7. Assessment Results, Conclusions, and Recommendations

The primary goal of this risk assessment is to evaluate the health and environmental threat to coastal Alaska posed by the FSU's dumping of radioactive wastes in the Arctic and North west Pacific Oceans. In particular, 16 nuclear reactors from submarines and an icebreaker were discarded in the Kara Sea near the island of Novaya Zemlya, of which 6 contained spent nuclear fuel; liquid and solid wastes were disposed in the Sea of Japan; a ^{90}Sr-powered radioisotope thermoelectric generator was lost at sea in the Sea of Okhotsk; and several disposal sites for liquid wastes were located in the Pacific Ocean east of the Kamchatka Peninsula. In addition to these known sources in the oceans, FSU waste-disposal practices at inland weapons-development sites have resulted in contamination of major rivers flowing into the Arctic Ocean; these are evaluated for their ongoing and potential sources. For these sources, the RAIG evaluated the potential for release to the environment, transport, and impact to Alaskan ecosystems and peoples through a variety of scenarios.

7.1 Assessment Context

This assessment addresses the potential for ecological and human risk, resulting from known and predicted levels of contaminants in the Arctic Ocean and its immediate vicinity. The assessment does not address inventories in currently operating Russian or American naval vessels, or in wastes currently being managed at Russian naval yards.

The first principal activity for the risk assessment was to characterize the sources of radionuclides in the Arctic seas. This included not only the FSU sources of interest in the Kara Sea and Northwest Pacific, but potential sources through riverine transport from Russian watersheds to the Arctic Ocean. Additionally, to place these sources into perspective and to obtain a comprehensive understanding, also characterized were the already existing fallout levels of key radionuclides; wastes from the Chernobyl incident and from European fuel reprocessing facilities at Sellafield (United Kingdom) and La Hague (France); and naturally occurring radioactivity. The initial list of potential contaminants was screened to a manageable number of contaminants likely to produce the greatest risk to the environment or human health. This process was based on a set of simple exposure equations. The final list was established to provide reasonable assurance that the preponderance of the risk of either long-term carcinogenicity of humans or long-term survival of aquatic biota was addressed. Additional considerations were given to known sources of radioactive materials.

The spatial domain and spatial scale of the analyses were established in consultation with ONR and other ANWAP researchers. The agreed focus was on coastal Alaska. To best represent the environmental conditions and state of knowledge relative to contaminant transport in the Arctic, the study area was divided into 21 compartments. A compartmental model was developed to predict the transport of radionuclides from disposal sites to other portions of the Arctic.

The RAIG established the indicators that would be used to judge the degree of hazard. For the ecological risk assessment, this consisted of defining a set of indicator species for which comparisons against toxicological benchmarks would be made, and for humans, a range of potential dietary exposures for Alaskans with subsistence life-styles was chosen. The selection of the indicator species is described in Section 5. For the human risk assessment, a suite of nine human exposure scenarios relating to subsistence life-styles at different locations was developed, described in Section 6. Human risk is limited to individual long-term carcinogenicity. The scenarios cannot address cultural impact or multigenerational impact of the exposures.

7.2 Assessment Results

7.2.1 Sources

Screening analyses indicate that the principal radionuclides of concern are ^{241}Am, ^{137}Cs, ^{239}Pu, and ^{90}Sr. The screening indicates that the most credible sources in terms of future impacts to Alaskan waters are the wastes disposed of in the Kara Sea and the liquid radioactive wastes stored at inland locations in Russia. Other sources, such as those in the Sea of Okhotsk or the Sea of Japan, are essentially inconsequential in Alaskan Arctic waters.

Background concentrations resulting from historical nuclear testing and past accidents currently exist in the Arctic. Relatively uniform levels of the key radionuclides are present throughout the Arctic waters from these sources. In addition, operation of the Sellafield nuclear reprocessing facility in Great Britain has resulted in the discharge of about 41,000 TBq of ^{137}Cs and 590 TBq of ^{239}Pu to the Irish Sea through 1992. Of this amount, an estimated 9,000 TBq of ^{137}Cs and 20 TBq of ^{239}Pu is estimated to have reached the Arctic Ocean. Concentrations from these sources in Alaskan waters are currently about 0.001, 2, 0.005, and 1 Bq/m^3 of ^{241}Am, ^{137}Cs, ^{239}Pu, and ^{90}Sr, respectively, down from highs in the 1960s of about 0.009, 14, 0.05, and 9 Bq/m^3. In contrast, naturally occurring ^{210}Po is present worldwide at about 1 Bq/m^3 in seawater.

Marine reactors dumped in the Kara Sea contain about 1,000 TBq of ^{137}Cs and 6 TBq of ^{239}Pu. These will be released over time from corrosion/dissolution of the fuel. In addition, inland storage of liquid radioactive wastes holds about 1,400 TBq of ^{90}Sr and 24 TBq of ^{137}Cs. These sources of radionuclides were modeled using two different types of scenarios: one to represent acute or accidental releases and the other to represent chronic or expected releases. The time-dependent chronic-release scenario results from the reactors in the Kara Sea are presented in Figure 2-7. The chronic-release scenario results from the inland sources consist of a base discharge of 40 TBq/yr of ^{90}Sr from reservoir leakage that declines as a function of time with the radioactive decay of the ^{90}Sr. The acute releases for both the Kara Sea and inland sources are essentially instantaneous releases of the entire inventories.

7.2.2 *Transport*

A compartmental modeling approach was used to simulate the transport of radionuclides from the Kara Sea nuclear wastes and riverine sources to Alaskan waters. Water flows between compartments were estimated using a coupled ice-ocean circulation model. Radionuclide losses within a given compartment were modeled to occur via sedimentation and radioactive decay. The model is capable of simulating discrete as well as time-varying releases of radionuclides to Arctic Ocean waters over long periods of time (decades to centuries). Because of low sorption coefficients and low particle loadings in the Arctic Ocean, radionuclide transport is dominated by water currents rather than sedimentation processes. The RAIG also found that the transport capacity of the coastal currents also is greater than the capacity associated with ice and entrained sediment. It benchmarked its simulations against other models of the transport of radionuclides in the Arctic, and found good agreement.

The predicted concentrations in the Beaufort, Bering, and Chukchi seas of the four key radionuclides from FSU releases were much lower than either historic or current levels. Measured data on the concentrations of these radionuclides in Alaskan waters indicate that the highest levels occurred in the 1960s as a result of global fallout. The highest predicted concentration of ^{137}Cs is 0.032 Bq/m^3 in the Beaufort Sea following an assumed instantaneous release to the Kara Sea from the disposed nuclear wastes. This level is much lower than the 2 Bq/m^3 of ^{137}Cs measured in the 1990s, and lower still than the 14 Bq/m^3 measured in the 1960s. A more realistic scenario, in which the radionuclides are released slowly to the Kara Sea as a result of corrosion and dissolution processes, results in predicted peak concentrations of only 0.0007 Bq/m^3. The time-dependent concentrations of the key radionuclides are presented in Figures 3.8 through 3.10.

7.2.3 *Ecological Risks*

In order to evaluate the future exposures to marine biota, and humans that eat them, the RAIG compiled data on bioconcentration factors (BCFs). The BCFs are a commonly used, unitless, parameter that describe bioaccumulation processes resulting from transfer of radionuclides from ecosystem components (water, particulate matter, food) into organisms. The RAIG was able to recommend BCFs for groups of marine organisms from different trophic levels in Arctic ecosystems. A key result is that BCFs in Arctic systems do not seem to vary significantly from those in more temperate ecosystems.

The RAIG established minimum dose and dose rate levels, called No Observable Effects Levels (NOELS), for radiation effects on biota. The effects considered included mortality, sterility, and reduced fertility. The NOELS for fertility correspond to the lowest concentrations of radionuclides in seawater.

Using the predicted radionuclide concentrations in water with the BCFs, the team calculated accumulation of the key radionuclides in Arctic biota, and then estimate the radiation dose rates to these biota. Our predicted dose rates from incremental increases in radiation from FSU sources are all three to five orders of magnitude lower than our lowest dose-rate NOELS. Therefore, the following are the conclusions from our risk assessment for marine biota in Alaskan waters:

- The dose and dose rates that cause mortality to marine species are not expected to occur in the Arctic as a result of FSU dumping.

- The doses and dose rates causing sterility, or even decreased fertility, are not expected to occur in the Arctic as a result of FSU dumping.

- There is no indication that there will be any decrease or loss in indigenous populations or any damage to ecosystems through decreases in biodiversity.

7.2.4 Human Risk

Our analyses of doses associated with naturally occurring ^{210}Po and background levels of ^{137}Cs and ^{90}Sr in Arctic water indicate that the largest doses to individuals living in Alaskan coastal communities who consume subsistence seafoods is from ^{210}Po, followed by ^{137}Cs and ^{90}Sr derived global nuclear fallout. Doses from ^{210}Po can range as high as 1,500 μSv/yr; doses from fallout were as high as 10 μSv/yr in the 1960s, and are now around 1 μSv/yr.

Although very low, the highest predicted doses to Alaskan coastal residents were for the instantaneous release of ^{241}Am, ^{137}Cs, ^{239}Pu, and ^{90}Sr contained in the Kara Sea wastes. The highest of these estimated values was about 0.1 μSv/yr. However, the highest predicted doses from FSU sources were well below doses from background levels of ^{210}Po and nuclear fallout. The corrosion-driven chronic release of nuclides from the nuclear reactors, which is a far more realistic release scenario, results in doses that are about 100 times lower than the acute case, with a peak of about 0.001 μSv/yr.

The acute and chronic discharges of ^{90}Sr and ^{137}Cs from wastewater storage ponds and reservoirs into the Ob and Yenisey rivers produce doses that are as low as chronic discharge of radioactive wastes in the Kara Sea, generally no higher than about 0.001 μSv/yr.

7.3 Extension of Results to Other Contexts

The human risk assessments documented in Section 6 focus on Alaskan coastal residents consuming a subsistence diet. This is the set of people in Alaska, and in fact in the United States, most highly exposed to radionuclides from FSU dumping in the Arctic and other FSU waste-related sources. Based on the results from this group, additional conclusions may be drawn regarding non-subsistence residents, visitors and tourists, and the Alaskan fishing industry as a whole.

7.3.1 Non-Subsistence Residents

Almost the only significant pathway of exposure to radioactive contaminants in Arctic waters is via the consumption of Arctic seafoods. Therefore, the radiation dose to residents who do not live a subsistence life-style is directly proportional to the quantity of seafoods eaten. In general, non-subsistence residents would be expected to eat less seafood than the types of subsistence residents defined in Section 6. The current and projected doses to the subsistence residents from FSU radionuclides were extremely low. It is reasonable to assume that doses to non-subsistence residents would be even lower, and that no impacts are to be expected to any residents of Alaska exposed via the seafood pathway.

7.3.2 Visitors and Tourism

Tourism and ocean sport fishing are a growing part of the Alaskan economy. Again, the primary pathway of exposure to visitors and tourists would be through the ingestion of seafoods caught in Alaskan waters. For most visitors, the amount consumed would be small relative to the diet of substance residents. Some individual sportsmen might bring home a substantial catch, and the resulting radiation dose could approach that of a subsistence resident. The doses and risks to any individual sportsman would be no larger than that of the subsistence residents, however, and no health impacts would be expected. There is no reason to expect that FSU dumping should have any impact on sport fishing or tourism in Alaska.

7.3.3 Alaska Fishing Industry

During immersion in seawater, fishing gear may entrain particles of sediment on which radioactivity is adsorbed. This applies particularly to fiber strands of which many items of fishing gear (e.g., ropes, nets, and pots) are composed. The potential for radiation doses from handling contaminated fishing gear has been evaluated for similar northern ocean fisheries. Models for exposure to fishermen have been developed (Hunt, 1984), applied at various sites (e.g., Shinohara and Asano, 1992), and even verified against direct measurements (Hunt, 1992). Exposures via this pathway are universally described as being of minor importance compared with the ingestion pathways (Hunt, 1984; Hunt, 1992; Shinohara and Asano, 1992). Because the doses via ingestion of fish are very low, such that health effects are not expected, the doses to fishermen from handling fishing gear will be inconsequential.

The incremental concentrations of FSU radionuclides projected for seafoods in the future are much lower than currently existing concentrations derived from fallout. These incremental concentrations will not be detectable above the background levels. Risks to any consumers of fish exported from Alaska would be no higher than those to subsistence residents. Therefore, there should be no danger of consumer resistance to Alaskan fish, and no risk to the Alaskan fishing industry from past FSU waste dumping.

7.4 Possible Use of Results in Future Contexts

The sources of radioactive release evaluated in this report are those currently in or entering the Arctic Ocean. However, the methods developed are applicable to other potential sources. Such sources could include nuclear submarines or stored spent nuclear fuel at military bases in Murmansk or Vladivostok (Dyer et al., 1996; Nilsen and Bohmer, 1994; Nilsen et al., 1996), and upcoming events such as expedited decommissioning of Russian nuclear submarines as envisioned under the U.S./Russian START II Treaty. These sources could potentially be very large, but because the plans for Russian disposition of these wastes are in a state of rapid change, they are not addressed in this report. The focus of funding for ANWAP was marine and riverine Russian sources.

As radionuclide inventories, either planned or already disposed of in various locations around the Arctic Ocean, are identified, the methods described in this report could be applied and doses to people around the Arctic Rim could be estimated.

7.5 Conclusions

There is no indication that concentrations of radionuclides in Alaskan waters are currently elevated as a result of dumping by the FSU. The predicted concentrations of radionuclides in Alaskan waters from FSU dumping activities to date are so low in all cases as to make them undetectable against current background levels.

The ecological risks estimated for the coasts of Alaska are generally about 5 orders of magnitude below levels at which any effect would be expected. There is no indication that there will be any decrease or loss in indigenous populations or any damage to ecosystems through mortality, changes in fertility, or decreases in biodiversity.

The potential health risks associated with the ingestion of Alaskan seafoods containing radionuclides derived from releases from Russian nuclear wastes are extremely low, which essentially means that those wastes pose no threat to human health. No health effects are predicted. Alaska Native communities need not alter any of their dietary habits associated with subsistence foods obtained from Alaskan waters on the basis of concern over radioactivity stemming from waste-management practices in the FSU. Other economic or cultural activities should be unaffected.

7.6 Recommendations

7.6.1 Monitoring

The research revealed a dearth of information regarding uptake of radionuclides in Arctic marine mammals. Although it is unlikely that more information would change the conclusions of this report, more sampling of marine mammals, of organs as well as muscle consumed by residents, would strengthen the capability to predict impacts. Concurrent sampling of ocean water would help develop more accurate bioconcentration factors. Similar information about uptakes in birds, eggs, and other commonly eaten foods is needed. This research need not be performed only in Alaskan waters—data from other northern countries would be valuable as well.

Radionuclide fluxes down the major Siberian rivers contribute as much risk as the materials dumped directly into the Arctic. Very little sampling has been done in the long northern portions of these rivers. Additional monitoring data in these rivers' water, sediment, and biota would help in the understanding of their potential for transporting contaminants to the Arctic.

7.6.2 Research

Much of the information in this analysis for the inland sources of contamination is derived from general descriptions lacking in detail. Additional international research on the current contents of the FSU fuel-cycle facilities at Krasnoyarsk, Tomsk, and Mayak is needed. The inventories and availabilities of all radionuclides in lakes, holding ponds, and groundwater sources are needed to better define the long-term potential for releases. In particular, better detail is needed on the long-lived, environmentally mobile radionuclides other than the easily detected ^{137}Cs or ^{90}Sr.

The modeling done in this assessment for uptake and transport of radionuclides by ice showed it to be a minor contributor to radionuclide concentrations near Alaska. Part of the reason for this insensitivity to this transport route is that ice appears to primarily transport material across the Arctic from near Novaya Zemlya towards Greenland. Future assessments of the north Atlantic would benefit from additional study of this pathway's processes.

The dose modeling performed here assumes that the biota are at equilibrium with the surrounding seawater. The RAIG has no integrated view of the role of sediment and biota in the transport of radionuclides. More data on contaminant bioavailability in sediments, sediment transport, and biotic migration would improve assessments.

7.6.3 Modeling

The experience gained in conducting this assessment shows that there is an opportunity for closer cooperation between assessment modelers and the scientific groups developing ocean circulation models or performing tracer studies. The various groups involved in Arctic-contamination research should continue to work together to provide integration of ongoing experimental work into useful assessment information.

7.6.4 Other

Additional data on transport of materials in the Arctic Ocean could benefit assessment of numerous other contaminants. Much of the data used in the preparation of this report is of recent origin, and validation or verification is needed. Particularly important would be additional information on Arctic currents: their stability and longevity, influence of wind, and possible seasonal changes.

Although the analyses of this report suggest that transport of radionuclides in ice is not a major mechanism for moving contamination towards Alaska, it does appear to somewhat increase the transport towards Greenland. If the models and techniques developed for this report are considered for future assessments for other countries of the Arctic, additional information on the mechanisms of incorporation of sediments and contaminants in ice, and their transport, would be valuable.

The results of this report suggest that the largest impacts will be in the immediate vicinity of the Russian waste dump sites. Future monitoring to further evaluate the sources, locate others, and to validate the modeled source terms is suggested.

This report focused on aquatic sources and foods. It appears that the doses are dominated by natural background levels of ^{210}Po and radionuclides from global fallout. For complete perspective, equivalent assessments of the terrestrial pathways for native subsistence life-styles would be beneficial.

The scope of this report was existing radioactive wastes in the marine environment and ongoing potential inland releases. Additional potential sources of radioactivity exist in the Russian Arctic, particularly nuclear wastes associated with Russian naval activities in Murmansk, Vladivostok, and other naval bases. The techniques developed here could also help evaluate the possible impact of hypothetical, or future actual, accidents in those areas.