# Environmental and Health Effects of Nuclear Waste Dumping in the Arctic

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At the heart of the tremendous interest in the nuclear waste dumping that was carried out by the former Soviet Union in the Arctic and North Pacific are concerns over the potential human health effects or ecological impacts. People have wondered how seriously the dumped wastes might contaminate the environment, and whether they pose current or future hazards to human health or ecosystems.

Understanding both current and future risks to human health requires information about the nature and amount of radionuclides released into the environment, and information about their transport through the environment and through food chains to reach human beings. Understanding risks to ecosystems requires additional information about the effects of radiation on the variety of different organisms that make up the ecosystems.

Important questions remain at each step described above. Since the release of the Yablokov report describing dumping in the Arctic, more has been learned about some of the wastes, but their condition and likely radionuclide release rates remain largely unknown. As described in chapter 2, current levels of radionuclides in the seawater and sediment in Arctic seas do not suggest that significant releases have occurred. Even though current risks do not appear to have increased as a result of the dumping, release rates and pathways to people remain to be evaluated to understand the magnitude of future risks.

Models used to approximate the behavior of agents in the environment require a tremendous amount of site-specific information. Much of the specific information required is not yet known for the Arctic environment or for particular dump sites, although it is being gathered. Several different efforts are underway to model the environmental transport of radionuclides dumped in the Arctic as well as those released at sites in Russia along rivers that drain into the Arctic.

The most likely route of human exposure to radionuclides in the seas is through the food chain. Thus, in addition to information about radionuclide movement through the physical environment, data specific to the Arctic regions must be compiled about biological pathways to human beings. The marine food web is complex, and most available data were collected in temperate, rather than Arctic, settings. Therefore, information is required about the way in which radionuclides are transferred—and sometimes concentrated—through the food chain under the special local and regional conditions existing there.

People of the world are not equally at risk from radionuclides dumped in Arctic seas or in the Russian Far East. Current and future investigations have to focus on gathering relevant information about the dietary habits and other characteristics of the populations who are most likely to be exposed, such as Native northern populations and others who rely on Arctic marine resources. This information will be critical for a thorough risk assessment to estimate the most likely effects on human health.

If the released radionuclides come in contact with people in amounts sufficient to cause health effects, these effects are most likely to be cancers. Radiation is a known cause of cancer and other health effects at high doses, but at the low doses that might occur from environmental contamination, the effects are difficult to study and therefore less certain. For the protection of public health, international experts have developed recommended dose limits for the general public from human practices. These can be used to consider potential radiation exposures and the degree of hazard they might pose.

Radiation effects on Arctic ecosystems are still not well known. Sensitivity to radiation varies among species, but in general, plant and animal populations do not appear to be more sensitive than humans to the effects of radionuclides in the environment (26,28). Relevant data from Arctic environments are extremely limited.

No comprehensive risk assessment of the impacts likely from the radioactive waste dumping has yet taken place. Ideally, the process of carrying out a thorough risk assessment would entail evaluating the available information to address a specific question about risk. What is the likelihood of a certain specific population experiencing a health effect such as cancer? A systematic attempt to address such questions would help make clear the data gaps that remain. Until such a careful analysis is carried out, it will remain difficult to integrate the increasingly available information to arrive at a clear answer about future risks.

Several rough approximations of risk from the dumped radioactive wastes have been made; these suggest that even worst-case scenarios for sudden release of the wastes do not pose a severe global hazard. However, they are made in the absence of specific information that could elucidate which populations are most at risk and what the risks might be. A more thorough assessment is required to answer these questions.

As more information is gathered and the risk assessment is carried out, it is critical that the public be involved in the process. Genuine efforts must be made to ensure that the potentially affected communities participate in decision making, provide input, and have access to the information collected.

After a brief review of the health effects of radiation, this chapter examines current understanding of the health and ecological effects of the radioactive contamination that has occurred from the dumping of nuclear waste in the Arctic and North Pacific (or that might result from future contamination events). Some of the major gaps in information and understanding are also identified.

## HUMAN HEALTH EFFECTS FROM RADIATION

### Radiation and Radioactivity

Radiation is the transport of energy through space. The energy can be in the form of particles or electromagnetic waves. When radiation transfers enough energy to displace electrons from atoms and break the bonds that hold molecules together, it is called ionizing radiation. Ionizing radiation may be released when unstable atoms called radionuclides decay to more stable forms or may be produced in man-made devices such as x-ray tubes. Because biological systems are highly structured and specific at the molecular level, the changes caused by ionizing radiation are usually damaging to the function of the cell, tissue, or organ involved.

Ionizing radiation is frequently categorized into particles and electromagnetic waves. Particulate radiation includes alpha particles, beta particles, neutrons, and protons and ionizes matter by direct atomic collisions. Both alpha and beta particles have mass and can travel only short distances in air or human tissue because they rapidly transfer their energy through ionizing collisions. Both x-rays and gamma rays are electromagnetic waves or photons; they are referred to as penetrating radiation because they travel long distances and can penetrate dense material. Penetrating radiation ionizes matter as it passes through tissue and interacts with atoms, imparting energy.

Radioactivity is the property of certain unstable atoms (radionuclides) to disintegrate spontaneously, releasing radiation and forming a different "daughter" nuclide. Radionuclides share the chemical characteristics of their stable forms in the periodic table, except that they give off energy (radiation) as they decay to more stable states. For example, carbon-14 is an atom that is produced both in the atmosphere by the interaction of cosmic rays with matter and in nuclear reactors. It behaves like carbon-12 in almost every way except that it is unstable. When it decays, it emits ionizing radiation, resulting in stable nitrogen-14. Daughter nuclides can also be unstable, proceeding to undergo radioactive decay themselves. Strontium-90, a man-made radionuclide, decays to yttrium-90 with the emission of radiation. Yttrium-90 in turn decays to zirconium-90 as more radiation is released (6).

## Radiation Health Effects

The release of radioactive contamination into the environment is of concern because of the potential harm to people and ecosystems from radionuclides. Radionuclides are carcinogens and, at high doses, can also cause rapid sickness and death.

The health effects of exposure to radiation depend on many factors, including the type of radiation, the amount of energy it delivers, the length of time over which exposure occurs, the organs or tissues the radiation interacts with, and characteristics of the exposed person (host factors such as age). Most credible scenarios for radiation doses to people from environmental contamination are based on internal exposure rather than external—that is, radionuclides that are inhaled or ingested rather than those that are outside a person. Radionuclides in the body are referred to as internal emitters, because they continue to impart energy to the surrounding tissue from within and, thus, can continue to harm or alter cells for extended periods.

## Mechanism of Action

The hazards posed by radiation depend on its interaction with living tissue. At the molecular level, the electrons set in motion by ionizing radiation can directly impact cellular macromolecules such as DNA (deoxyribonucleic acid). Radiation can also act indirectly by ionizing water molecules to create reactive molecules (free radicals) that can in turn attack DNA or other cellular components as oxidizing agents. Both direct and indirect mechanisms cause damage to the cell, particularly as a result of damage to DNA.

The mechanism of damage to DNA and other important cellular macromolecules is not unique to radiation. Normal cellular processes, as well as many other agents, cause similar oxidative damage. As a result, natural processes exist that can rapidly repair DNA damage. Serious effects can result, however, when the damage is too great for such repair processes or when a lesion is not repaired.

When ionizing radiation passes through an organism, several different results are possible. If changes or damages wrought by the ionization are not fully repaired, the cell can be killed or prevented from reproducing. Alternatively, the cell can be modified while still being able to reproduce. These situations describe two categories of effects from radiation—"deterministic" and "stochastic."

## Deterministic Effects

Deterministic end points are almost all due to high doses that overwhelm cellular repair processes and cause cell death. Damage that kills one or a few cells may not even be noticeable, but beyond a certain threshold, the loss of cells will be reflected in loss of tissue function, possible organ impairment, and death. Below the threshold the probability of such harm is zero, but above some dose level at which tissue function is lost, the severity of the harm will increase with dose (28). Thus, at high doses of radiation, the threshold for damage in several tissues is exceeded, and severe biological effects are predictably observed.

When humans are exposed to relatively high doses of radiation (greater than 50 rads[1]; see the discussion of units used to describe radioactivity and radiation dose in box 3-1) to the whole body, deterministic effects of radiation will occur within hours, days, or weeks. These effects are called acute radiation syndrome and include nausea, vomiting, fatigue, and a lowered white blood cell count. The symptoms and their severity depend on the dose of radiation received. Death can result from infection, dehydration, or low white blood cell count, and is increasingly likely at doses greater than 100 rads. An estimate of 300 rads has been made for the median lethal dose to humans within 60 days (35).

## BOX 3–1: Units Used to Describe Radioactivity and Radiation Doses

An array of different terms and units are used to convey radiation levels and the doses of radiation to which people are exposed. In 1980 the International Commission on Radiation Units and Measurements adopted the International System of Units (known as SI units) for radiation quantities and units to be used internationally (69). Adoption of the SI nomenclature in the radiation field in the United States has been slow, with the result that both the previous conventional system and the SI system are currently in use. Conventional units are used throughout this report, with the SI conversion factors provided in this box and equivalencies provided as necessary.

Radioactivity is the phenomenon of radioactive disintegration in which a nuclide is transformed into a different nuclide by absorbing or emitting a particle. The activity of a radioactive material is the number of nuclear disintegrations per unit time. The conventional unit used to express activity is the curie (Ci), which is $3.7 \times 10^{10}$ nuclear transformations per second and approximates the activity of 1 gram of radium-226. The SI unit for activity is the becquerel (Bq), where each becquerel is one nuclear transformation per second (thus, 1 curie = $3.7 \times 10^{10}$ Bq).

The half-life of a radioactive substance is the time required for it to lose 50 percent of its activity by decay. Each radionuclide has a unique half-life. Activity and half-life are related, so that radionuclides with higher specific activity (activity per gram) have shorter half-lives, and vice versa.

Levels of contamination are frequently reported in terms of activity (curies or becquerels) per unit volume or area. For example, measurements of the activity in the Kara Sea by the Joint Russian-Norwegian Commission in 1992 found levels of cesium-137 at 3–20 Bq/$m^3$ in sea water ($8 \times 10^{-11}$ –$5.4 \times 10^{-10}$ Ci/$m^3$) (30). Such measurements convey the amount of a radioactive substance present in a certain medium. Alone, however, they provide no information about risks to human health. To understand possible risks to health requires a host of additional information that can be used to calculate and interpret a radiation dose.

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[1] 1 rad = 0.01 joule/kg = 0.01 gray.

### BOX 3–1: Units Used to Describe Radioactivity and Radiation Doses (Cont'd.)

For any potential harm from radioactivity, radiation must interact with the cells and tissues of the human body and deliver a dose. Several different units are used to describe radiation dose. Absorbed dose is the energy absorbed per unit mass, given in units called rad. SI units for absorbed dose are gray (Gy), and 1 Gy is equivalent to 100 rads.[a] The biological effect of radiation is related to the absorbed dose, but it also depends upon several other factors, such as the type and energy of the radiation causing the dose. A "radiation weighting factor" is applied to the absorbed dose to account for differences in the relative biological effectiveness observed experimentally, for example, between low-energy x-rays and alpha particles, which deposit much greater amounts of energy over the distance they travel. Adjusted with the weighting factor, the measurement of dose is called the equivalent dose, and is measured in units called rem. The SI unit for equivalent dose is the sievert (Sv); 1 Sv = 100 rem. Since the probability of stochastic effects also depends upon the organ or tissue irradiated, still other weighting factors are used to account for differences in the effect of radiation on different tissues in the body. This dose, now weighted to account both for tissue differences and differences in the energy and type of radiation, is called the effective dose (formerly effective dose equivalent) (28).

Some additional dosimetric terms are also used in this report. The committed effective dose takes into account the continued doses to the body when radionuclides are taken into the body and become internal emitters. The collective effective dose relates to groups of people, rather than individuals, taking account of the number of people exposed by multiplying the average dose to the exposed group by the number of people in the group. The unit of this quantity is the person-rem, which is an effort to represent the total consequences of the exposure to a population. Sometimes the collective effective dose is accumulated over a long time, spanning successive generations, depending upon the quantity and half-life of the radionuclides (28).

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[a] One rad = 0.01 joule/kg = 0.01 Gy.

SOURCE: Office of Technology Assessment, 1995.

## Stochastic Effects

At doses lower than those that produce acute symptoms, the effects of radiation on human health are less predictable. If a damaged DNA site is misrepaired or not repaired, and the modified cell is still able to reproduce, its propagation may ultimately result in cancer. Development of a cancer is understood to be a multistep process in which modification of a cell's DNA is a critical step that must be followed by other steps to eventually lead to uncontrolled growth. Thus, not every cell with damaged DNA will go on to become cancerous. However, the more cells that contain damaged DNA, or the more damage sites that occur in the DNA of a single cell, the more likely it is that one of them will ultimately develop into a cancer. Once sufficient changes have taken place at the molecular level, cancer develops; cancer from low or moderate doses is no different from one induced by high doses. In other words, the likelihood, but not the severity, of a cancer is roughly proportional to dose and probably has no threshold (28). This type of effect is called stochastic, meaning "of a random or statistical nature."

Numerous studies in humans and animals have established that radiation can cause cancer and that the incidence of cancer increases with increasing radiation dose. What is less certain is the relationship between the size of the dose and the likelihood of developing cancer. At low dose levels such as might be encountered from contamination in the environment, it is almost impossible to collect quantitative data on human risk. Therefore, it has been necessary to extrapolate from data collected on humans exposed to much higher doses and dose rates, such as atomic bomb survivors or medically irradiated people. The need to estimate effects based on data from very different conditions necessarily leads to uncertainties in describing risks.

Other factors add to the difficulty of estimating the risks of low-level radiation. The long period (called a latency period) between a main exposure and the appearance of a tumor makes studies to understand the relationship between dose and cancer likelihood challenging. Furthermore, since cancer causes nearly 20 percent of all deaths in the United States, and cancers resulting from radiation do not have features that distinguish them from those due to other causes, the subtle increases in cancer rates that might be attributable to various environmental causes are difficult to detect (45).

Despite these challenges, efforts have been made to estimate the cancer impacts from low levels of radiation. These estimates have been adjusted repeatedly over the years, particularly as more information has been gleaned from studies of the atomic bomb survivors as they age and experience their greatest risks from cancer. The estimates differ for different cancer sites and for different ages at time of exposure, but overall, the National Research Council's Committee on the Biological Effects of Ionizing Radiations (BEIR) most recently estimated that a single equivalent dose of 10 rem (see box 3-1) to the whole body carries a lifetime excess risk of death from cancer of 0.8 percent, or 8 out of 1,000. If the same dose is accumulated over weeks or months rather than all at once, the risk is estimated to be reduced by as much as a factor of two or more[2] (45). It is important to reiterate that these estimates are based on studies of effects at relatively high doses and high dose rates; "studies of groups chronically exposed to low-level radiation . . . have not shown consistent or conclusive evidence of an associated increase in the risk of cancer" (45). As mentioned above, however, a variety of factors makes it extremely difficult to observe such effects in epidemiological studies.

Genetic effects as well as cancer fall into the category of stochastic effects of radiation. Radiation damages the genetic material in reproductive cells, leading to mutations that can be passed to successive generations. Like the cancer effects of low-dose radiation, the genetic effects of radiation are difficult to study. Because the effects are manifest in the offspring rather than the person exposed to radiation, there can be a long delay in observing them. Massive epidemiological studies with long-term follow-up would be required to gather enough data for statistical analysis. Furthermore, the same mutations that radiation causes can occur spontaneously; therefore, estimating the contribution from radiation is very difficult (45). Studies on the children of atomic bomb survivors failed to detect elevations in rates for genetic abnormalities, but because of the size of the study population, such effects are not ruled out. It is also possible that such effects could manifest themselves in future generations as recessive mutations which are hidden until carried by both parents (8). Based on studies in laboratory animals and studies of the offspring of atomic bomb survivors, the percentage of genetic diseases attributable to natural background radiation is currently estimated to be low; however, these estimates are based on many uncertainties (67).

The embryo is highly sensitive to radiation. Various malformations and developmental disturbances result from irradiation of the embryo at critical stages in the development of each organ. Most notable in studies of atomic bomb survivors has been a dose-dependent increase in intelligence impairment and mental retardation in people irradiated by fairly high doses between the eighth and 15th weeks after conception. To a lesser extent, mental retardation is also seen in those exposed between the 16th and 25th weeks (68). Several epidemiological studies also sug-

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[2] Both of these findings are made with respect to low linear energy transfer radiation, such as x-rays and gamma rays.

gest an increased risk for leukemia from irradiation of the fetus in the first trimester of pregnancy (45).

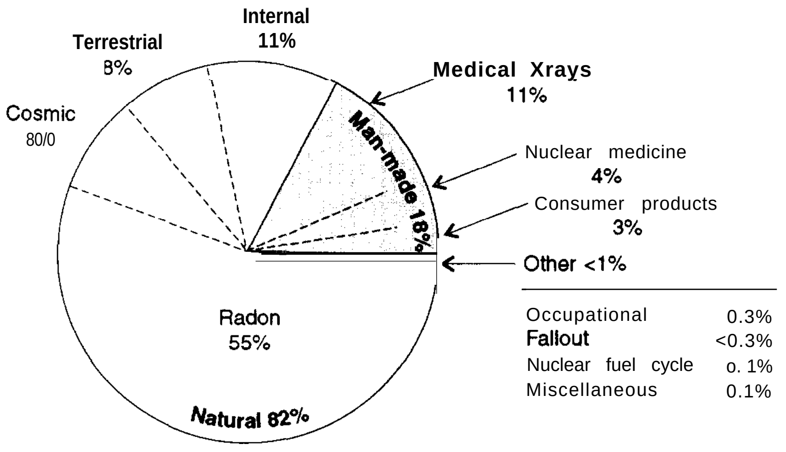
## SOURCES OF IONIZING RADIATION

Ionizing radiation is a natural part of our environment, but humans have developed additional sources of potential radiation exposure through the use of nuclear medicine, weapons, and power. In the United States, natural sources of radiation provide most of the average annual effective dose to the population, which is estimated at approximately 360 mrem each year (3.6 millisieverts (mSv); see figure 3-1) (44). These natural sources include radioactive elements present in the earth, cosmic rays given off by the sun and other celestial bodies, and naturally occurring radionuclides in the human body. To some degree, exposure to these natural sources is inevitable, although exposure to some can vary depending on location and other factors. For example, exposure to natural radioactive elements such as the potassium-40 in our bodies from air, food, and water is inevitable (54). On the other hand, people living at higher elevations have greater exposure to cosmic radiation than those living closer to sea level. People receive enhanced radiation exposure during air travel at a rate of about 0.5 rem per hour (44). More background radiation is also found in areas with higher levels of radium, uranium, and potassium in the earth's crust. Location, housing materials, and housing ventilation can influence the exposure to radon and its decay products, which on average make up the largest contribution to average annual effective dose.

Man-made sources constitute the remaining 18 percent of the average effective dose to the U.S. population. Use of x-rays for diagnosis and nuclear medicine such as radiotherapy for cancer are estimated to contribute most to exposures of this type. Occupational exposures, fallout from nuclear testing, and exposures from the nuclear fuel cycle contribute small fractions to the average.

The pie chart of figure 3-1 illustrates the substantial contribution of background radiation to a typical person's total exposure to radiation in the United States (300 mrem or about 82 percent). However, our concern in this study is not with doses averaged over entire populations, but with situations in which subpopulations or individuals, in the United States or elsewhere, might experience increased exposures because of man-made radioactivity released into the environment.

FIGURE 3-1: Contributions of Various Radiation Sources to the Total Average Effective Dose in the U.S. Population



SOURCE: Used with permission from the National Council on Radiation Protection and Measurements, *Ionizing Radiation Exposure of the* Population *of the United States,* NCRP Report No. 93 (Bethesda, MD: 1987).

## Radiation Protection Standards and Guidelines

Over the years, guidelines for the protection of populations from the health effects of radiation have been developed and revised as understanding of these effects has evolved. The current recommended dose limits of the International Commission on Radiological Protection (ICRP) are presented in table 3-1. Standards adopted by the U.S. Nuclear Regulatory Commission (NRC) in 1991 and effective in 1994 for limits on radiation exposures from facilities licensed by the NRC are nearly identical (51). The ICRP dose limits are intended as a guide in considering human practices that are carried out as a matter of choice and are not intended to apply to doses that might occur from exposure to natural or artificial radiation already in the environment (28). Nonetheless, the recommended annual dose limits of 2 rem for workers and 0.1 rem (100 mrem) for the general public provide some reference point for considering the scale of other radiation exposures. They are based on an estimate of the probability of fatal cancer after low-dose, low-dose-rate, low linear energy transfer (LET) radiation to the total population of 5 x $10^{-4}$ per rem (28). The annual dose limit for the public of 0.1 rem results in a risk of cancer mortality of about $10^{-5}$ (1 in 10,000) per year (9).

TABLE 3-1: ICRP Recommended Dose Limits

| | Dose limit (rem) | |
|---|---|---|
| **Classification** | **Occupational** | **Public** |
| Effective dose | 2 per year (averaged over 5 years) | 0.1 per year (averaged over any consecutive 5 years) |
| | 5 (in any one year) | |
| Annual equivalent dose in: | | |
| Lens of the eye | 15 | 1.5 |
| Skin | 50 | 5 |
| Hands and feet | 50 | |

SOURCE: International Commission on Radiological Protection, *1990 Recommendations of the ICRP*, ICRP Publication 60 (New York, NY: Pergamon Press, 1991).

## POTENTIAL HEALTH EFFECTS FROM NUCLEAR CONTAMINATION IN THE ARCTIC AND NORTH PACIFIC

For contamination in the environment to result in human health effects, several conditions must be met. The contaminants or their metabolites must be hazardous to biological systems. There must be contact of these contaminants with people. Last, exposure to the contaminants must occur at concentrations and for periods of time sufficient to produce biological effects. Understanding the potential hazard therefore requires understanding the agent, the exposure, and the subject (32).

In trying to understand the potential health impacts of radioactive contamination from nuclear waste dumped in rivers and oceans, it is clear that the dumped radioactive wastes are potentially hazardous to biological systems, posing, as described above, risks of cancer and genetic and teratogenic (causing malformations or developmental disturbances of the fetus) effects, as well as more acute immediate illness at high doses. Many unknowns exist, however, both in the potential contact of these wastes with people and in the exposure concentrations and times that can be anticipated. The following sections examine what has been learned and what remains to be understood about the dumped wastes, the possible pathways of human exposure, and the populations that may be exposed. Efforts that have been carried out to estimate human health risks despite the large data gaps are reviewed, along with information on possible ecological effects.

## Assessing Human Exposure

Several means are used to measure or estimate human exposure to hazardous agents. Biological markers can be used in some instances to measure agents in the biological fluids or tissues of exposed individuals. This approach provides the best measure of an individual's actual exposure, but suffers the drawback that some exposure to the substance or agent has already occurred (whole body counts, counts in teeth). A frequent approach to estimating human exposure is environmental monitoring, the practice of measuring levels of an agent in the air, water, and food to which people are exposed. That information is then used to estimate how much of the agent might find its way to or into people based on estimates of breathing rates, skin areas, or water and food ingestion rates. In the absence of, or as a supplement to, information from biological markers or environmental monitoring, knowledge of the source term is also important. The source term refers to the quantities and types of released radionuclides and their physical and chemical conditions (64). This information can provide an upper bound on the amount of the agent released into the environment and perhaps the rate of its release. Estimates can then be made about how the agent might move through the environment and potentially lead to human exposure.

The further a measurement is taken from the potential human target, the more estimates and assumptions are required to anticipate how much human exposure might actually occur. In considering the health and environmental impacts of radioactive waste dumped in the Arctic, two questions must be addressed. Are any significant impacts currently taking place or imminent, and are any serious future impacts likely? Information about current levels of radioactive contamination in the environment can be used to consider questions of current human exposure and effects, and information about the source term can be applied toward considering potential future effects.

## Current Levels of Radioactive Contamination in the Environment

As discussed in chapter 2, measurements of radioactivity in seawater and sediments in the Arctic and Russian Far East that have been collected and analyzed to date do not suggest elevated levels indicative of large releases from the dumped wastes. It is not clear, however, that the waters in question have yet been sampled sufficiently and adequately to provide complete confidence in these results. Once all data gathered to date are compiled and compared, it should be clear where extensive sampling has occurred and where more information from additional sampling is needed.

According to the sampling that has taken place and been reported thus far, particularly in the course of three expeditions by the Joint Russian-Norwegian Expert Group for Investigation of Radioactive Contamination in the Northern Areas, the level of cesium-137 (Cs-137) measured in the Kara Sea is between 3 and 20 bequerels per cubic meter (Bq) ($8 \times 10^{-11}$–$5.4 \times 10^{-10}$ curies/$m^3$), compatible with levels seen over the years from nuclear test fallout and European reprocessing (30). To consider these values in perspective, intervention levels derived by the International Atomic Energy Agency (IAEA) to control doses to the public in the event of a radiological emergency are 700,000 Bq/$m^3$ ($2 \times 10^{-5}$ curies/$m^3$) of Cs-137 in *drinking water*, thousands of times higher than the levels measured in seawater (60). Many samples from cruises carried out over the summer of 1994 are still being analyzed and should be helpful in covering the seas of interest more thoroughly.

### *Russian Far East*

Expeditions in 1993 to sample the waters and sediments of the Far Eastern seas found Cs-137 levels in the surface waters of about 3 Bq/$m^3$ ($8 \times 10^{-11}$ curies/$m^3$) and lower levels in the deeper waters (22). These measurements are consistent with expected atmospheric input from fallout and do not suggest Russian waste dumping as a significant source of contamination in the region at this time. Data from a joint expedition of Russia, Korea, the IAEA, and Japan in 1994 are not yet available.

## Source Term

Although measurement of current levels of radioactivity in the environment is critical for assessing current risks to human health and the environment, an important step in trying to consider future risks posed by dumped wastes is to know what wastes were dumped, how much, where, and how rapidly they may release radionuclides into the environment. In radiological assessments this information is called the "source term," referring to the quantity and types of released radionuclides and their physical and chemical conditions (64).

As described elsewhere, the Yablokov report gives information about both liquid and solid wastes dumped in the Barents and Kara Seas in the Russian North, and the Sea of Japan, Sea of Okhotsk, and off the Kamchatka Peninsula in the Russian Far East (13). Aside from providing the total activity at the time of dumping, the report gives little information about the liquid wastes dumped between 1960 and 1991 in the Barents and Kara Seas or those dumped in the Russian Far East since 1966. Because the radionuclide composition is unknown, current contamination levels cannot be estimated. Based on the small volumes and irregular timing of dumping, however, it is unlikely that the dumped liquid wastes were from spent nuclear fuel reprocessing. Rather, it is believed that these were wastes from reactor cooling systems and ship cleaning operations (49). In this case, radioactive contamination is most likely to originate from tritium (hydrogen-3; H-3), with possible additional contamination by activation products such as cobalt-60 (Co-60), nickel-63 (Ni-63), and iron-55 (Fe-55).

The low level and rapid dilution of liquid wastes suggests that they have contributed only minutely to the radiation present in these waters both from man-made sources such as fallout and reprocessing and from the natural radiation expected in seawater.

The solid wastes pose a considerably greater hazard. They included 16 naval reactors from former Soviet Union submarines and the icebreaker *Lenin*, which were dumped in the Kara Sea and shallow fjords of Novaya Zemlya. Six of the reactors still contained their spent fuel, and about 60 percent of the spent nuclear fuel from one of the *Lenin* reactors was disposed of in a reinforced container. The Yablokov report estimates a total radioactivity of 2,300 kCi (kilocuries) of fission products in the spent nuclear fuel and 100 kCi of Co-60 in the reactor components. Almost no other radionuclides were identified, nor was an estimate provided of current levels of radioactivity (13).

Since the release of the Yablokov report in the spring of 1993, great efforts have been made by the international community to better understand the magnitude of the risks that the dumped wastes might pose. The Source Term Working Group of the International Arctic Seas Assessment Project (IASAP, described in chapter 5) has made substantial progress in gathering information relevant to the amount and containment of the dumped radionuclides. In January 1994, the Kurchatov Institute in Russia issued a report to IASAP containing a detailed inventory of radionuclides and information on the structure of the *Lenin*'s dumped reactor section. Then in July 1994, essential details of the structure, operational history, and characteristics of the dumped spent submarine fuel were declassified by Russian authorities. Thereafter, radionuclide inventories of the water-cooled submarine reactors and lead-bismuth cooled reactors were also made available to IASAP (24). Further information on the *Lenin* reactor and the submarine reactors was presented at a November 1994 meeting of the Source Term Working Group by researchers at the Kurchatov Institute and the Institute of Physics and Power Engineering (40).

Experts participating in the Source Term Working Group of IASAP have combined this early information with that provided by the Yablokov report, and made an array of calculations and conservative assumptions based on the submarines' fuel and working histories to reach a refined estimate of the total activity at the time of dumping of about 991 kCi (40). When decay is considered, the activity estimated to remain in the icebreaker *Lenin* reactor compartment in 1994 was about 59 kCi (41,61). The estimate of the activity remaining in the submarine reactors and spent fuel in 1994 was about 68 kCi (36), giving a total of 127 kCi for the estimated current activity of the high-level wastes described in the Yablokov report. This revised figure can provide a useful basis for estimating releases of these radionuclides into the environment and, potentially, into the food chain and ultimately their contact with humans. Several vital questions about the quantity and condition of the dumped wastes remain outstanding, however.

Some of these questions concern a substance called furfural, a compound prepared from cereal straws and brans. A resin based on furfural was used in the preparation and sealing of some of the dumped reactors, including the spent fuel from the *Lenin* reactor. Estimates quoted in the Yablokov report were that the furfural-based mixture would prevent seawater contact with the spent fuel for up to 500 years (13), but other experts have questioned this claim and few hard data exist to confirm it. Apparently three different organizations within the Russian Federation produce furfural, but their production methods are not necessarily uniform (38). Thus, the precise composition and characteristics of the furfural sealed in various reactors are not known. This information is of great interest because of the role the sealant may play in delaying release of the radionuclides and remains among the critical unanswered questions about the source term. For the purpose of modeling the release of the contaminants over time, both furfural and the concrete are being assumed to last for 100 years (39).

Several other important issues remain unknown, such as the condition of the reactors containing spent fuel, the corrosion rate of the fuel in Arctic seawater, and the thickness of the reactor compartment walls (38). All of these factors are important in estimating how rapidly or slowly radionuclides may be released into the environment and how much of their radioactivity will remain as that occurs. The nature and the condition of other dumped solid wastes are unknown.

The Source Term Working Group is attempting to address these issues, via contracts with experts at the Kurchatov Institute in Moscow and the State Scientific Center of Russia in Obninsk to help gather and analyze additional information. Some officials in the Russian Navy seem to feel that the Yablokov report revealed too much sensitive information, and they are reluctant to declassify additional information requested by IASAP. Nonetheless, the group anticipates concluding its work on the submarines and reactors in late 1995 and then shifting its focus to other wastes described in the Yablokov report (those described only in terms of “Sr-90 [Strontium-90] equivalents”). A final report is expected in early 1996 (42).

Although a considerable array of unknowns about the condition of the dumped wastes remain, there is no evidence to indicate that large releases of radionuclides have occurred. As described in chapter 2, levels of radionuclides measured in the open Barents and Kara Seas do not indicate sources beyond the contributions due to fallout from atmospheric testing and discharges from European reprocessing plants. Expeditions carried out by the Joint Russian-Norwegian Expert Group have thus far visited and sampled near several sites where nuclear waste dumping was described in the Yablokov report. In Tsivolka Bay, where the *Lenin* reactors were reported to be dumped, Co-60—which may have originated from the dumped nuclear waste—was measured in the upper sediments, but components of the *Lenin* were not located (31). Analysis of sediment samples from near the hull of a submarine containing two reactors with spent fuel in Stepovogo Bay suggests some leakage of fission products from the submarine reactors. Increased concentrations of Cs-137 (about 10 times the amounts measured in the open Kara Sea in 1992) and the presence of Co-60 in the bay also suggest leaching from dumped solid radioactive wastes other than the reactors with spent fuel (31). Concentrations of Cs-137 in surface sediments of the Novaya Zemlya Trough, also mentioned in the Yablokov report as a site for nuclear waste dumping, were similar to those in the open Kara Sea in 1992. In the Abrosimov Fjord, three of four reported submarine reactor compartments and three of four dumped barges were located, and there are elevated levels of radionuclides in the sediments near these objects (10).

From the limited information available, any leakage that may have occurred so far from dumped wastes appears, at most, to have led to only very local contamination. More extensive inspection of the dumped objects (particularly, all of the reactors with spent fuel) and sampling of the environment nearby are necessary.

## Potential Pathways of Human Exposure

Since effects from radiation can come about only if radioactive contamination comes in contact with humans, understanding health risks to humans from existing or potential sources of radioactive contamination in the environment requires an understanding of the varied pathways through which radionuclides can eventually result in direct external radiation exposure or can be ingested or inhaled. This is a considerable challenge. Given the complexities of human activities and diets, myriad different pathways to humans are conceivable through inhalation, ingestion, direct contact, or proximity.

The challenge is not new, however. Pathways to human exposure from radionuclide contamination in the environment have been studied since the 1960s when concerns were raised about widespread environmental contamination from fallout due to nuclear weapons testing. Diagrams such as figure 3-2 were developed to help understand the fate and transport of radionuclides and possible routes through the environment to humans. Such conceptual models can serve as the framework for computational models that approximate the transport of radionuclides from their source to humans. Increasingly, complex dose reconstruction models have been developed and used to try to calculate doses to humans from a variety of sources; such models have become important for nuclear facilities and their regulators.

The most sophisticated computer model is only as good as the data used to construct and test it, however. Since a tremendous number of unknowns remain in this area, the development and particularly the validation of models of environmental transport are limited by these unknowns and associated uncertainties. For example, an estimate of the dose to humans through a cow’s grazing in a field contaminated by rainfall through a radioactive cloud requires a good estimate of at least 14 different parameters, from the rate of rainfall to soil-to-plant uptake via root absorption to the quantity of meat and milk consumed by humans (8,9). Each of these parameters must be entered into the model, but some are not known to within an order of magnitude. Since many such parameters must be combined in the models, the uncertainties surrounding them can span orders of magnitude. Frequently, the models are used for situations in which validation prior to decisionmaking is impossible (potential accidents, etc.).

Improvements have come about as experience with models has increased. Most progress has been made in atmospheric environmental modeling, such that concentrations downwind from a continuous point source emission can now be estimated reliably (8). Much more progress is needed to refine and develop models for aquatic and terrestrial systems, however. “Atmospheric diffusion, while so complex that it is not yet fully understood, is a relatively predictable process compared to transport through geologic media, or convection, diffusion, and sorption processes encountered in the aquatic environment.”[3] Such statements are made with respect to the modeling of processes in temperate zones. However, such processes are even less understood in Arctic conditions.

“Above all, it needs to be recognized that the Arctic is a very different environment than most people are familiar with. Residence times of materials, in marine and terrestrial ecosystems and in the atmosphere, are generally much longer due to the lack of moisture passing through the system. Paradigms borrowed from experiences of radioactive waste treatment at mid-latitude

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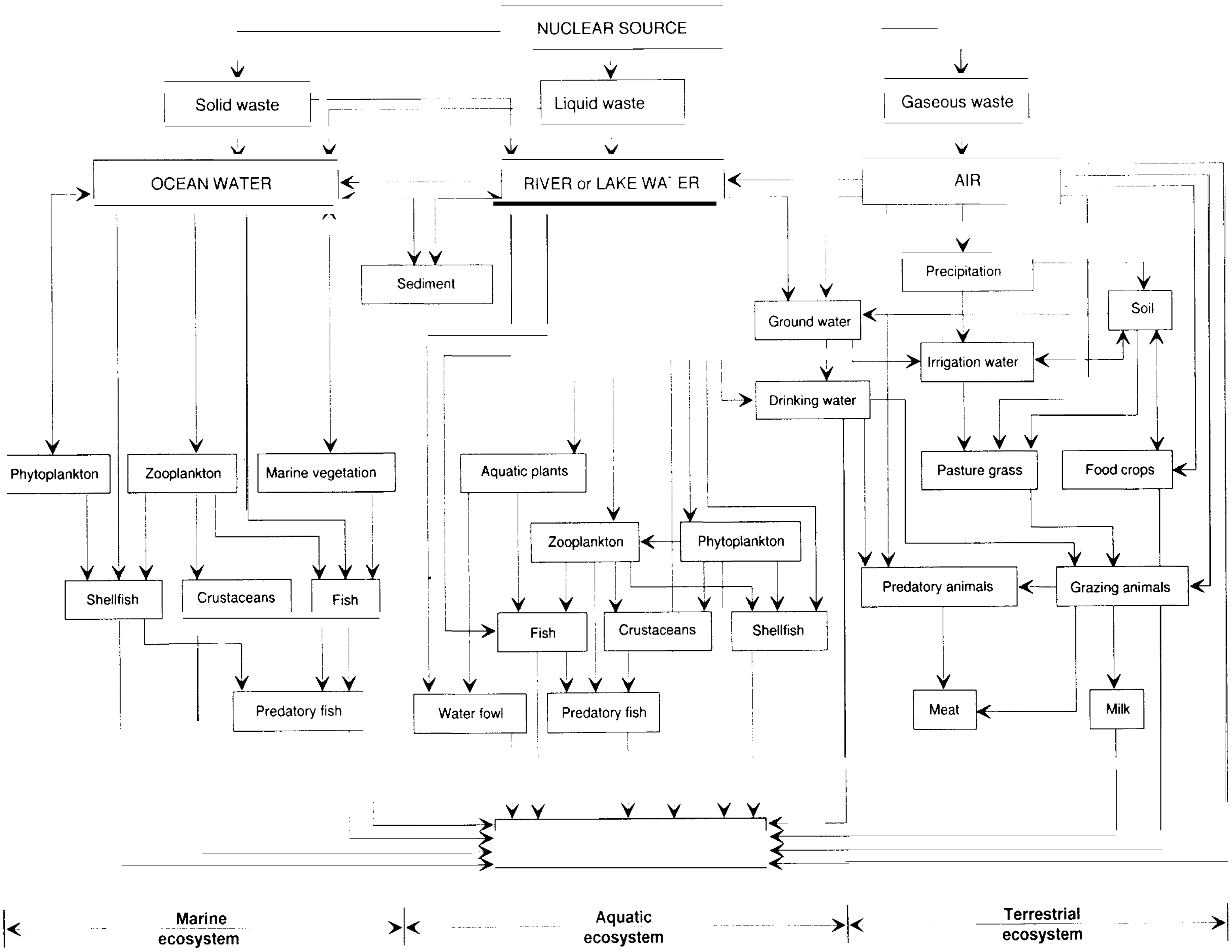
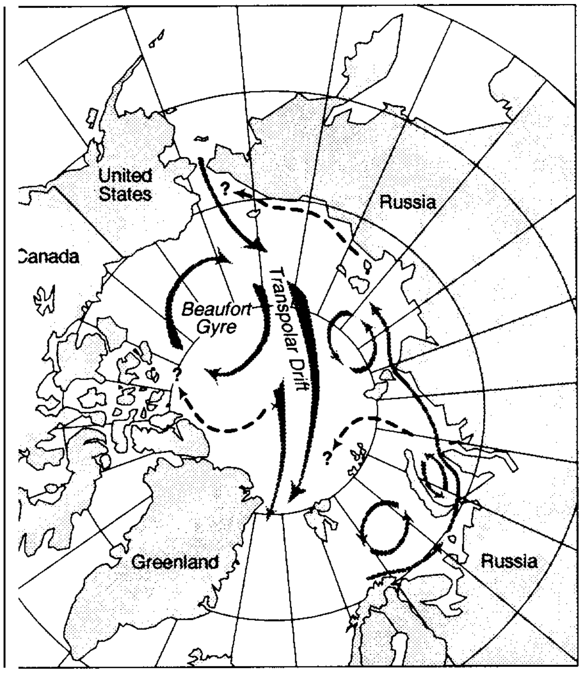
[3] M. Eisenbud, Environmental Radioactivity, 3rd ed., (Orlando, FL: Academic Press, 1987)



SOURCE: Office of Technology Assessment, 1995, adapted from Peterson, H.T., "Terrestrial and Aquatic Food Chain Pathways," Radiological Assessment: A Textbook on Environmental Dose Analysis, J.E. Till and H.R. Meyer, (eds.), (Oak Ridge, TN: Oak Ridge National Laboratory, 1983).

sites are inappropriate for the Arctic conditions."[4]

FIGURE 3-3: Possible Pathways of Radionuclide Transport Via Sea Water or Ice



Legend: View of Arctic Region. Gray arrows indicate predominant sea and ice currents. Dashed black arrow. illustrate hypothetical sea water or ice transport pathways of contaminants which are currently under study.

SOURCE: Office of Technology Assessment, 1995.

Given the nuclear waste dumping that has taken place so far in the oceans and at sites along rivers feeding the oceans, the marine and aquatic environments are those of greatest current interest in trying to understand potential hazards to humans and the environment. In particular, researchers are interested in several potential pathways in sea water or ice through which radionuclides might move, illustrated in figure 3-3. The likelihood of these pathways cart be examined through data collection and modeling. General models alone are unlikely to provide easy answers to questions of the effects that dumping is likely to have. A tremendous amount of detail about a body of water is necessary to begin to describe the mixing that takes place in it. Site specific information is necessary about water depth, bottom shoreline configuration, tidal factors, wind, temperature, and the depth at which the pollutant is introduced, among others. “Each stream, river, bay, lake, sea, and ocean has its own mixing characteristics that vary from place to place and from time to time.”[5]

Attempting to understand and predict the dispersion of a radionuclide in a water body is further complicated by other chemical, physical, and biological processes. Do its chemical characteristics make it more likely to be found in solution or in the soils and sediments? The behavior and distribution of radionuclides in water environments depend a great deal on how likely they are to become associated with particles. Contaminants in solution cart be assimilated by plants and animals or can fix themselves to suspended solids, which then become part of the substrate that supports bottom-dwelling communities. Contaminants that adhere to sediments can remain there indefinitely or be a source of contamination later if the sediments are disrupted through turbulence or changing chemical conditions (8). Prediction of the dispersion of pollutant species that favor the particulate phase is more difficult than for those that remain in solution. In general, radionuclides of strontium, technetium, antimony, cesium, uranium, and H-3 are relatively soluble and less likely to associate with particles than the radionuclides of lead, thorium, neptunium, plutonium, americium, and curium (54). Beyond generalities, however, radionuclide-specific, site-specific information is necessary to begin to anticipate the behavior of such contaminants.

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[4] Glenn E. Shaw, professor of Physics, Geophysical Institute, University of Alaska, Fairbanks, Alaska, “Transport of Radioactive Material to Alaska,” Radioactive and Other Environmental Threats to *the United States and the* Arctic *Resulting from Past Soviet Activities,* hearing before the Select Committee on Intelligence, United States Senate, Aug. 15, 1992, S. Hrg. 102-1095 (Washington, D.C.: U.S. Government Printing office, 1992).

[5] M. Eisenbud, Environmental Radioactivity, 3rd ed., (Orlando, FL: Academic Press, **1987)**

### *Modeling Environmental Transport*

In the face of these challenges, some efforts are being made to use environmental transport models to better understand the potential outcomes from the dumping of nuclear wastes in the Kara Sea, as well as in major rivers emptying into the Arctic Ocean.

A large-scale modeling effort is in progress at the U.S. Naval Research Laboratories funded by the Arctic Nuclear Waste Assessment Program (ANWAP). The model covers the area from the North Pole south to about 30° N latitude, including the Far Eastern seas and the Labrador Sea. It incorporates ocean currents, wind, and ice with a resolution of 1/4°. The model has now been used to simulate inputs from the Ob and Yenisey Rivers, from solid and liquid dump sites in the Kara Sea and the Russian Far East, and from the Sellafield reprocessing plant on the Irish Sea. The simulations suggest movement of the radionuclides out of the Kara Sea along three pathways, and indicate that after 10 years of constant release from dump sites in the Kara Sea, concentrations of radioactivity in seawater near the Alaskan coast would be about 100,000-fold lower than those in the Kara Sea (58). The model continues to be refined and requires additional data from measurements in the oceans to be validated.

Another group funded through ANWAP has focused on modeling radionuclide contamination of the Kara Sea from the Ob and Yenisey River systems. Using existing data, as well as data currently being gathered and analyzed on the characteristics of the radioactive sources and of the rivers and estuaries, the modelers will try to estimate river contributions of Sr-90, Cs-137, and plutonium-239 (Pu-239) to the Kara Sea. The models will address two different scenarios—a steady continuous release of contaminants and a sudden large release of radionuclides as from dam breakage or a flood (see box 2-2 in chapter 2).

Modeling efforts are also under way under the auspices of the Transfer Mechanism and Models Working Group of the IAEA's Arctic Seas Assessment Program. Seven laboratories are involved in efforts using seven different models, and researchers are currently carrying out benchmarking studies to see how the various models compare in cases of instantaneous release and constant release.

As all of these models are developed, it is critical that, where possible, results be compared with empirical data or with alternative models to ascertain the value of these results. Sensitivity analysis—an effort to assess which inputs or components of a model have the most impact on the results—can shed light both on how the model works and, to the extent that it successfully represents the real system, on what environmental factors can benefit most from further study (49). Some uncertainty in the models is inevitable, and should be described and quantified. Uncertainty stemming from natural variability cannot be reduced, but uncertainty arising from gaps in knowledge should be used to direct research toward filling those gaps. Proprietary models are problematic because models benefit greatly from testing, peer review, and open scrutiny of their features.

### *Transport Through the Food Chain*

In addition to trying to understand how radionuclide contaminants in the rivers and oceans will disperse over time through physical mixing and dilution, it is important to consider other factors that will play a role in human exposure to contaminants. Since the radionuclides have been dumped into water environments, exposure through inhalation is an unlikely or fairly remote possibility; exchange of radionuclides into the air can occur to some extent but should contribute very little to human exposure. Exposure through direct contact with radionuclides in the water is possible but, particularly in the icy Arctic waters that are the focus of this study, not likely to be widespread or frequent. Radionuclides may be deposited on beaches by the waters washing them, however, or through transport by windborne spray, as observed near the Sellafield plant in England (56).

The pathway most likely to lead to human contact with radioactive contaminants dumped in the oceans, however, is ingestion. Consumption of marine food that has become contaminated with radionuclides is logically the most probable path of human exposure, but is difficult to assess. Particularly in water environments, understanding the complex interrelationships within food webs and the predator-prey hierarchy leading to humans is daunting (figure 3-4). Whereas the terrestrial food chain leading to humans generally consists of two or three separate steps that can be controlled or modified as in farming, the marine or aquatic environment is less defined or regular (9). The same predator may eat several different types of prey from different "trophic levels," or steps in the food chain. Furthermore, there are species in the aquatic environment that can move considerable distances during their lives. This added complexity leads to use of the term "food web" to describe the complex consumption relationships in aquatic, marine, and estuarine settings (55).

Another factor that makes estimating radionuclide contamination from the food chain difficult is the phenomenon of bioaccumulation. Some environmental transport processes can lead to physical, chemical, or biological concentration of radionuclides to levels that are considerably higher than its initial concentration in air or water at the point of release (55). For example, concentration can occur as a result of purely physical processes, such as adsorption of radionuclides onto silt or suspended solids which then accumulate on the ocean floor (8). In addition, radionuclides can concentrate in organisms that consume other radionuclide-containing organisms, leading to "biomagnification."

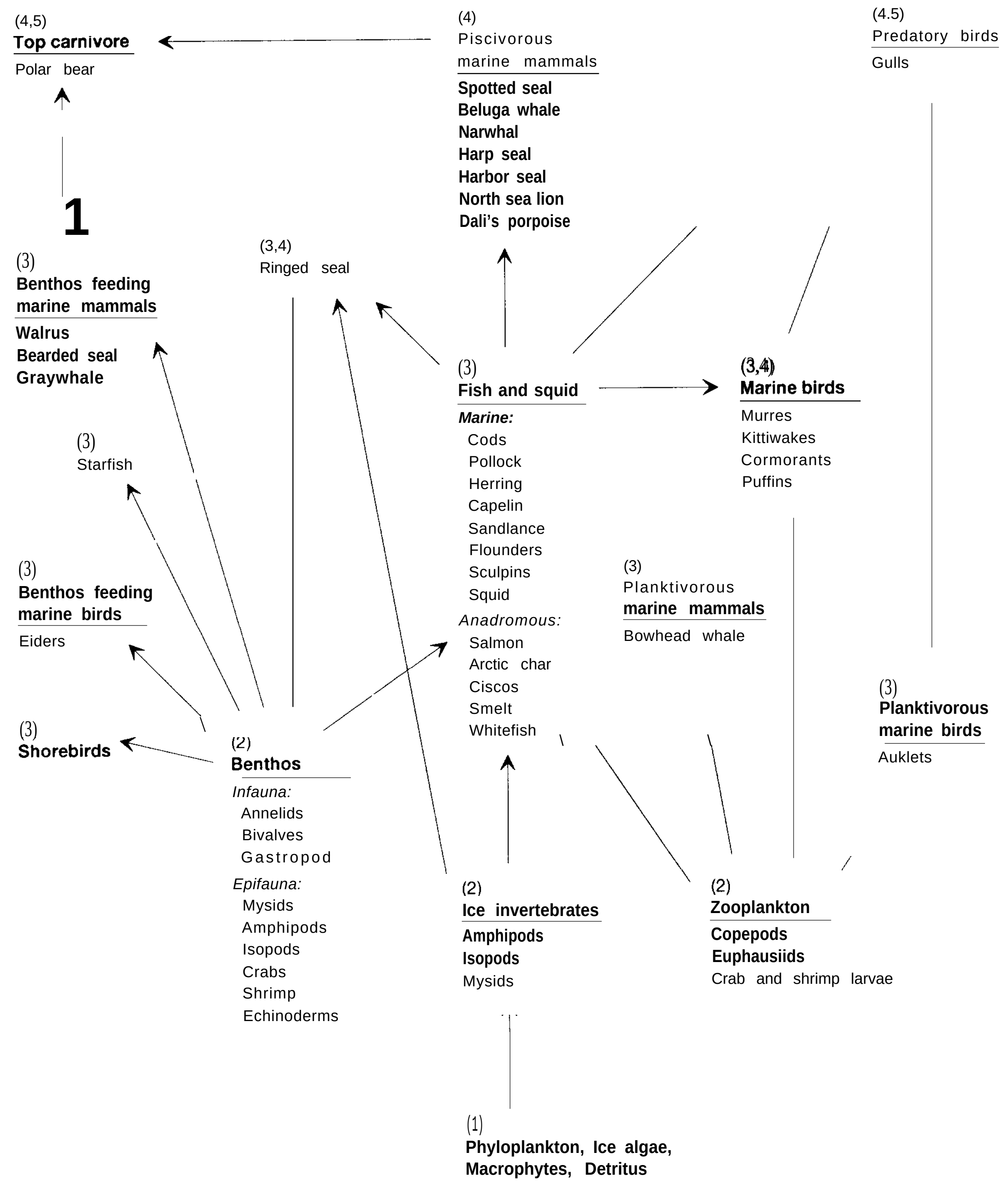
Concentration in biological organisms has been an important focus of study for understanding environmental transport. Concentration factors (CF) are ratios of the concentration of the radionuclide in the organism to its concentration in the ambient medium. They have been measured in a variety of different species and settings, both through laboratory research and in natural systems, and should be measured under conditions in which the organism has reached equilibrium with the environment (see table 3-2). These factors tend to vary widely, partly because the uptake of radionuclides by organisms in water can be strongly influenced by the presence of chemical analogs in the water. For example, the high concentration of potassium (K) in seawater means that the uptake of Cs-137 in marine environments is lower than that observed in freshwater or estuarine (brackish) settings (8). Given the variability in CFs observed in different studies, some site-specific information is required to select an appropriate value.

In analyzing the concentrations of radionuclides that may accumulate in an organism and thence into a pathway for human consumption, it is important to consider where the radionuclides collect in the animal and whether this is relevant to the human diet. For example, clams, oysters, and scallops concentrate Sr-90, but the concentration occurs in their shells, which are ordinarily not consumed (8). In general, muscle tissue tends to have the lowest concentration of radionuclides, whereas liver, kidney, and other organs involved in storage or excretion have the highest concentrations (54). Thus, a CF for the specific tissues consumed by humans is far more useful than one derived for the entire organism.

Generalizations about concentration factors across organism types must also be avoided, and data must be gathered that is specific to the diet of the people in question. Several types of seaweed growing in waters near the nuclear waste discharges of Sellafield were observed to concentrate radionuclides. However, different species of seaweed concentrated different radioactive elements to varying degrees so it was important to know which type people actually ate (7). It is critical to gather both site-specific and species-specific information, coupled with good information about the diet of critical populations.

Without site-specific information about the food web and the diets of critical populations, only a few generalizations are possible about the radionuclides that might be of most concern for human exposure through aquatic and marine food webs (see box 3-2). In any one generation,

FIGURE 3-4: Arctic Marine Ecosystem Food Web



NOTE: Numbers in parentheses indicate trophic level in ascending order. Examples of each major category of biota are also listed

SOURCE: adapted from Becker, P., "Characterization of the Arctic Environment," Proceedings of Workshop on Arctic Contamination, *Arctic Research of the United States, 8: 66-76, 1993.*

TABLE 3-2: Concentration Factors in Marine Organisms

| Element | Fish | Crustaceans | Mollusks |
|---|---|---|---|
| H-3 | 1 | 1 | 1 |
| Cs | 100 | 30 | 30 |
| Sr | 5 | 2 | 1 |
| Co | 50 | 5,000 | 5,000 |
| Fe | 3,000 | 5,000 | 30,000 |
| Mn | 400 | 500 | 5,000 |
| Mo | 40 | 100 | 100 |
| Ni | 670 | 1,000 | 2,000 |
| Zn | 5,000 | 50,000 | 30,000 |
| I | 10 | 10 | 10 |
| Am | 250[a]<br>25[b]<br>5[c] | 500 | 20,000 |
| Cm | 250[a]<br>25[b]<br>5[c] | 500 | 30,000 |
| Np | 250[a]<br>25[b]<br>5[c] | 100 | 400 |
| Pu | 250[a]<br>25[b]<br>5[c] | 300 | 3,000 |

[a] Bottom-feeding fish.
[b] Planktivorous fish.
[c] Piscivorous fish.

SOURCES: T. Poston and D. Klopfer, "Concentration Factors Used in the Assessment of Radiation Dose to Consumers of Fish: A Review of 27 Radionuclides," *Health Physics* 55:751–766, 1988. Ministry of Agriculture, Fisheries, and Food, *Radioactivity in North European Waters: Report of Working Group 2 of CEC Project MARINA.* (Lowestoft, UK: 1989).

the largest contributions to committed doses[6] from dietary contamination are most likely to come from radionuclides of only moderately long half-lives (tens of days to tens of years), such as cesium, ruthenium, strontium, and zirconium; also from H-3, and in certain circumstances, from iodine-131 and actinides (56).

In summary, considerable information crucial to understanding the transport and fate of radioactive contaminants is lacking. Much of this information must be site specific to be of most use in modeling or otherwise anticipating likely pathways for radionuclides. Information about local physical and chemical characteristics of the water body, resident biota and their concentration factors, and the behavior of the specific radionuclides in the specific environment is needed. Data needs must be considered in the context of the routes of exposure most likely to lead to human beings, by taking into account the diets and habits of people and exploring the most appropriate transport pathways.

## Possible Critical Populations

Estimates or analyses of risk from environmental contaminants usually focus on "critical populations," groups who are most likely to be exposed (or to have the highest exposures) to the agent of interest. Who are the populations with greatest likelihood of exposure to radionuclides dumped in the Arctic and North Pacific Oceans? Without an exhaustive understanding of the life-style, habits, and diet of everyone, common sense suggests that those with the largest proportion of seafood, shellfish, and marine mammals in their diets might have the greatest potential exposure to radionuclides released in the ocean. Similarly, those relying most heavily on fish and aquatic organisms from freshwater sources might be most exposed to radionuclides released into rivers. This describes, in particular, Native northern peoples all over the Arctic, including those in Russia, Canada, Greenland, and the United States (Alaska). In keeping with the scope of this report, the focus here is on possible critical populations in Alaska.

In Alaska, many of the Native people continue traditional life-styles that involve a significant dietary component from fishing and marine mammals.[7] A study of the diet of Alaskan Native adults in the late 1980s indicated a high consumption of fish—a mean daily intake more than

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[6] Committed doses take into account doses received over time from internal emitters (see box 3-1).

[7] Game meats such as caribou also constitute an important part of the diet, particularly in the winter months. Caribou meat in the Arctic frequently contains appreciable levels of radionuclides because of the caribou's consumption of lichens (see later text).

## BOX 3–2: Radionuclides of Potential Biological Impact in Dumped Nuclear Waste

No comprehensive listing of the various radioactive elements present in nuclear wastes dumped in the Arctic and North Pacific Oceans exists. However, it is possible to surmise some of the constituents, based on what is known about the nature of the waste types discarded there. The wastes dumped by the Russian Navy were primarily wastes generated in the use of nuclear reactors to power submarines. Other wastes that may contribute to contamination in the oceans are from the reprocessing of spent nuclear fuel to recover plutonium for use in weapons production. The following table notes those radionuclides that might be of most concern from a human health and ecological perspective, because of physical and chemical characteristics of the elements.

| | Radionuclide | Half-Life |
|---|---|---|
| Fission products[a] | | |
| | Ruthenium-103 | 40 days |
| | Ruthenium-106 | 373 days |
| | Cerium-144 | 284 days |
| | Zirconium-95 | 64 days |
| | Strontium-90[b] | 29 years |
| | Yttrium-90 | 64 hours |
| | Cesium-137[b] | 30 years |
| | Iodine-129 | 16,000,000 years |
| | Technetium-99 | 213,000 years |
| Activation products | | |
| | Zinc-65 | 244 days |
| | Iron-55 | 2.7 years |
| | Iron-59 | 45 days |
| | Cobalt-57 | 271 days |
| | Cobalt-58 | 71 days |
| | Cobalt-60 | 5.3 years |
| | Nickel-59 | 76,000 years |
| | Nickel-63 | 100 years |
| | Manganese-54 | 312 days |
| | Chromium-51 | 28 days |
| | Carbon-14 | 5,730 years |
| Actinides | | |
| | Plutonium-239 | 24,411 years |
| | Neptunium-239 | 2.3 days |
| | Americium-241 | 432 years |
| | Americium-243 | 7,370 years |
| | Curium-242 | 163 days |

*(continued)*

## BOX 3–2: Radionuclides of Potential Biological Impact in Dumped Nuclear Waste (Cont'd.)

NOTES: a) Fission products are radioactive fragments produced when a nucleus is split. Activation products are produced when neutrons released during fission react with elements nearby. These elements can be located in the shielding and containment, fuel cladding, and reactor structural materials. Actinides are elements numbered 89 and above on the periodic table and include the transuranium elements produced by neutron bombardment of uranium. They tend to have longer half-lives and therefore will be contributing radioactivity for longer periods of time.

b) Cesium-137 and strontium-90 deserve special mention because they make up a significant amount of fission products and because of their potential to deliver internal doses over a long time. With half-lives of about 30 years each, either can be taken up in the body and do harm to body tissues for extended periods before being cleared by tissues or decaying. Strontium behaves like calcium in the body, eventually being deposited in the bone where it can provide a source of radiation for years. Cesium behaves like an analog of potassium in the body; it is rapidly absorbed into the bloodstream and distributed to active tissues where it and its decay product barium-137 emit beta and gamma irradiation. In adult body organs, the effective half-life of strontium-90 is 18 years (bone), and the effective half-life of cesium-137 is 70 days (whole body) (68). The effective half-life takes into account both the physical half-life of the radionuclide and the time required for metabolic processes to eliminate the material, so that it reflects the actual time that the radioactive substance is in contact with the body. In general, cesium-137 and strontium-90 are of less concern for accumulating in marine biota than in freshwater because in seawater they are much more diluted by potassium and calcium ions, their chemical analogs. Conversely, radionuclides of elements that are biologically essential but in scarce supply in a given environment will accumulate significantly in organisms (72).

SOURCES: M. Benedict, T. Pigford, and H. Levi, *Nuclear Chemical Engineering*, 2nd ed. (New York: McGraw-Hill, 1981); International Atomic Energy Agency, *Assessing the Impact of Deep Sea Disposal of Low Level Radioactive Waste on Living Marine Resources*, Technical Reports Series No. 288 (Vienna: 1988); Robert C. Weast, (ed.), *CRC Handbook of Chemistry and Physics*, 69th ed. (Boca Raton, FL: CRC Press, 1989); F.W. Whicker and V. Shultz, *Radioecology: Nuclear Energy and the Environment, Volume I.* (Boca Raton, FL: CRC Press, 1982).

six times the U.S. national average intake (46).[8] Ongoing studies also indicate that sea mammal consumption continues to be a very significant part of the diet in some communities (47).

Some sampling and studies have been carried out to determine the levels of radionuclides present in the Alaskan marine environment and food chain. Funded primarily by the Office of Naval Research's ANWAP, the National Oceanic and Atmospheric Administration (NOAA) has overseen the analysis of five relevant sample sets to date (16,18). Analysis of sediment samples from the Beaufort Sea in 1993 indicated a range of Cs-137 from nondetectable up to 12 Bq/kg dry weight ($3.2 \times 10^{-10}$ curies/kg), lower than or comparable to measurements in sediment samples collected in the Kara Sea in 1992. Almost 100 times more gamma and beta radioactivity was attributable to the decay of naturally occurring K-40 than to Cs-137. Ratios of plutonium isotopes measured in the samples indicated global fallout as the principal and perhaps sole source of plutonium. Analysis of bottom-dwelling animals from the same area for plutonium isotopes and Cs-137 showed levels that were almost all non-detectable by high resolution gamma spectroscopy. Chemical separation techniques resulted in Cs-137 activities ranging from 0.3 to 1.1 Bq/kg ($8.1 \times 10^{-12}$–$2.9 \times 10^{-11}$ Ci/kg). In comparison, Cs-137 activities in mussels and oysters collected in 1990 in coastal areas of the contiguous United States had an average value of 0.2 Bq/kg, with a range of 0.02 to 0.4 Bq/kg (70).

In 1994, samples were collected from larger animals that serve as subsistence food sources, including bowhead whale (blubber, lung, and liver), king eider (bone and muscle), and bearded seal (blubber and kidney) (16). Very low levels of both anthropogenic and naturally-occurring radionuclides were found, with the highest measurement in bowhead whale liver samples of 0.44 Bq/kg of Cs-137 activity (screening values from the Food and Drug Administration, U.S. Department of Agriculture Chernobyl task force are 370 Bq/kg of Cs-137 in food) (60). A limited number

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[8] This study did not include communities from the North Slope, Interior Alaska, or the Aleutian Chain, however, where diets may differ somewhat.

of samples from anadromous[9] and marine fish gathered across the Arctic had Cs-137 levels of generally less than 1 Bq/kg dry weight. Exceptions were Arctic cod (2.6 Bq/kg), Arctic char (4.2 Bq/kg) from a Siberian river, and Arctic cisco from Prudhoe Bay (2.9 Bq/kg). Arctic cisco and Arctic char are important subsistence species in both Alaska and Russia, and Arctic cod is ecologically important throughout the Arctic seas. Activity levels of plutonium isotopes and americium-241 were below the detection limits of the analysis.

Fish and bottom-dwelling animals from the southeastern Bering Sea and Norton Sound in 1994 showed nondetectable levels of Cs-137—except in the case of fish where values were generally less than 1 Bq/kg. Additional samples, including bowhead whale, caribou, and polar bear collected in the spring and summer of 1995 by the North Slope Borough in Alaska, are still undergoing analysis (16). All told, the findings to date suggest very low levels of contaminants in these foods, with global fallout rather than other nuclear events (Chernobyl, waste dumping or discharges, etc.) as apparent sources (15).

Apart from the sporadic sampling done recently as a result of increasing concerns about contaminants in the food chain in Alaska, no routine monitoring of the marine environment is carried out, nor is there monitoring of the food chain, including subsistence food resources. Recommendations for such monitoring are included in a recent report by the Alaska State Emergency Response Commission considering radiological threats to Alaska (2) and have been proposed to ANWAP (14). While sampling carried out thus far has been adequate to describe the background levels of radionuclides in the Bering Sea, including Bristol Bay and the Norton Sound, sampling in the Beaufort and Chukchi seas has been much less comprehensive, and as a result the data base is not yet adequate to describe background levels of radionuclides (17).

A cooperative effort between NOAA and the North Slope Borough of Alaska is under way in which tissue samples from animals harvested for food will be analyzed and information about the findings disseminated to local residents. Contingent on FY 95 funding from ANWAP, the effort may include workshops that can provide a forum to hear the concerns of the communities and discuss the interpretations of collected data (16,52).

Clearly, a variety of other Arctic populations might also face potential exposures as radionuclides from dumped wastes are transported through the environment. In particular, Native people throughout the Arctic continue traditional life-styles that might make exposure from the marine food web more likely. More than 28 different groups of Native peoples live in the European and Siberian North and the Russian Far East. Since the 1920s and 1930s these groups have been treated as distinct, with special ordinances applied to them. Two of the groups, the Komi and the Yakuts, are larger (populations of 344,500 and 382,000, respectively, according to the 1989 census) and were given their own autonomous republics within the USSR. More than 26 smaller groups subsist as hunters, trappers, and reindeer herders, although the tundra, taiga, and forest regions of their homelands are increasingly damaged by industrial development, particularly oil and gas. Populations of the groups in 1989 ranged from 190 to 34,665 (29). In Russia’s Siberian Arctic, for example, a nomadic Nenets tribe of at least 5,000 reindeer herders still live on the Yamal Peninsula as they did in the fifth century, eating fish, reindeer, and other food foraged from the land and rivers. Other Nenets have settled to live as fishermen (62). In the summer months, nomadic reindeer herders as well as settled community dwellers are large consumers of fish.

Indeed, all along the Arctic coast of Russia, both Native people and “newcomers” depend heavily upon fishing for their food supplies. This dependence has increased in recent years. The

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[9] Anadromous fish (e.g. salmon) are born in fresh water, live as adults in salt water, and return to fresh water to reproduce.

demise of the Soviet Union has lead to decreases in incoming food supplies from other regions. The converse is that fish caught commercially are sold locally even more than in the past, because shipping and transportation have become more difficult[10]. Thus, although people living traditional subsistence life-styles could be expected to have the highest exposures to contaminants in fish, even those in cities along the coasts have significant dietary input from fish. Consumption of sea mammals is limited primarily to the Chukchi people in the far northeast (34,53).

In Canada, concerns about radionuclide exposures of the population through the diet have focused primarily on the terrestrial route, but an effort to examine the variety of sources of radioactivity in the Canadian Arctic has taken place through the Canadian Department of National Health and Welfare. The total population of the Canadian Arctic region is about 85,000, roughly half of whom are Native peoples, many continuing traditional food-gathering activities (66). The recently completed study examined the available data on environmental radioactivity and arrived at estimates of radiation doses to groups in six different communities, five of them Native (or First Nation) communities, with one non-Native community as a reference point (20). Estimates of doses were made for each community for a typical adult (eating a mixed diet of subsistence, or “country” foods, and non-country foods), a 1-year-old child, and an adult whose diet consists almost entirely of country foods. Estimated doses from all sources ranged from slightly more than 200 to 1,400 mrem a year. The average estimated dose to the hypothetical child was about 45 percent higher than to the adult with a mixed diet, while estimated doses to the adult eating only country foods were 75 percent higher than those to the adult eating the mixed diet. The ingestion of polonium-210 through the food chain was the most important contributor to dose, as has been found in other studies (see box 3-3). Table 3-3 shows typical concentrations of naturally occurring radionuclides in seawater.

The study drew attention to “significant gaps in the radiological monitoring database, inconsistencies in the information of dietary quantities and components of native diets, particularly for children, and possible reservations regarding the applicability of the dose conversion factors to the Arctic circumstances” (20). These concerns and data gaps appear to be equally relevant, if not more so, to information about exposures elsewhere in the Arctic—for example, in Alaska.

Concern about dietary radionuclide exposures of people with traditional or subsistence life-styles exists in the context of a well-known precedent: the concentration of Cs-137 from fallout in the lichen-reindeer-human food chain. In the 1960s researchers discovered that reindeer herders in several northern countries had elevated levels of Cs-137 in their bodies (1). Subsequent studies revealed that lichens have considerable ability to absorb and retain atmospheric particulates. They have a large surface area and a long lifespan, with no deciduous portions through which to shed radionuclides annually. Lichens are the primary food source for reindeer and caribou during the winter months. About a quarter of the cesium eaten by caribou is absorbed in the gastrointestinal tract and concentrates mostly in muscle tissue (63). Reindeer and caribou consumers ingest the meat and, thus, take the cesium into their bodies, where it is distributed to the tissues and remains in the body delivering a radiation dose for some time. Several studies have monitored Cs-137 levels in the bodies of reindeer herders over time, observing fluctuations correlating with the atmospheric testing of nuclear devices and variations in diet (19,66). In northern Alaskan Eskimos, estimated annual doses from Cs-137 in fallout reached 140 mrad in 1964 and 1966; by 1979 this annual dose had decreased to 8 mrad because of changes in diet and slow decreases in the amount of Cs-137 present in lichen (19). The lichen-reindeer-human saga has

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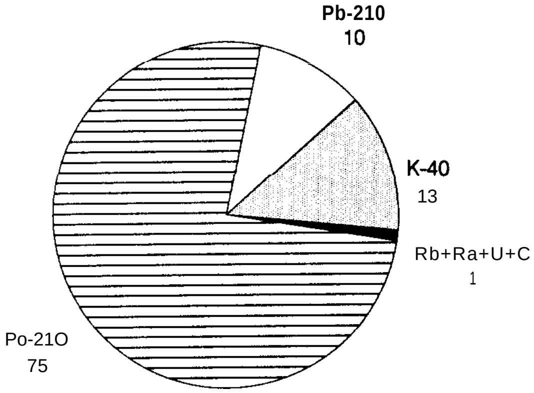
[10] There is an important commercial fishery in Ob Bay; fishing is done through the ice in the winter. As transport mechanisms have broken down, some people are flying in and buying fish privately and then reselling these fish elsewhere, although this is illegal (53).

## BOX 3-3: Naturally Occuring Radiation in Seafood Diets

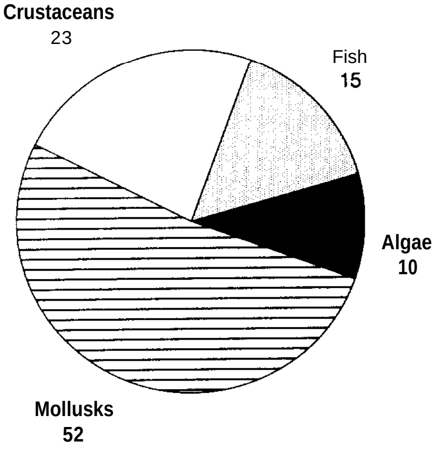
When considering contributions to human exposure from man-made radionuclides in the aquatic or marine food chain, it is important to note that people whose consumption of seafood is high can receive a significant portion of natural radiation from this source. Ocean waters and sediments contain naturally occurring radionuclides that can be concentrated through the food web just as anthropogenic radionuclides are. A rough estimate of annual dose to a person eating a daily diet of 600 grams of fish, 100 grams each of crustaceans, mollusks, and seaweed; 3 grams of plankton; and 60 grams of deep-sea fish is an annual dose of about 200 mrem per year from naturally occurring radionuclides (54). Most of the contribution is from Polonium-21 O, particularly from mollusks (see figure). For comparison, doses of this size are about twice the International Commission on Radiological Protection recommended limit of effective dose to members of the public from human practices (28).

SOURCE: Office of Technology Assessment, 1995.

(a) **Contribution by nuclides (%)**



(a) **Contribution by dietary items (%)**



Estimated relative contributions of (a) naturally occurring radionuclides and (b) dietary items to the annual dose rate to critical groups consuming 800 grams of fish and 100 grams of crustaceans, mollusks, and algae per day.

Source: Pentreath, R. J., "Radionuclides in the Aquatic Environment, " Radionuclides in the Rood Chain, M.W. Carter (cd.) (New York: Springer-Verlag, 1988).

TABLE 3-3: Naturally Occuring Radionuclides in Seawater—Typical Concentrations

| Radionuclide | Concentration (picocuries[a] per liter) |
|---|---|
| K-40 | 320 |
| H-3 | 0.6–3.0 |
| Rb-87 | 2.9 |
| U-234 | 1.3 |
| U-238 | 1.2 |
| C-14 | 0.2 |
| Ra-228 | (0.1–10) x $10^{-2}$ |
| Pb-210 | (1.0–6.8) x $10^{-2}$ |
| U-235 | 5 x $10^{-2}$ |
| Ra-226 | (4.0–4.5) x $10^{-2}$ |
| Po-210 | (0.6–4.2) x $10^{-2}$ |
| Rn-222 | 2 x $10^{-2}$ |
| Th-228 | (0.2–3.1) x $10^{-3}$ |
| Th-230 | (0.6–14) x $10^{-4}$ |
| Th-232 | (0.1–7.8) x $10^{-4}$ |

[a] 1 picocurie = 1 x $10^{-12}$ curies = 0.037 becquerels

SOURCE: adapted from R.B. Clark, *Marine Pollution,* 2nd ed. (Oxford: Clarendon Press, 1989).

been instructive as an example of increased exposure resulting from special dietary situations and suggests the need for vigilance in examining potential pathways for increased exposures.

In considering risks from environmental contaminants in the food chain, three important harmful effects must be considered that do not result directly from exposure to radiation. One is the fact that when a certain food is avoided because of concerns that it may be contaminated, other foods must be substituted. If these are less nutritious, are more expensive, or have more hazardous contaminants in them, the substitution has had a negative impact that must be weighed against the possible negative effects of eating the first foodstuff.

A second important result of concerns over contamination in food is one that may have particular impact on Native people living subsistence life-styles. Traditional foods and their hunting are a critical component of Native culture. Consuming subsistence foods is of course normal and natural, and part of a healthy life-style. Events centered around gathering or sharing foods (e.g., whale festivals) are important community events. To suggest that eating the foods could be harmful or should be avoided for some reason could cause tremendous disruption of life-style and contribute to disintegration of the culture (23,48).

A third important impact, related to the second, is the great psychological stress that can result from fear of contaminants in food and the surrounding environment. Many people in the Chernobyl and Chelyabinsk (see box 2-4 in chapter 2) populations have health problems they believe are caused by exposure to nuclear contamination. They suffer physically and have a changed outlook on life (11,12). Whether or not their health problems are caused by radioactive contamination, the people of the region observe a heavy toll of physical effects, which also leads to psychological stress. Similar impacts are possible in other areas, such as Alaska, where people fear they are experiencing health effects from radiation exposure. Many Alaska Natives have concerns about previous exposures to radiation such as those from nuclear weapons testing fallout in the 1950s and 1960s (21). They are very concerned that these exposures have had a health impact on their communities. The potential for additional exposures can only add to those concerns and the stress experienced.

In summary, a tremendous number of unknowns remain in considering the populations that might be most at risk of exposure to radionuclides dumped into the Arctic and North Pacific Oceans. Detailed studies of the dietary habits of many coastal peoples are almost nonexistent, as is any monitoring of the locally harvested foods and good information about the size of the harvests. Without such information, it is difficult to estimate what exposures are currently taking place from background and fallout radiation, and what concerns might be appropriate regarding future dissemination of the dumped wastes.

## Risk Assessments Completed or in Progress

A thorough assessment of the risks posed by nuclear waste dumping in the Arctic and North Pacific would incorporate understanding of the source term, detailed information on the pathways through which human exposure might occur, and knowledge of the critical populations to arrive at an estimate of the likely risk. Such assessments have been carried out in the past for other sources, as described in box 3-4. However, the preceding sections describe the fact that vital information, particularly about Arctic pathways and peoples, is sorely lacking. In its absence, several efforts have nonetheless been made by various investigators to estimate the risks in an effort to get a rough sense of the appropriate levels of concern.

Several of these estimates use population doses such as the collective effective dose to consider the potential total cancer impacts on populations rather than the risks to particular individuals. As described in box 3-1, the collective effective dose is calculated by multiplying the average dose to the exposed group by the number of people in the group. It could therefore be the same for a very low dose to a large population or a higher dose to a smaller population. Use of the word *commitment* takes into account the fact that when radioactive material enters the body, the material gives a dose to the person for a certain period of time. Collective doses are most frequently used for the purpose of comparing estimates of total cancer impacts of one radiological source with another, using units of person-rem.

Two such estimates were presented at a conference addressing the issue of radioactive dumping in the Arctic in June 1993. A crude estimate of global cancer risks from Arctic contamination was carried out based on a worst-case scenario of instant release of the calculated 1993 inventory of radionuclides in the dumped reactors (43). The analysis multiplied World Health Organization dose conversion factors (DCFs) for each radionuclide by the estimated radionuclide inventory to arrive at collective dose commitments. The collective dose commitments were summed and multiplied by a cancer risk factor for ionizing radiation of 0.05 fatal cancer per 100 rem (28) to arrive at an estimate of 0.6 fatal cancer from exposure to the radionuclide inventory from the nuclear wastes dumped in the Arctic. The authors compared this to an estimate of 17,000 fatal radiation-induced cancers that could occur as a result of the Chernobyl accident (43).

Another estimate of risks was based on the same radionuclide activity inventory. Baxter et al. used the inputs of Mount et al. (43), with a 16-box model called ARCTIC2, which incorporates oceanographic and hydrographic information about the relevant seas (3). The model output

### BOX 3–4: Dose Assessment from Anthropogenic Radionuclides in the Ocean: Precedents

Despite the many challenges associated with trying to assess the potential radiation doses from ocean discharges or dumping of radionuclides, two notable precedents exist. One such assessment was carried out on the Northeast Atlantic Dump Site, by the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD). The other was the result of Project MARINA, an effort to assess the impact of several sources of radioactivity in marine waters on European Community populations.

The Northeast Atlantic dump sites are deep sea sites used by eight European countries to dump low-level nuclear wastes between 1949 and 1982. The NEA is requested to review the suitability of the dump sites in use every five years, considering the likely radiological impact of dumping operations on both humans and the environment. Such an assessment was carried out for NEA by the multinational Coordinated Research and Surveillance Program (CRESP) in 1985 (50).

*(continued)*

## BOX 3–4: Dose Assessment from Anthropogenic Radionuclides in the Ocean: Precedents (Cont'd.)

Because surveillance data indicated no significant radionuclide concentrations in water, sediment, or biota, a source term model was developed to estimate a release rate from the dumped objects. An oceanographic model then was used to predict radionuclide concentrations in water and sediment as a function of time, and the data generated were used to estimate doses to critical groups. Calculations were carried out for three scenarios including the past dumping, the past dumping plus five additional years at the rates typical of past dumping, and past dumping plus five years at rates 10 times those typical of the past. The following table shows the estimated peak annual doses to individuals in potentially exposed groups as they were calculated in the assessment. The peak doses calculated were to those eating mollusks in the Antarctic and fell orders of magnitude below the 100 mrem (0.1 rem) dose limit of the International Commission on Radiological Protection for members of the public.

| Source | Estimated source term at release (curies) | Estimated peak annual doses[a] to individuals (mrem) | Pathway, location |
|---|---|---|---|
| Northeast Atlantic dump site | 1.1 million | 0.002 | Consumption of mollusks Antarctica |
| Sellafield | >5.2 million | 30-350[b] | Fish and shellfish, Irish Sea |
| Fallout from weapons testing | 55 million | 0.1–1.0 | Fish, north European waters |
| Naturally occurring radiation | | 200 | Mollusks, crustaceans |

[a] Committed effective dose arising from intakes of radionuclides in the same year.

[b] Doses from Sellafield were calculated to have peaked in the early 1980s and to be well below 100 mrem by 1986.

SOURCES: Ministry of Agriculture, Fisheries, and Food, *Radioactivity in North European Waters: Report of Working Group 2 of CEC Project MARINA*, Fisheries Research Data Report No. 20, (Lowestoft, U.K., 1989); Nuclear Energy Agency, *Review of the Continued Suitability of the Dumping Site for Radioactive Waste in the North-East Atlantic* (Organization for Economic Cooperation and Development, 1985).

Both monitoring data and simple models were used to assess the likely doses to critical groups from marine pathways in the European Community in Project MARINA (37). The assessment considered radioactivity from several different sources, including liquid wastes from nuclear fuel reprocessing plants, liquid wastes from nuclear powerplants and other nuclear industry sites, wastes from solid waste disposal in the northeast Atlantic (referred to above), fallout from Chernobyl, and naturally occurring radionuclides. The table shows the estimated doses calculated in this effort due to discharges from the nuclear fuel reprocessing plant at Sellafield and from weapons testing fallout and naturally occurring radiation.

provides radionuclide concentration data, which are used with IAEA-recommended concentration factors to estimate corresponding concentrations in fish. Radionuclide intake in humans is then estimated based on fisheries data, with assumptions made about typical fish consumption. Finally, conversions to dose were made with gut transfer factors and DCFs from the International Commission on Radiological Protection.

The results from this modeling and risk estimate found a range of collective dose commitment from a maximum of 15,000 person-rem (for instantaneous release of all dumped activity according to the Yablokov report) from Cs-137 down to much lower values with more realistic assumptions. Individual doses for fish eaters ranged from about 6 mrem per year to 0.1 mrem per year. As discussed in box 3-3, individuals who consume large amounts of seafoods can receive about 200 mrem a year from naturally occurring radionuclides. Similar estimates were made for the other radionuclides in the dumped wastes, with the conclusion that Co-60 and Cs-137 would dominate the contribution to total dose commitment from an instantaneous release, whereas C-14 would create most of the dose commitment after a slower release (500 years). The authors concluded that the amount of radioactivity due to wastes disposed in the Arctic seas will be low—either comparable to or less than those from natural or other man-made sources (3).

Two other dose assessments are presented in the Joint Russian-Norwegian Expert Group report from the 1993 expedition to the Kara Sea. In one assessment, doses to critical groups are calculated based on current levels of radioactive contamination in the Barents and Kara Seas. The estimates rely on dynamic models of radionuclide migration and accumulation through living organisms (31). The models take into account temperature, stable chemical analogs, and concentration factors. Average and maximum concentrations of Cs-137 and Sr-90 in the Barents and Kara Seas from 1961 to 1990 were used with experimental and calculated concentration factors and assumptions about fish consumption to arrive at estimates of dose. Based on measured seawater radionuclide concentrations during these years, dose maxima were observed that resulted from the heaviest fallout of weapons testing in the early 1960s and from a peak in nuclear waste disposal at Sellafield in the early 1980s. Results are presented in terms of annual risk of fatal cancer and do not exceed $8 \times 10^{-7}$ (31).

A second estimate of potential doses by the Joint Russian-Norwegian Expert Group is based on consideration of release of the dumped wastes; it represents ongoing work to model different release scenarios, transport processes, sedimentation, uptake in various marine species, and consumption of these species by humans. The model is being developed by Riso National Laboratory, Denmark, in collaboration with the Norwegian Radiation Protection Authority and the Institute of Marine Research in Norway. The model is based on two different regional box models covering European coastal waters, the Arctic Ocean, and the North Atlantic, with input of experimental data from the Barents Sea. Differential equations describe the transfer of radionuclides between regions in the mode. Radioactive decay, transfer to and from sediments, and burial by additional sedimentation are taken into account. Because data on the source term remain limited, the current model assumes the presence of only four radionuclides (Cs-137, Co-60, Sr-90, and H-3) in equal amounts of activity at the time of discharge. Parts of the model have been tested for reliability with measured observations, but this has not yet been done for the Kara Sea with site-specific information.

Two different release scenarios have been considered with this model. One assumes instant release of all the radionuclides at the time of dumping. The second assumes release over a period of 100 years. According to preliminary estimates from this model, "the collective dose will be small for both scenarios." However, investigators acknowledge that incomplete information still severely limits the ability to estimate the potential total dose (31).

In a pilot study by the North Atlantic Treaty Organization (NATO) Committee on the Challenges of Modern Society, another estimate of the potential cancer mortality from dumped spent nuclear fuel is presented (49). Because many characteristics of the spent fuel and its containment are still unknown, the estimate necessarily incorporates several assumptions about release rates and exposure routes. If no fission products are released for years, the estimated total collective dose commitment from Cs-137 and Sr-90 combined is 300 person-rem through the food chain. The contribution of Pu-239 to collective effective dose is estimated to be about 170 person-rem, and the contribution of Am-241 estimated to be about the same. The total collective effective dose commitment from the dumped spent nuclear fuel is summarized as less than 1,000 person-rem to the world population, and it is noted that this is equivalent to a few seconds of natural background radiation.

The term "risk assessment" is used rather loosely to describe a variety of analyses ranging from back-of-the-envelope calculations to exhaustive consideration of all possibilities to arrive at an estimate of the probability of an event and associated uncertainties. Back-of-the-envelope estimates provide some useful information but clearly have considerable weaknesses. In estimating the total cancer mortality or collective dose, they assume distribution of the radiation dose over the global population. This permits a form of comparison with other sources of environmental radiation, such as fallout from weapons testing or natural radiation. It does not convey, however, the range of doses that individuals may experience and the potential local impacts on small communities. Also, by smoothing over the myriad uncertainties and information gaps using rough guesses, these estimates suggest an ease and confidence in assessing risks that are misleading.

Nonetheless, in the absence of more thorough and detailed risk assessments, the rough estimates carried out thus far do provide valuable information in considering the potential scale of the radiological impact. They suggest that the global effects of the dumping that has taken place to date are unlikely to be catastrophic, on the scale of a Chernobyl, and may not be detectable against the effects from other radiation, both natural and man-made. It is clear, however, that more information is necessary to better understand the range of risks to individuals and to local communities.

## ECOLOGICAL EFFECTS OF RADIATION IN THE ARCTIC AND NORTH PACIFIC REGIONS

Particularly in an environment such as the Arctic, where Native people continuing traditional lifestyles rely heavily on the local ecosystems for food and other aspects of survival, it is artificial to evaluate the risks to human health independent of the impacts on the surrounding ecology. In these settings, humans and other populations (sea mammals, caribou, fish, etc.) are interconnected, with humans dependent on the other populations that make up their environment. For this reason, it is of particular interest to understand what impacts from environmental radioactive contamination may result to other populations in the ecosystem.

Earlier sections indicated that radionuclides can be transported and even concentrated through the food chain to lead to human exposure. Beyond this, however, how are the populations that make up the food chain and ecosystem affected by radiation exposure? As with the study of radioactivity's effects on humans, the study of radioactive impacts on plants and animals began to be of concern after the first nuclear detonations occurred in the 1940s. After many early studies focusing only on acute effects, emphasis had shifted by the late 1950s to more ecologically relevant research—longer-term experiments with much lower dose rates and more attention to responses other than mortality (26). Considerable activity continued in this field in the United States until the 1970s when many such programs were scaled back.

Repeatedly, as standards were developed to protect human beings from the hazardous effects of exposure to radiation, it was assumed that these safety levels would also prove protective to other species, if not individual members of those species (27). The most recent ICRP statement on the subject follows:

> The Commission believes that the standard of environmental control needed to protect man to the degree currently thought desirable will ensure that other species are not put at risk. Occasionally, individual members of non-human species might be harmed, but not to the

> extent of endangering whole species or creating imbalance between species.[11]

A recent IAEA publication examined this assumption, reviewing the relevant literature for aquatic and terrestrial biota (26). Several effects of radiation on plants and animals were evident from the literature. For example, reproduction (including the processes from gametogenesis through embryonic development) is likely to be the most limiting end point in terms of population maintenance for both terrestrial and aquatic organisms. Also the total accumulated dose at which a given response was observed increased as the dose rate declined. Furthermore, sensitivity to the effects of radiation varies among species. In the case of aquatic organisms, radiosensitivity increases with increasing complexity. The publication concluded:

> There is no convincing evidence from the scientific literature that chronic radiation dose rates below 1 mGy [milligray] per day [0.1 rad/day] will harm animal or plant populations. It is highly probable that limitation of the exposure of the most exposed humans (the critical human group), living on and receiving full sustenance from the local area, to 1 millisievert per year [100 mrem/year] will lead to dose rates to plants and animals in the same area of less than 1 mGy/d[ay]. Therefore, specific radiation protection standards for non-human biota are not needed.[12]

The document concludes, therefore, that plant and animal populations appear to be no more sensitive than humans to the effects of radiation in the environment. The literature from which this is drawn, however, is severely lacking in studies carried out in the extreme environment of the Arctic.

Because of the special conditions in the Arctic, relationships or radionuclide behavior based on observations in nonpolar regions cannot necessarily be expected to hold. For example, radioactive fallout deposited on land is cleansed much more slowly in Arctic than in more temperate regions. The reason for this difference lies in the relatively ineffective natural dissipative processes in the Arctic compared with other regions. Short growing seasons and limited supplies of heat, nutrients, and moisture lead to slower biological turnover rates that aid in the dispersal of radionuclides (63). Similarly, concentration factors in organisms might be different in food webs unique to the Arctic environment.

Some studies have examined the effects of low temperature and salinity on radiation responses in several aquatic animals. Changes in salinity tend to increase metabolic demands and thus make the animals more sensitive to radiation. Salinity itself, however, can be protective since nonradioactive chemical analogs of radionuclides that might otherwise be taken up and stored in tissues can dilute the radionuclide concentration (65). Low temperatures lengthen cell cycle times and slow the development of lethal biochemical lesions, but they may also slow repair processes (25). Whether these factors combine to make Arctic fauna more or less sensitive to radiation effects is not clear. In particular, improved information about the doses to reproductive tissues in critical species is needed, along with an understanding of the distribution of radionuclides in these tissues (25).

Effects on fertility in aquatic organisms are first observed in sensitive organisms at dose rates between 0.2 and 5 milligrays (mGy) per hour (0.2 and 0.5 rad per hour), comparable to the range observed in some mammals and indicating that aquatic organisms are not necessarily more radiation resistant than mammals (25). Data still more useful for assessing the impacts of radiation on populations would be studies on the "intrinsic rate of natural increase," or *r*, which takes into account both the death and the birth rates. Such data are almost nonexistent. In the

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[11] International Commission on Radiological Protection (ICRP), *1990 Recommendations of the International Commission on Radiological Protection*, ICRP Publication No. 60 (New York, NY: Pergamon Press, 1991).

[12] International Atomic Energy Agency (IAEA), *Effects of Ionizing Radiation on Plants and Animals at Levels Implied by Current Radiation Protection Standards*, Technical Reports Series No. 332 (Vienna: IAEA, 1992).

freshwater crustacean *Daphnia pulex*, however, *r* was reduced to zero at about 70 rad per hour.

The Arctic and sub-Arctic ecosystems are inherently more dynamic and unstable than more temperate regions. Interdependent populations of many animals fluctuate with different periodicities, leading to intermittent peaks and crises (33). Since many unknowns remain about the populations most vulnerable to the effects of radiation in the Arctic environment, it is not evident how the effects of environmental radiation would manifest themselves against this background. At this point, no "sentinel organisms" have been identified that can serve as early warnings of radiation threats to the Arctic ecology.

The only published information on actual evaluations of the effects of nuclear waste disposal in the deep sea on marine organisms has been reports on the Northeast Atlantic dump site used by the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD). For more than 40 years, low-level radioactive waste from nuclear powerplant operations, fuel fabrication and reprocessing, industrial and medical use, and dismantling and decontamination of nuclear plant equipment have been dumped at deep-sea sites in the Northeast Atlantic. Periodically, the Nuclear Energy Agency reviews the continued suitability of the site, assessing the likely radiological impact of the dumping on both humans and the environment (50). Modeling is used to estimate the dispersion of radionuclides and the dose rates to organisms from past dumping practices as well as from potential future dumping at the site. According to the modeling, which is carried out with conservative assumptions, the dose rates received by fish, mollusks, and crustaceans from both past and projected dumping would not result in discernible environmental damage. Peak doses from the dumping of low-level waste, except for benthic mollusks at the site, were within the range of doses received through natural background radiation in the deep sea (25).

## CONCLUSIONS

The nuclear wastes dumped in the Arctic and Far East raise questions about impacts on human health and the environment, both currently and in the future. Current risks appear to be very low since there is no indication of significant leakage or migration of radionuclides from the dump sites. More thorough investigation of the sites is necessary to confirm this.

There is not yet a clear answer to questions of what the future health and ecological impacts of nuclear wastes dumped in the Arctic and North Pacific will be. Estimates and approximations of future impacts based on the information available do not suggest a noticeable effect on human health or on plant and animal populations. However, many unknowns remain, from the status of the dumped wastes, to the likely movement of the radionuclides through the environment, to the dietary intakes of those most likely to be exposed.

Decisions about public health must often be made in the absence of complete information, however. In this case, concerns for public health suggest several important needs. One is the need to prevent further such releases of nuclear wastes into the environment, in accord with the London Convention. Despite the uncertainties in and controversy about the effects of low-dose exposure to radiation, there is general agreement among relevant international commissions and national regulatory bodies that radiation exposures should be "as low as reasonably achievable (ALARA), economic and social factors being taken into account."[13] This concept of ALARA stems from scientific consensus that it is unlikely that the presence or absence of a true threshold for cancer in human populations from radiation exposure can be proved. In the absence of a threshold the principles of prevention dictate minimizing exposure to the extent possible by weighing the other factors involved. As discussed in chapter 2, once radionuclides have been released into the

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[13] International Commission on Radiological Protection (ICRP), *1990 Recommendations of the International Commission on Radiological Protection*, ICRP Publication No. 60 (New York, NY: Pergamon Press, 1991).

environment it is very difficult to completely anticipate or characterize their movement through environmental pathways and eventual human exposure to them. Preventing their release to the extent possible is an obvious way of minimizing human exposure and, thus, human health risk.

The second need is to fill some remaining information gaps to determine whether the estimates of negligible effect are well grounded. These include inspecting each of the dumped nuclear reactors containing spent fuel to ascertain its condition, any local contamination that may have occurred, and the anticipated release rates of radionuclides. Other dumped wastes should also be located, and their contents determined to the extent possible. Where it is learned that releases may have occurred, strategic monitoring of critical pathways and the food chain should take place to ensure protection of populations.

As more information is gathered and as monitoring systems are considered, it is critical that the public be involved in the process. Genuine efforts are needed to ensure that potentially affected communities participate in decisionmaking, provide input, and have access to the collected information. Protecting public health in circumstances of limited or inadequate information involves:

1. *Understanding the concerns of critical populations:* What potential sources of exposure are of most concern to the people? What is their understanding of the hazard and its source? What information can they provide about foods and habits that can help improve the understanding of potential exposures?
2. *Communicating the state of knowledge to critical populations*: What is known and what gaps in understanding remain? How can these be made known to people without scientific training who distrust many sources of information?
3. *Setting up a system of monitoring that the population accepts and understands:* Does the system address the concerns of the community, and is access to the collected information provided?
4. *Using public input to design a warning system*: What is the best way to advise people of information from the monitoring system? At what point and in what manner should people be cautioned about potential exposures?

As research and efforts to assess risk continue, they must be carried out with complete openness about both current knowledge and knowledge gaps, and with sincere efforts to involve the public in future decisionmaking.

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