprehensive environmental assessments of accidents involving submarines in operation and the associated release mechanisms and source terms. Earlier studies concentrated on releases from sunken submarines to the marine environment (Eriksen, 1990; IAEA, 1997) or releases from decommissioned non-defuelled submarines (NATO, 1998) to sea and air. A consideration of submarines in operation, such as the *Kursk*, might indicate more severe consequences owing to the greater amount of short-lived radionuclides present.

Estimates of the radiological consequences for the marine environment of potential radionuclide releases from the *Kursk* were performed for Scenarios 1 and 2, using a box model to estimate radionuclide transport over large distances (>1000 km) and long time-scales (up to centuries or millennia). The model included terms that describe the dispersion of radionuclides into the marine environment over time (Iosjpe and Strand, 1999; Iosjpe *et al.*, 1997, 2002).

Transport, transfer to fish, and collective doses to humans were modelled for a range of radionuclides present in the reactors. However, most attention was focused on ^{137}Cs because this has a relatively long physical half-life (30 years), readily dissolves in water, and accumulates in edible parts of fish and shellfish. For ^{137}Cs dispersion in oceanic surface water for the worst case potential accidental release, with immediate release of spent fuel and high burn-up (Scenario 1, Version 2), the model predicted that 0.5 years after a hypothetical accidental release of 100% of the inventory, the average activity concentration in Barents Sea water would be 160 to 210 Bq/m^3 in the vicinity of the submarine. Activity concentrations would decrease rapidly and after ten years the average incremental water activity concentration in the Barents Sea was estimated at 0.1 to 2.8 Bq/m^3.

For ^{137}Cs activity concentrations in fish from the Barents Sea region (also for Scenario 1, Version 2) the calculations indicate that during the first few years of potential dispersion, the activity concentrations would vary widely depending on the habitat of the fish. During the early stages of dispersion, the Barents Sea would contain areas with relatively high levels of contamination and areas that were completely unaffected. The calculated transfer to fish is subject to large uncertainties and other transfer pathways, such as particle ingestion, were not considered. The maximum ^{137}Cs activity concentration in fish was calculated as between 0 and 100 Bq/kg during the first year after a hypothetical leak from the *Kursk*. By comparison, the intervention level for ^{137}Cs in basic foodstuffs, as recommended by the EC and adopted by several countries, including Norway, is 600 Bq/kg.

For Scenario 1, the collective dose to man is dominated by the contribution from ^{137}Cs. Calculations show that a collective dose of 61 manSv would be attributable to the intake of ^{137}Cs from the Barents Sea alone, while the total collective dose from all radionuclides from the whole marine area would be 97 manSv. For the latter, contributions from ^{137}Cs and ^{239}Pu correspond to collective doses of 69 and 5.5 manSv, respectively. For comparison, collective doses from other radionuclides for Scenario 1 are estimated at 6.5, 4.3, 2.2, 0.37, and 0.27 manSv for ^{90}Sr, ^{134}Cs, ^{241}Am, ^{147}Pm, and ^{106}Ru, respectively. For Scenario 2, Version1, the total collective dose was estimated at 8.4 manSv. Furthermore, approximately 80% of the collective dose from the Barents Sea was attributable to ^{137}Cs exposure. There is no significant contribution from ^{239}Pu to the collective dose for Scenario 1. For Scenario 2, however, the contribution of ^{239}Pu is comparable to that of ^{137}Cs. This mainly results from the comparatively short radioactive half-life for ^{137}Cs of 30 years.

No indications of leakage from the *Kursk* submarine were observed during the expeditions to the site in August and October 2000. Elevated levels of radioactivity were not observed in any dose-rate readings or in any environmental samples from close to or inside the submarine, even after the submarine was taken ashore in Roslyakovo.

7.3.1.2. *Komsomolets*

The *Komsomolets* submarine sank in 1989 in the Norwegian Sea, south of Bear Island (Bjørnøya). The radioactive inventory at the time of the accident is estimated at 2.8×10^{15} Bq of ^{90}Sr and 3.1×10^{15} Bq of ^{137}Cs in the reactor, and 1.6×10^{13} Bq of plutonium in the warheads. Minor releases of radioactivity from the reactor compartment have been detected but large-scale releases are thought to be unlikely as the containment barriers will prevent corrosion of reactor fuel for at least a thousand years.

7.3.1.3. Other nuclear submarines

There are 70 decommissioned submarines moored around the Kola Peninsula at the bases from which they operated, some close to international borders. Fifty-two are waiting to be defuelled and are in various states of repair. Some have damaged cores due to accidents, which has prevented the removal of the fuel from the reactor compartment. Decommissioning submarines with damaged cores is a major problem requiring large investment and often significant radiation risk to workers.

In 1993, the International Arctic Seas Assessment Project (IAEA, 1997) began a study of the radiological and environmental hazard posed by the reactor compartments dumped in the Barents and Kara Seas in the 1960s and 1970s. Six were dumped with spent nuclear fuel onboard (two being complete submarines) and ten were dumped without fuel. An environmental survey of the disposal sites found limited evidence of contamination that could be attributed to the reactor compartments (Strand *et al.,* 1997). Transport and dispersion models using isotope release rates indicated that the maximum annual dose would be received by local populations, although this was <0.1 μSv/yr. However, military personnel that patrol Novaya Zemlya were projected to receive a potential annual dose of up to 700 μSv (comparable to natural background doses). The global collective dose over the next 1000 years from ^{14}C in the inventory was estimated at 8 manSv.

NATO has considered accident analysis in some detail (NATO, 1998). For an environmental release to occur, an event with sufficient energy to dislodge the radioactive material from its normal location and a failure of the containment boundary are required. Fuel within the reactor compartment is the most probable area for such an event to take place due to existing defects, mechanical damage, or overheating. Events can be internal or external (specific to the mooring location) and the main concern is core overheating or a LOCA. This is used as the reference event and indicates the upper limit for consequences arising from other events. The activity release from a core containing spent fuel is estimated at 100 TBq of ^{90}Sr and 600 TBq of ^{137}Cs immediately after the event. The NATO report does not attempt to estimate the quantity of radioactivity that could be released for each internal event analyzed.

The number of potentially hazardous radionuclides likely to be dispersed following a criticality accident on a decommissioned but non-defuelled submarine is relatively small, taking into account core activity, the release fraction, and exposure pathways for radiological effects.

Actinides and fission products provide the greatest potential hazard. Short-lived radionuclides may dominate immediately after an accident and their presence is important in the vicinity of the accident site, but they do not cause extensive spatial contamination. The majority of the dose from an atmospheric release is contributed by ^{137}Cs, ^{134}Cs, and ^{90}Sr, with source terms estimated at 350, 35, and 70 TBq, respectively.

A decommissioned, non-defuelled moored submarine can sink and release radioactivity to the sea as a result of lapsed maintenance. The consequences are not necessarily severe since reactors and submarines are designed to withstand considerable pressure. There may be some activity release from corrosion of the outer surfaces of the nuclear reactor. However, if the reactor compartment was breached, as for example in the event of a collision, corrosion of the fuel could occur rapidly and release fission products to the sea. Estimates based on models using data from Ara Bay, near Murmansk, suggest that the release in the year of the accident would be 1.6 PBq, with actinides providing <1 TBq of the release and fission products dominating. Over time, the predominant isotopes would change owing to differential decay and mobilization.

It is also possible for an undamaged submarine to sink and such a scenario was examined for Ara Bay. Sinking in such shallow water (a few tens of meters) is unlikely to damage a submarine’s primary systems. Releases of the four major activation isotopes, ^{60}Co, ^{59}Ni, ^{63}Ni, and ^{14}C, were estimated at around 300 MBq one year after sinking, decreasing to 180 MBq after 20 years (IAEA, 1997). Except for ^{14}C, these isotopes would adsorb onto coastal sediments and ultimately settle to the sea floor or remain on the hull. Models indicate little activity in the waters of Ara Bay and even less 1.5 km from the release site.

Such studies indicate that recovery of sunken submarines or reactor compartments is not too difficult if the reactor is undamaged but that the effects of a criticality accident are difficult to predict, making the consequences difficult to estimate. Nevertheless, the risks of radionuclide release to the Arctic are considered to be negligible.

7.3.2. Civilian icebreakers

The Murmansk Shipping Company operates the Russian icebreaker fleet. According to Ølgaard (2001) the fleet currently comprises six operational icebreakers (*Arktika*, *Rossiya*, *Sovetskiy Soyuz*, *Yamal*, *Taymyr*, and *Vaigach*), and one icebreaking container ship (*Sevmorput*). These are stationed at the Atomflot Repair Technical Plant near Murmansk. Two icebreakers have been decommissioned and defuelled (*Lenin* and *Sibir*). A new icebreaker, *50 let Pobyedy* (50 Years of Victory), is currently under construction at the Baltiysky shipyard in St. Petersburg.

7.3.3. Decommissioned, currently-fuelled submarines

The decommissioning of Russian nuclear submarines in the Arctic has caused considerable concern since the end of the Cold War. In 1992 and under the auspices of the NATO Committee on the Challenges of the Modern Society, Norway initiated a study on cross-border defense-related environmental problems. At an early stage, the working group decided to focus on decommissioned but still fuelled submarines. Operational submarines and nuclear weapons were beyond the scope of the working group. A direct comparison of the risks was not undertaken.

Three scenarios were used to examine releases to the sea: sinking of an undamaged submarine; sinking of a damaged submarine; and a criticality accident followed by sinking. Using the release rate model established during the International Arctic Seas Assessment Project, the dose rate to an individual on a small craft in the harbor of Ara Bay, chosen as the location of the sunken submarine, was 100 μSv/hr. At 2 km north of the site, average dose rates from the water surface to personnel in a small craft decreased to about 10 μSv/hr. At the mouth of Ara Bay, the level decreased to 1 μSv/hr. This work did not include uptake by edible fish species; however, Klopkhin *et al.* (1997), based on model considerations of a radionuclide plume in water, suggest that fish swimming in the plume do not accumulate enough activity to justify restricting their consumption.

Of the many scenarios discussed, only criticality accidents, LOCAs, and hull damage due to sinking or ship collision were considered potential causes of cross-border contamination. Weather conditions during an incident may lead to contamination of foreign territory. For example, using Ara Bay as the accident venue a Gaussian puff model was used to calculate the dispersion of radioactivity for stable weather conditions with winds toward Kirkenes and the county of Finnmark in Norway. Kirkenes is an urban environment, whereas Finnmark represents a critical group with a high consumption of locally produced foodstuffs. For dry deposition only, the ^{137}Cs deposition at Kirkenes was about 10 kBq/m^2 and for ^{134}Cs and ^{90}Sr was typically a factor of ten lower. The maximum annual effective dose for adult members of the public for the two cross-border receptor areas assuming a ‘worst-case’ scenario (NATO, 1998) is shown in Table 7·4. With dry conditions during the passage of the radioactive cloud, the average individual effective radiation dose received in the first year is <1 mSv. Rainfall during cloud passage may lead to enhanced deposition of radioactivity, which would cause significantly higher long-term radiation doses.

7.3.4. Storage of spent fuel

Russian marine reactors and spent fuel are of international concern. One hundred and eighty-eight nuclear submarines have been decommissioned in Russia. Of these, 48 have been dismantled, 28 are being dismantled, and 112 are waiting for dismantling to start. Most still contain loaded reactors. While the focus on military nuclear issues and spent fuel began around 1990, the infamous service ship *Lepse*, containing more than 600 spent fuel assemblies, is still harbored near Murmansk. According to the CEG (2003), fuel arising from 130 submarine nuclear reactor cores is currently being stored in northwestern Russia, while fuel from an additional 20 cores is located in far eastern Russia. An average reactor core has approximately 455 fuel assemblies. In Decem-

Table 7·4. Maximum annual effective dose estimates for adult members of the public for two cross-border receptor areas assuming a 'plausible worst-case' accident scenario (NATO, 1998). 'Short-term' refers to the first 24 hr of the event (cloud passage) and 'long-term' to the first year excluding the first 24 hr. 'Wet' refers to the assumption of moderate rainfall during passage of the radioactive cloud.

	Kirkenes (urban)		Finnmark (rural)	
	dry	wet	dry	wet
Ground deposition of ^{137}Cs, kBq/m^2	10*	250*	1	25
Integrated air concentration of ^{137}Cs, MBq s/m^3	10	10	1	1
Effective dose from exposure pathway, mSv				
Short-term**				
Inhalation***	0.19	0.19	0.02	0.02
Cloud-shine	–	–	–	–
Ground-shine	–	0.02	–	–
Short-term subtotal	0.19	0.21	0.02	0.02
Long-term				
Ground-shine****	0.08	1.9	0.02	0.5
Ingestion***	0.03*	0.9*	0.19	4.5
Long-term subtotal	0.11	2.8	0.21	5.0
First-year				
Total annual dose	0.30	3.0	0.23	5.0

* average contamination of the wider surroundings of Kirkenes is set equal to 30% of the Kirkenes value;
** no protection assumed in the early phase of the incident;
*** effective dose commitment;
**** corrected for runoff (urban environment only) and shielding (rural area lower than urban environment).

ber 2000, there were reports of large quantities of fuel ready to be taken ashore (Moltz, pers. comm., 2000).

The scenarios for an accident or inappropriate use of a Russian marine reactor or its fuel are numerous, as evidenced by various incidents throughout the 1990s. For example, the sinking of *Komsomolets* and the *Kursk*, several thefts of fresh fuel from bases in northwest Russia, and an attempt to blow up the *Vepr*, an Akula Class submarine, by a distressed Russian sailor after a serious hostage situation at the Gadzhiyevo Naval Base on 11 September 1998. The scenarios include: releases to air, sea and/or the terrestrial environment; sabotage and other radiological incidents initiated deliberately; and thefts or other illegal, organized acquisitions of radiological or fissile material by terrorists.

Earlier impact assessments concentrated on releases from sunken submarines to the marine environment (Eriksen, 1990; IAEA, 1997) or releases from decommissioned, non-defuelled submarines to sea and air (NATO 1998). There is need for additional understanding of criticality issues related to remediation and clean-up activities; damaged cores; and the types of spent fuel configurations currently stored at naval bases such as those at Andrejeva Bay and Gremikha Bay.

7.4. International transport of spent nuclear fuel from commercial use

Between 1992 and 1999 there were six shipments of plutonium and vitrified high level radioactive waste from France to Japan and one shipment of mixed oxide reactor fuel from the United Kingdom to Japan. Such shipments, if carried out in a manner consistent with international guidance and existing IAEA Conventions paying specific attention to the prevention of criticality accidents, pose only minor risks to human health. The risk of accidents for such transport has been reviewed extensively over recent years in a comprehensive cooperation between the IMO and IAEA (IAEA, 2001). The doses to a maximally exposed individual that might be caused by the loss of a flask at sea were estimated to range from 5×10^{-12} Sv/yr for the loss of a vitrified high level waste flask to the deep ocean, to 2×10^{-6} Sv/yr for the loss of a high burn-up irradiated fuel flask to shallow coastal waters.

It is difficult to predict the long-term trend in such traffic. However, if mixed oxide fuel is increasingly used as a means of safeguarding surplus weapons-grade plutonium and if investment in nuclear power generation increases as a means of reducing dependence on fossil fuels and emissions of carbon dioxide to the atmosphere, the quantities and frequency of such shipments may increase substantially. A seminar on the transport of spent nuclear fuel in Norwegian coastal areas convened for Norwegian senior officials in March 2002 concluded that, even if the calculated risk is low, there is a need for consideration of possible release scenarios and for detailed impact assessments. The possible transfer of spent nuclear fuel through Arctic areas has caused controversy, for example in Norway, and will continue to do so if such concerns are not addressed properly.

In the case of transport of spent fuel within, for example, Russian territory, there are potential problems associated with Russian transport ships not adhering strictly to international transport regulations. Any foreign assistance, such as the provision of Norwegian transport ships for assisting Russian authorities in the dismantling of nuclear submarines, would probably demand and ensure adherence to international regulations and standards (IAEA, 2001).

7.5. Reprocessing and production plants

7.5.1. Mayak

Operations at the Mayak PA installation have resulted in serious nuclear environmental contamination. Two accidents have resulted in severe contamination outside the Mayak site boundary. In 1957, an explosion in a high level waste storage tank caused severe ^{90}Sr contamination of a 1000 km^2 area within the Chelyabinsk, Sverdlovsk and Tyumen regions. This is referred as the 'Kyshtym accident'. In 1967, wind dispersal of contaminated sediment from the dried-out bed of Lake Karachay (a storage reservoir for liquid radioactive waste) resulted in ^{137}Cs deposition over 1800 km^2 surrounding the site. Between 1949 and 1956, authorized discharges of intermediate-level radioactive waste directly into the Techa River resulted in severe contamination downstream from the release point. Although operational procedures have been revised extensively since the late 1950s, as has also been the case at other nuclear installations, the possibility of accidents remains. The human population in the vicinity of Mayak is at most risk from an accident and has, together with the environment, suffered the adverse effects of previous accidents. However, since the Mayak installation is sited at the head of the Techa River, which is a tributary of the major Ob River, there is also the possibility of long-range transport of radionuclides to Arctic areas. AMAP has therefore recommended studies on the transport of radionuclides from land-based sources through river catchments (AMAP, 1998). The possible consequences of far-field transport of radionuclides released as a result of various hypothetical accidents at the Mayak installation have been assessed by the Joint Norwegian–Russian Expert Group on Radioactive Contamination (JNREG, 2003). The study focused on six accident scenarios.

1. *An explosion in a storage tank for high level waste.* This is a modern analogue of the Kyshtym accident. It results in radioactive contamination of the environment and subsequent washout of radionuclides into the river system.
2. *A tornado in the Lake Karachay area.* A tornado passing over Lake Karachay lifts and disperses contaminated water and sediment over the surrounding area in a similar manner to the events of 1967.
3. *Inflow of water from Reservoir 11 to the Techa River due to:*

   a. *a dam break*, which brings dissolved and particulate radionuclides as well as washout from the Techa riverbed and floodplain into the river system;

   b. *a controlled release* that results in a discharge of dissolved radionuclides from Reservoir 11 into the Techa River.
4. *Release of radionuclides from the Asanov Swamp.* This was heavily contaminated by early operational discharges of radionuclides into the Techa River, due to flooding.
5. *An accident at the reprocessing plant.* This is comparable to scenario 1, although on a smaller scale and with other radionuclides being involved.
6. *Groundwater contamination from Lake Karachay* reaches the river system.

The accidents vary in size, impact, and duration. Some allow time for the introduction of measures to reduce their severity; others represent serious, acute accidents (e.g., a dam failure) that allow little possibility of mitigation. All incidents have the potential to release radionuclides that could result in impacts on biota and humans in the surrounding area, both in the near and far field.

Because of the concern regarding long-range river transport, a major focus has been to model the transport of radionuclides through the Techa-Iset-Tobol-Irtysh-Ob River system to Ob Bay and the Kara Sea. In some cases,

Table 7·5. Consequences for Arctic areas of six hypothetical contamination scenarios at Mayak PA (JNREG, 2003).

	Total inventory	Release to environment	Discharge to the Techa River	Collective dose, manSv	Maximum dose per person, mSv/yr*
Current runoff		1.2 TBq/yr ^{90}Sr	0.6 TBq ^{90}Sr for 50 yr	0.01	0.009
Scenario 1. Waste tank explosion	370 PBq – single tank; 20000 PBq – total	15.2 PBq ^{90}Sr + ^{90}Y 20.4 PBq ^{137}Cs	180 TBq ^{90}Sr 59 TBq ^{137}Cs	0.39	1.9
Scenario 2. Tornado	4400 PBq	4.4 PBq ^{90}Sr + ^{137}Cs	5 TBq ^{90}Sr, 0.5 TBq ^{137}Cs	0.005	0.006
Scenario 3a. Dam burst	In water: 650 TBq	300 TBq ^{90}Sr 3.7 TBq ^{137}Cs	300 TBq ^{90}Sr 3.7 TBq ^{137}Cs	1.0	4.8
	In sediment: 1500 TBq	205 TBq ^{90}Sr 150 TBq ^{137}Cs	205 TBq ^{90}Sr 150 TBq ^{137}Cs		
Scenario 3b. Controlled release	650 TBq ^{90}Sr + ^{137}Cs	13 TBq ^{90}Sr 0.16 TBq ^{137}Cs	13 TBq ^{90}Sr 0.16 TBq ^{137}Cs	0.009	0.05
Scenario 4. Asanov Swamp	19-22 TBq ^{90}Sr 170-190 TBq ^{137}Cs	3.2 TBq ^{90}Sr	3.2 TBq ^{90}Sr	0.002	0.01
Scenario 5. Plant accident			1.1 TBq**	0.0007	0.004
Scenario 6. Groundwater contamination	4400 PBq	22 TBq/yr ^{90}Sr	0.6 TBq ^{90}Sr for 50 yr	0.00008	0.00007

*for a diet containing 28 kg fish per year; **estimate for all radionuclides.

other transport processes (e.g., atmospheric transport of radioactive debris) have also been considered. The models, developed by scientists at Mayak PA and SPA Typhoon, include radionuclide transport in river systems, and tornado, flood, and groundwater contamination. Where possible, the models are based on existing scientific knowledge concerning the transport and behavior of radionuclides in the area surrounding Mayak and on the outcome of previous accidents, both at Mayak and other installations. Information on the physico-chemical forms of radionuclides and the influence of speciation on transport processes and mechanisms was also included. Finally, major uncertainties, variability, and model sensitivity has been assessed.

The models required particular variables (release inventory, radionuclide composition, meteorological conditions, etc.) for each scenario. Each scenario will vary according to the course of events, particularly concerning the quantity of radionuclides released, which could be more or less than the hypothetical estimate. Therefore, the estimates derived using the models have large uncertainties. Worst-case conditions were generally considered for each scenario.

The outcome of the modelling exercise is compared with current run-off in Table 7·5. For each scenario, the table presents estimates for the total radionuclide inventory and estimates of radioactive releases to the environment outside the Mayak PA area. Radioactive discharges to the upper Techa-Iset-Tobol-Irtysh-Ob River system (mainly into the Techa River) can be much lower than those to the environment, if for example, contamination is due to washout from the water catchment area. Doses were estimated for Ob Bay and the Kara Sea for a 50-year period after the hypothetical accidents.

Scenarios 1 and 3a result in a very high radioactive discharge to the Techa River. The other scenarios result in much lower radioactive contamination of the Techa River.

The models indicate that ^{90}Sr transport through the river system will lead to a significant increase in contamination in the lower reaches of the Ob River compared to current levels. For example, the additional ^{90}Sr activity concentration for the first year after the dam break is estimated to be five times higher than background. Contamination of Ob Bay and the Kara Sea by other radionuclides is much lower. The longer-lived radionuclides released, ^{137}Cs and Pu, are less mobile in river systems than ^{90}Sr. For all six scenarios, the estimated activity concentration is much lower than the norms regulated by modern radiation safety standards. Overall, it was concluded that the potential doses to Arctic biota and human populations from hypothetical accidents at the Mayak PA installation are very low. However, for the local population, the consequences may be severe.

7.5.2. **Sellafield**

The U.K. Health and Safety Executive have produced safety assessment principles for nuclear plants (HSE, 1992) that address safety issues, including accident scenarios for the Sellafield site. There are a number of principles to ensure that safety is maintained throughout operations and in the event of design or beyond-design based accidents. During operation there are a number of design features that can mitigate an accident before it reaches a critical state. In the event of a design-based accident, the safety assessment principles state that 'there is no release of radioactivity except in the most severe of cases, and even then, no person will receive an effective dose of 100 mSv or more'.

The storage of Highly Active Liquor (HAL) is an important source of concern for severe accidents at the Sellafield site. HAL is a waste product from the reprocessing of irradiated nuclear fuel and is currently stored on-site in water-cooled storage tanks. It is converted into solid form via the process of vitrification (incorporation into borosilicate glass) at a rate limited by the capacity of the vitrification plant. The Nuclear Installations Inspectorate has instructed British Nuclear Fuels (BNFL) to vitrificate HAL from a current volume of about 1300 m^3 (1999) to a buffer volume of 200 m^3 (to feed the vitrification process) by 2015 in response to the potential hazard associated with these wastes (HSE, 2000). The main part of the activity in a typical HAL tank is due to ^{137}Cs and ^{90}Sr. There are in total 21 tanks containing about 7×10^{18} Bq of ^{137}Cs and 4.8×10^{18} Bq of ^{90}Sr (Turvey and Hone, 2000). Vitrified wastes are also stored on-site at Sellafield and are generally thought to be safer than HAL because the fission products are immobilized in a solid matrix and cooled by the circulation of air. They are thus not dependent on an active cooling system.

A major BNFL safety case for HAL stores was completed in 1994. This was followed by a Nuclear Installations Inspectorate assessment (HSE, 2000). The assessment concluded that the BNFL approach to accident analysis was incomplete and not best practice. In 1999, BNFL completed the Continued Operation Safety Report (COSR), which is the latest safety analysis associated with the HAL stores. Although this report is not publicly available, the Radiation Protection Institute of Ireland (RPII) was given access to the BNFL safety documentation and has published an evaluation report of the COSR (Turvey and Hone, 2000). The objectives of the RPII examination of the safety material were to determine whether the COSR includes all significant hazards; to evaluate the conclusions of the COSR on the probability of occurrence of a number of accident scenarios; to determine whether confidence can be placed in the database used in the COSR and to assess the significance of any shortcomings; and to assess the need for further improvements in safety. Turvey and Hone (2000) conclude that the risks of a severe accident associated with the HAL stores are low but identify some areas where the risks could be reduced further. The report also states that the risk of damage from a severe earthquake has not been fully analyzed. According to Turvey and Hone (2000), all other major accident scenarios appear to have been considered in the COSR. Despite the probability of an accident involving a significant release of radioactivity being considered low, Turvey and Hone (2000) identify certain safety weaknesses, e.g., that the water supplies for cooling the tanks are not fully independent of each other, that there is no instrumentation for detecting possible hydrogen build-up in the storage tanks, and that the consequences of very severe accidents have not been adequately assessed.

Low probability but high consequence events appear to pose the greatest environmental risk at Sellafield, and could even impact upon the Arctic. These include: seismic events; fire or explosion due to hydrogen generation as a result of radiolysis of HAL or red oil reactions (hot organic liquid and aqueous nitrate solution); extreme weather conditions; aircraft crashes; other man-made hazards (toxic gases); criticality; beyond-design basis accidents; and accidents as a result of human factors.

These issues have been considered by BNFL and the U.K. Health and Safety Executive (HSE, 1992, 2000) but estimates of the radiological consequences (i.e., radiation doses) of each accident scenario have not been assessed.

After 11 September 2001, the possibility of a terrorist attack on, or an airplane crash into, nuclear plants has received much attention. A report prepared for the European Parliament by an external contractor, WISE-Paris (WISE-Paris, 2001a), mentions this briefly and addresses the subject in greater detail in a later report (WISE-Paris, 2001b). The HAL stores are identified as the major risk for radioactivity releases. An assessment is made based on an estimated release of half the total ^{137}Cs content in the HAL tank, and then compared with consequences from the Chernobyl accident. However, these estimations are controversial and have received some criticism.

7.6. Conclusions

Risk assessments are important for establishing priorities. Even though the absolute results from these assessments have large uncertainties, their relative magnitudes may be compared in order to help identify where to focus efforts for risk reduction. The outcome of risk assessments and actual accidents indicate that the consequences of releases to the atmosphere, and subsequent fallout to the terrestrial environment, are greater than for releases to the marine environment.

This assessment has addressed the unintentional potential releases from reprocessing plants in central and southern Russia in detail. The first AMAP assessment concluded that possible consequences of accidents at these plants should be assessed for the Arctic population and environments, owing to the possible transport of radionuclides through the river systems. The present assessment shows that the consequences of such accidents for the Arctic are likely to be much less than previously expected.

That many of the sources to be evaluated in risk assessments are within the military domain, e.g., naval reactors and nuclear weapons, is a problem. Necessary information is often restricted. Openness regarding military sources should be promoted, such that risks to society as a whole can be compared and resources for risk reduction programs used optimally.

The increased awareness of terrorist activities since 2001 has also forced the nuclear industry to reassess the probability and consequences of a terrorist event. Although AMAP does not address security issues, and this matter has therefore not been discussed further, it should be noted that, with negative intentions, the results of an ‘accident’ could be worse than those estimated in the present scenarios.