Radiological assessment: Waste disposal in the Arctic Seas

Summary of results from an IAEA-supported study on the radiological impact of high-level radioactive waste dumping in the Arctic Seas

Almost five years ago, in 1992, international attention was focused on news reports that the former Soviet Union had, for over three decades, dumped radioactive wastes in the shallow waters of the Arctic Seas. The news caused widespread concern, especially in countries with Arctic coastlines.

At the global level, the IAEA responded by proposing an international study to assess the health and environmental implications of the dumping. The proposal received support from the Fifteenth Consultative Meeting of the Contracting Parties to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention 1972), which is under the auspices of the International Maritime Organization (IMO) in London. The Consultative Meeting requested that the study include consideration of possible remedial actions, such as the retrieval of the wastes for land storage.

Shortly thereafter, in 1993, the IAEA launched the International Arctic Seas Assessment Project (IASAP).* Its main objectives were to assess the risks to human health and to the environment associated with the radioactive wastes dumped in the Kara and Barents Seas; and to examine possible remedial actions related to the dumped wastes and to advise on whether they are necessary and justified. The study, which involved more than 50 experts from 14 countries and was under the direction of an International Advisory Group, concluded in late 1996. Partially supported by extrabudgetary funding from the United States, the project was co-ordinated with the work of the Norwegian-Russian Expert Group for Investigation of Radioactive Contamination in the Northern Areas. This article summarizes the results and conclusions of IASAP, drawing upon the Executive Summary of the final report of the study.

What the study examined

Through a co-ordinated research programme, technical contracts, consultancies, and other mechanisms, the study brought together a wide range of expertise in various disciplines. The adopted approach specifically focused on:

- Examination of the current radiological situation in Arctic waters to assess evidence for releases from the dumped waste;
- Prediction of potential future releases from the dumped wastes concentrating on the solid high level waste objects which contain the majority of the radionuclide inventory of the wastes;
- Modelling of environmental transport of released nuclides and assessing the associated radiological impact on man and biota;
- Examination of the feasibility, costs, and benefits of possible remedial measures applied to a selected high-level waste object.

The total amount of radioactive waste dumped in Arctic Seas was estimated to be approximately 90 PBq (90×10^{15} Bq) at the time of dumping, based on information con-

This article is based on the Executive Summary of the IASAP study which was prepared by the project's Advisory Group. Ms. K.-L. Sjöblom of the IAEA's Waste Safety Section in the IAEA Division of Radiation and Waste Safety served as IASAP project officer..

*The background and early progress of the IASAP study was described in an article by K.-L. Sjöblom and G.S. Linsley in the *IAEA Bulletin*, Vol. 37, No. 2 (1995).

tained in the "White Book of the President of Russia" (Facts and Problems Related to Radioactive Waste Disposal in the Seas Adjacent to the Territory of the Russian Federation, 1993). The dumped items included six nuclear submarine reactors containing spent fuel; a shielding assembly from an icebreaker reactor containing spent fuel; ten nuclear reactors without fuel; and solid and liquid low level waste. Of the total estimated inventory, 89 PBq was contained in high-level wastes comprising reactors with and without spent fuel. The solid wastes, including the reactors mentioned above, were dumped in the Kara Sea, mainly in the shallow fjords of Novaya Zemlya, where the depths of the dumping sites range from 12 to 135 meters and in the Novaya Zemlya Trough at depths of up to 380 meters. Liquid low-level wastes were released in the open Barents and Kara Seas.

Additional information regarding the nature of the wastes was obtained through technical contracts placed in Russian institutes. There are, however, certain important gaps in the available information. For example, not all of the dumped high-level wastes referred to in Russian Federation documents have been located or unambiguously identified. Furthermore, some information related, for example, to the construction of the dumped submarine reactors and their fuel type remained classified. Thus, the conclusions of the IASAP study are valid only in the context of the information publicly available at the time it was completed.

The results of the IASAP study will be published in the report *Assessment of the Impact of Radioactive Waste Dumping in the Arctic Seas — Report of the International Arctic Seas Assessment Project (IASAP)*. In addition, reports containing the findings of three different working groups will be published separately: (i) the environmental and radiological description of the Arctic Seas; (ii) the evaluation of the source term; and (iii) modelling and dose assessment. The study's Executive Summary has been provided to the Contracting Parties to the London Convention 1972 as agreed at the Fifteenth Consultative Meeting.

Current radiological situation

The current radiological situation in the Arctic Seas was examined by analyzing information acquired during a series of joint Norwegian-Russian cruises and other international expeditions to the Kara Sea. In addition, oceanographic and radiogeochemical surveys, many of them related to the IASAP study, provided new information on the physical, chemical, radiochemical, and biological conditions and processes in the Arctic Seas.* The open Kara Sea is relatively uncontaminated compared with some other marine areas, the main contributors to its artificial radionuclide content being direct atmospheric deposition and catchment runoff of global fallout from nuclear weapon tests, discharges from reprocessing plants in western Europe, and fallout from the Chernobyl accident.

The measurements of environmental materials suggest that annual individual doses from artificial radionuclides in the Kara and Barents Seas are only in the range of 1 to 20 microsieverts. In two of the fjords where both high- and low-level wastes were dumped, elevated levels of radionuclides were detected in sediments within a few meters of the low-level waste containers, suggesting that the containers have leaked. However, these leakages have not led to a measurable increase of radionuclides in the outer parts of the fjords or in the open Kara Sea. At the present time, therefore, the dumped wastes have a negligible radiological impact.

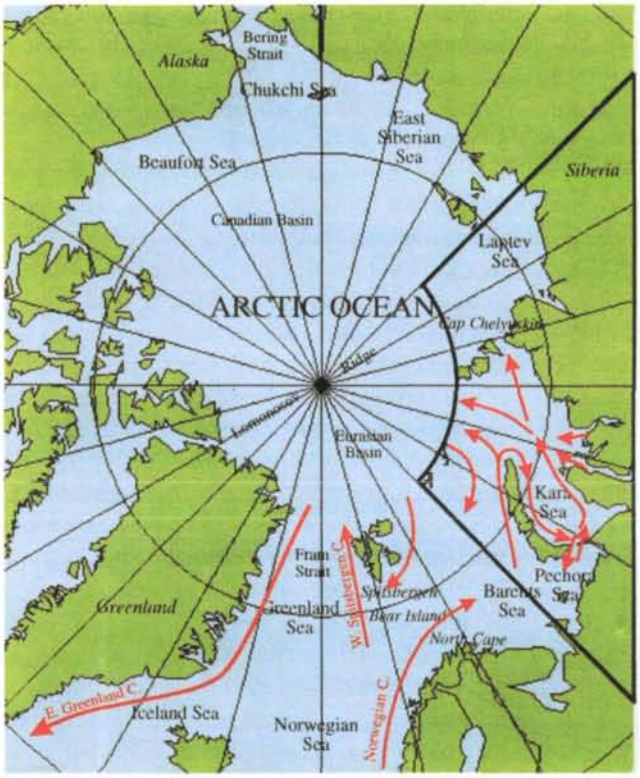
Future radiological situation

The assessment of the potential risks posed by possible future releases from the dumped wastes focused on the high-level waste objects containing the majority of the radioactive waste inventory. Release rates from these wastes were estimated and the corresponding radiation doses to man and biota were assessed using mathematical models for radionuclide transfer through the environment.

Source inventories and release rates. The characteristics of the dumped reactors and their operating histories were examined in considerable detail. This was done in order to provide appropriate release rate scenarios that can be used as input terms to the modelling of transport and exposure pathways leading to exposure estimates for humans and biota. This information, based on reactor operating histories and calculated neutron spectra, provided estimates of fission product, activation product, and

*For more information on Arctic environmental studies, see the article by P. Povinec, I. Osvath, and M. Baxter in the *IAEA Bulletin* Vol. 37, No. 2 (1995).

The Arctic Ocean, and the Kara and Barents Seas



The map at right shows the high-level waste dump sites on the east coast of Novaya Zemlya; the map at left shows the main sea currents relevant to the radiological assessment of the Arctic Seas. *(IAEA-MEL)*

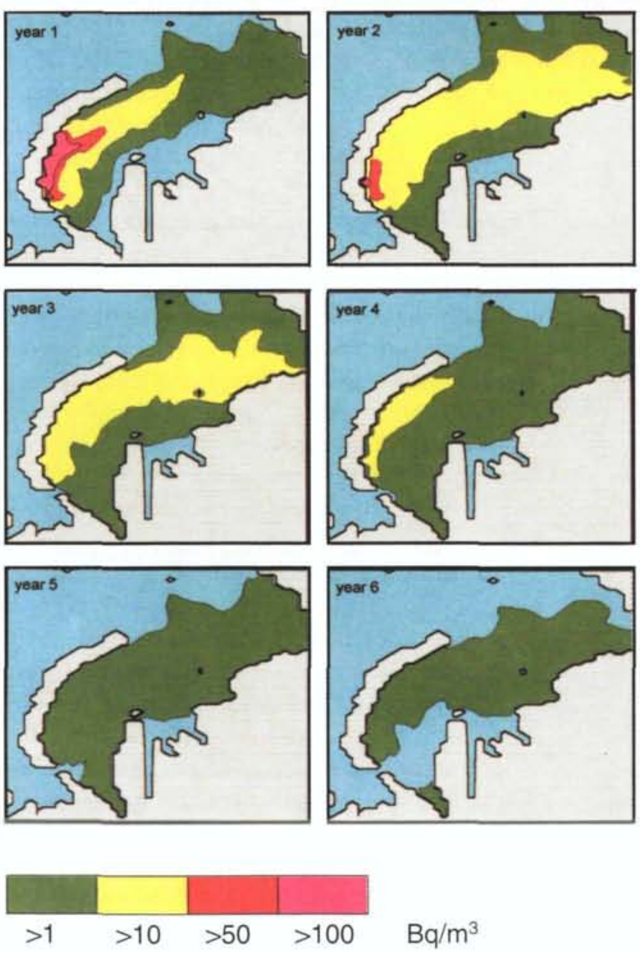


Photo: Marine scientists take water samples from the Arctic Seas. ***(IAEA-MEL)*** ***Graphs:*** Shown at left are predicted caesium-137 concentrations in seawater in the first six years after an instantaneous unit release from all dumping sites. These types of predictions were used for identification of potentially exposed populations. ***(Ingo Harms/IAEA-MEL)***

actinide inventories of the dumped reactors and fuel assemblies. It was concluded that the total radionuclide inventory of the high-level radioactive waste objects at the time of dumping was 37 PBq. The difference between this value and the preliminary estimate of 89 PBq given in the Russian White Book can be explained by the more accurate information on the actual operating history of the reactors provided to IASAP by the Russian authorities. The corresponding inventory of high-level dumped wastes in 1994 was estimated to be 4.7 PBq of which 86% are fission products, 12% activation products, and 2% actinides. The main radionuclides in these categories were strontium-90, caesium-137, nickel-63, and plutonium-241, respectively.

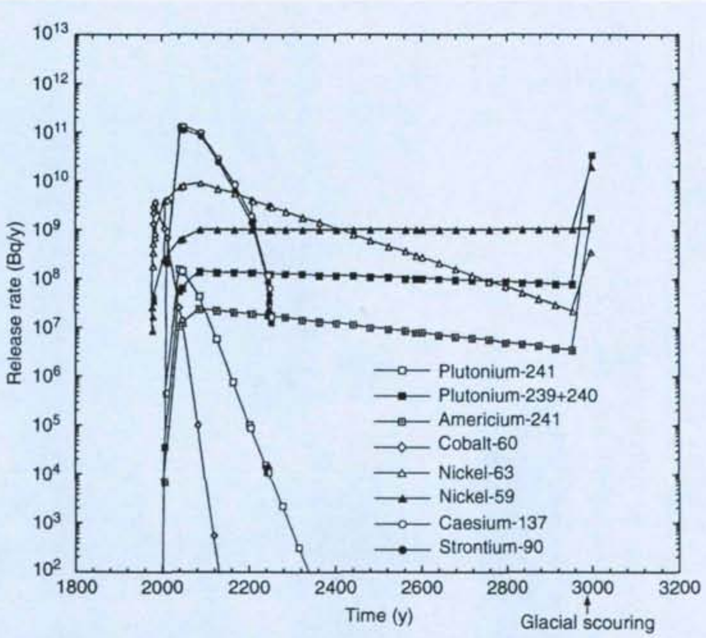
The rates of release of radionuclides to the environment will depend upon the integrity of materials forming the reactor structure, the barriers added prior to dumping, and the nuclear fuel itself. For each of the dumped high-level waste objects, the construction and composition of barriers were investigated in detail, weak points were identified, and the best estimates of the corrosion rates and barrier lifetimes were used in the calculation of release rates. External events, such as collision with ships or, more generally, global cooling following by glacial scouring of the fjords could damage the containment. This would lead to faster releases of radionuclides to the environment. In order to adequately represent the possible range of release rates to the environment, three release scenarios were considered:

- a *best estimate* scenario — release occurs via the gradual corrosion of the barriers, waste containers and the fuel itself;
- a *plausible worst case* scenario — normal gradual corrosion followed by a catastrophic disruption of two sources at a single dump site (the fuel container and the reactor compartment of the icebreaker) in the year 2050 followed by accelerated release of the remaining radionuclide inventory of these sources; and
- a *climate change* scenario — corrosion up to the year 3000 followed by instantaneous release, due to glacial scouring, of the radionuclide inventory remaining in all sources.

It should be noted that no attempt was made to assign probabilities to the events described in plausible worst case and climate change scenarios and the consequences have been assessed on the assumption that such events will occur in the years indicated.

For the *best estimate* scenario, the combined release rate from all sources peaks at about 3000 GBq/a (GBq = 10^9 Bq) within the next 100 years with a second peak of about 2100 GBq/a in about 300 years time. For most of the remaining time, total release rates lie between 2 and 20 GBq/a. The *plausible worst case* scenario results in a release "spike" of 110 000 GBq followed by releases of between 100 and 1000 GBq/a for the next few hundred years due to the accelerated release of radionuclides from the fuel container and reactor compartment of the nuclear icebreaker. In the *climate change* scenario, which assumes that glacial scouring causes an instantaneous release of the remaining inventory of all the wastes in 1000 years time, about 6600 GBq are released.

Examples of predicted release rates



Shown are examples of predicted release rates related to the climate change scenario applied to a single reactor dumped in the Novaya Zemlya Trough. The release of different radionuclides is assumed to be driven by corrosion until the year 3000 when, due to glacial scouring, the total disruption of all barriers and release of the whole remaining inventory is assumed to take place. ***(Neil Lynn, Royal Naval College, UK/Akira Wada, Nihon University, Japan)***

Modelling and assessment

The calculated release rates were used with mathematical models of the environmental behaviour of radionuclides to estimate radiation doses to people and biota. Different modelling approaches were adopted and experts from several countries and from the IAEA participated in the exercise. Substantial effort was devoted to a synthesis of existing information on marine ecology, oceanography, and sedimentology of the target area as a basis for model development.

Maximum total annual individual doses for selected population groups
(Doses in microsieverts)

Scenario	Annual doses to seafood consumers (Groups 1 and 3)	Annual doses to military personnel (Group 2)
Best estimate scenario	< 0.1	700
Plausible worst case scenario	< 1	4000
Climate change scenario	0.3	3000

Notes:
1 microsievert = 10^{-6} Sv.
For perspective, the annual doses to the critical Groups 1 and 3 from naturally occurring polonium-210 in seafood are 500 microsievert and 100 microsievert, respectively.
The worldwide total average annual dose from natural background radiation is 2400 microsievert.

Specific processes were identified as peculiar to the area and, thus, of potential importance for incorporation into models. Because of the need to provide predictions on very diverse space and time scales, a number of different models for the dispersal of radionuclides within and from the Arctic Ocean were developed.

Two main modelling approaches were adopted: compartmental or box models; and hydrodynamic circulation models. In addition, one hybrid model (using compartmental structure but at a finely-resolved spatial scale) was developed and applied. By modelling advective and diffusive dispersal, compartmental models provide long timescale, spatially-averaged, far-field predictions, while the hydrodynamic models provide locally resolved, short timescale results.

Separate attention was devoted to one of the most poorly-quantified transport pathways — sea-ice transport. A simple exemplar calculation, or scoping exercise, demonstrated that, for the radioactive waste sources considered here, sea-ice transport would make only a small contribution to individual dose compared with the transport of radionuclides in water.

For the estimation of doses to individuals, three population groups were considered. Calculations of individual doses were undertaken for time periods covering the peak individual dose rates for each of the three scenarios identified previously. Three groups were defined:

Group 1. A group living in the Ob and Yenisey estuaries and on the Taimyr and Yamal peninsulas whose subsistence is heavily dependent on the consumption of locally caught Kara Sea fish, marine mammals, seabirds and their eggs, and who spend 250 hours/year on the seashore. These habits are also typical of subsistence fishing communities in other countries bordering the Arctic.

Group 2. A hypothetical group of military personnel patrolling the foreshores of the fjords containing dumped radioactive materials, for assumed periods of 100 hours/year. The exposure pathways considered include external radiation and the inhalation of seaspray and re-suspended sediment.

Group 3. A group of seafood consumers considered representative of the Northern Russian population situated on the Kola peninsula eating fish, molluscs and crustaceans harvested from the Barents Sea. No consideration was given to the consumption of seaweed or marine mammals, nor to external radiation.

Maximum total annual individual doses for selected population groups

The maximum annual individual doses in each critical group of seafood consumers (Groups 1 and 3) for all three scenarios are small and very much less than variations in natural background doses. *(See table.)* Doses to the hypothetical critical group of military personnel patrolling the fjords (Group 2) are higher but, nevertheless, comparable to natural background radiation doses.

Collective doses were estimated only for the *best estimate* release rate scenario. The collective dose to the world population arising from the dispersion of radionuclides in the world's oceans (nuclides other than carbon-14 and iodine-129) were calculated for two time periods: (i) up to the year 2050 to provide information on the collective dose to the current generation; and (ii) over the next 1000 years, a time period which covers the estimated peak releases.

Because of the increasing uncertainties in predicting future events, processes, and developments, it was not considered meaningful to

Main conclusions of the International Arctic Seas Assessment Project

● **Monitoring has shown that releases from identified dumped objects are small and localized to the immediate vicinity of the dumping sites.** Overall, the levels of artificial radionuclides in the Kara and Barents Seas are low and the associated radiation doses are negligible when compared with those from natural sources. Environmental measurements suggest that current annual individual doses from all artificial radionuclides in the Barents and Kara Seas are at most 1 to 20 microsievert. The main contributors are global fallout from nuclear weapons testing, discharges from nuclear fuel reprocessing plants in western Europe, and fallout from the Chernobyl nuclear accident.

● **Projected future doses to members of the public in typical local population groups arising from radioactive wastes dumped in the Kara Sea are very small, less than 1 microsievert.** Projected future doses to a hypothetical group of military personnel patrolling the foreshores of the fjords in which wastes have been dumped are higher, up to 4000 microsievert but still of the same order as the average natural background dose.

● **Doses to marine fauna are insignificant, orders of magnitude below those at which detrimental effects on fauna populations might be expected to occur.** Furthermore, these doses are delivered to only a small proportion of the local fauna populations.

● **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 used as dump sites must, however, be maintained. This condition is specified to take account of concerns regarding the possible inadvertent disturbance or recovery of high level waste objects and the radiological protection of the hypothetical group of individuals occupying the beaches adjacent to the fjords.

Recommendations of the International Arctic Seas Assessment Project

● Efforts should be made to locate and identify all high level waste objects.

● Institutional control should be maintained over access and activities in the terrestrial and marine environments in and around the fjords of Novaya Zemlya in which dumping has occurred.

● If at some time in the future, it is proposed to terminate institutional control over areas in and around these fjords, a prior assessment should be made of doses to any new groups of individuals who may be potentially at risk.

● In order to detect any changes in the condition of the dumped high level wastes a limited environmental monitoring programme at the dump sites should be considered.

extend the assessment beyond 1000 years. The estimated collective doses are 0.01 man·Sv and 1 man·Sv, respectively in the two time periods. The calculations provide some illustration of the temporal distribution of the dose.

Appropriate global circulation models were used to calculate collective doses from carbon-14 and iodine-129, which are long-lived and circulate globally in the aquatic, atmospheric and terrestrial environments. Assuming the entire carbon-14 inventory of the wastes released around the year 2000 and integrating the dose to the world's population over 1000 years into the future (i.e., to the year 3000) yields a collective dose of about 8 man·Sv. The corresponding value for iodine-129 is much lower at 0.0001 man·Sv. Thus, the total collective dose over the next 1000 years to the world's population from all radionuclides in the dumped radioactive waste is of the order of 10 man·Sv. In contrast, the annual collective dose to the world's population from natural occurring polonium-210 in the ocean is estimated in other studies to be about three orders of magnitude higher. It is also informative to compare the collective dose associated with wastes dumped in the Kara Sea with the collective dose estimated for low-level radioactive waste dumped in the Northeast Atlantic. The collective dose to the world population is 1 man·Sv over 50 years and 3000 man·Sv over 1000 years from the latter practice.

The radiation dose rates to a range of populations of wild organisms, from zooplankton to whales, were calculated and found to be very low. The peak dose rates predicted in this assessment are about 0.1 milligray per hour — a dose rate that is considered unlikely to entail any detrimental effects on morbidity, mortality, fertility, fecundity, and mutation rate that may influence the maintenance of healthy populations. It is also relevant to note that only a small proportion of the biota population in local ecosystems could be affected by the releases.

Remediation options

Feasibility and costs. A preliminary engineering feasibility and cost study was conducted for five remediation options for the container of spent fuel from the nuclear icebreaker. This source was chosen because it contains the largest radionuclide inventory among the dumped waste objects and is the best documented regarding construction and introduced container barriers.

The five specific options initially selected for evaluation were:

Option 1. Injection of material to reduce corrosion and to provide an additional release barrier.

Option 2. Capping *in situ* with concrete or other suitable material to encapsulate the object.

Option 3. Recovery to a land environment.

Option 4. Disposal into an underwater cavern on the coast of Novaya Zemlya.

Option 5. Recovery and underwater transport to a deep ocean site.

Further consideration of these options by salvage experts screened out options 1, 4 and 5. Option 1 was screened out on the grounds that the spent fuel package has been previously filled with a special polymer, Furfurol(F), which might make the injection of additional material difficult. Option 4 was omitted from further consideration because the creation of an underwater cavern would be too expensive a proposition for a single recovered source and would have to be justified in a larger context. Option 5 was discarded because first, it is doubtful whether special approval could be obtained from the London Convention 1972 for an operation that entailed re-dumping of a high-level waste object in the ocean, and second, underwater transport on the high seas would involve undue risks of losing the package during carriage to a new disposal site.

Further evaluation of remedial actions was therefore confined to the two remaining options, i.e., *in situ* capping and recovery for land treatment or disposal. Both options were deemed technically feasible. The costs of marine operations were estimated to be in the range US $6 million to $10 million. It should be appreciated that for the recovery option, there would be major additional costs to those considered here for subsequent land transport, treatment, storage, and/or disposal. Radiation exposures to the personnel involved in remedial actions were considered as was the likelihood of a criticality accident. It was concluded that, with the appropriate precautions and engineering surveys proposed as a basis for proceeding with remediation, the radiation risks to the personnel involved in remedial activities would not be significant.

Radiological protection considerations for the justification of remediation. The basic concepts of radiological protection relevant to this project are those recommended by the International Commission on Radiological Protection (ICRP) and incorporated into the *International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources* (BSS) of the IAEA and other international organizations. These documents identify two classes of situation in which humans may be exposed to radiation — those in which protection measures can be planned prospectively, before sources of exposure are introduced, and other situations, where the sources of exposure are already present and protection measures have to be considered retrospectively. These are characterized respectively as practices and interventions.

The situation considered in the IASAP study falls within the category of interventions. In this case, intervention could in principle be applied at source or, following radionuclide release, to the environmental exposure pathways through which humans might be exposed. Intervention at source could include, for example, the introduction of additional protective barriers for the waste objects to prevent radionuclide release. Intervention applied to environmental exposure pathways could involve restricting consumption of contaminated food and/or limiting access to contaminated areas. In either case, it is required that remedial actions are justified on the basis that the intervention does more good than harm, i.e., the advantages of intervening, including the reduction in radiological detriment, outweigh the corresponding disadvantages, including the costs and detriment to those involved in the remedial action. Furthermore, the form and scale of any intervention should be optimized to produce the maximum net benefit.

There are a number of factors that require consideration in reaching a decision about the need for remedial actions. From a radiological protection perspective, the most important aspects are:

- The doses and risks to the most exposed individuals (the critical group) if action is not taken and the extent to which their situation can be improved by taking action; and
- The total health impact on exposed populations and how much of it can be avoided by taking remedial action. The total health impact is proportional to the collective dose, i.e., the sum of individual doses in an exposed population.

The dumped high-level radioactive wastes in the Kara Sea and adjoining fjords are in discrete packages that are expected to leak at some time in the future. They therefore constitute a potential chronic exposure situation where the concern relates to future increments of dose to exposed individuals resulting from releases of radionuclides from the dumped wastes. Depending on the physical condition of these sources, intervention (remediation) at source is the most viable course of action rather than intervention at some later time in environmental exposure pathways. The precondition for intervention is that it is both justified and optimized.

Currently, there are no internationally agreed criteria for invoking a requirement to remediate in chronic exposure situations except in the case of exposure of the public to radon, a naturally occurring radioactive gas, where international guidance suggests an action level at an incremental annual dose in the range 3 to 10 millisievert (3000 to 10 000 microsieverts). Both the ICRP and IAEA have under development guidance for applications to other types of intervention situation.

The radioactive waste sources in the Barents and Kara Seas are predicted to give rise to future annual doses of less than 1 microsievert to individuals in population groups bordering the Kara and Barents Seas. The risk of fatal cancer induction from a dose of 1 microsievert is estimated to be about 5×10^{-8} — a trivial risk. Therefore, members of local populations will not be exposed to significant risks from the dumped wastes. The predicted future doses to the members of the hypothetical group of military personnel patrolling the foreshores of the fjords of Novaya Zemlya are higher than those predicted for other members of the public and are comparable with doses from natural background radiation. (The average annual radiation dose due to natural background including radon exposure is 2400 microsieverts.) Taking into account that the doses to this hypothetical group could be controlled if required, none of the calculated individual doses indicates a need for remedial action.

Although the risks to each individual may be trivial, when summed over a population some health effects might be predicted to arise as a result of the additional exposure. These health effects are considered to be proportional to the collective dose arising from the dumped radioactive wastes. The collective dose to the world's population over the next 1000 years from the radioactive wastes dumped in the Barents and Kara Seas is of the order of 10 man·Sv. This calculated collective dose is small but can, nevertheless, be considered further in reaching a decision about the need for remediation. A simplified scoping approach to considering collective dose in a decision-making framework is to assign a monetary value to the health detriment that would be prevented if remedial action was implemented. If this scoping approach indicates that remedial action might be justified, a more detailed analysis in which the components of the collective dose are more closely examined would be warranted. Using the scoping approach it can be shown that remedial measures applied to the largest single source (the spent fuel package from the nuclear icebreaker) costing in excess of US $200 000 would not appear to offer sufficient benefit to be warranted. Since any of the proposed remedial actions would cost several million US dollars to implement it is clear that, on the basis of collective dose considerations, remediation is not justified.

Overall, from a radiological protection viewpoint, including consideration of the doses to biota, remedial action in relation to the dumped radioactive waste material is not warranted. However, to avoid the possible inadvertent disturbance or recovery of the dumped objects and because the potential doses to the hypothetical group of military personnel patrolling the Novaya Zemlya fjords used as dump sites are not trivial, this conclusion depends upon the maintenance of some form of institutional control over access and activities in the vicinity of those fjords.

Finally, it is noted that the discussion of the IASAP study was confined to the radiological aspects of decision-making regarding the need for remedial action. The political, economic, and social considerations that must form an important part of the decision-making process are not considered and are largely matters for the national government having jurisdiction and responsibility regarding the dumped radioactive wastes. ❐