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ECOLOGICAL ASPECTS OF ENVIRONMENTAL ASSESSMENT OF CONTAMINATED AREAS

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Ecological Aspects of Environmental Assessment of Contaminated Areas

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I. Introduction

When large landscapes are contaminated by radionuclides released from nuclear activities, physical processes, such as atmospheric and hydrological transport may move the radioactive materials over large distances resulting in direct external exposure of man and organisms. Of equal concern are ecological processes that may result in internal exposure when contaminated drinking water or foodstuffs are ingested. Atmospheric and hydrological processes and external dose exposure are discussed in a report by the National Council on Radiation Protection and Measurements (NCRP 1984) and will not be discussed here.

This paper provides an overview of the modeling of radionuclide movement through defined ecological pathways, describes some ecological problems at remediated sites, and briefly reviews effects of environmental radiation on terrestrial and aquatic biota. This paper does not discuss definitive models for each of the processes that occur in the

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ecological pathways; these can be obtained from the literature. Rather, this paper describes pathways that should be considered when conducting environmental dose assessments for radionuclides released to the environment.

2. Modeling of Terrestrial Pathways

The study of terrestrial transport of radionuclides through the food chain to people takes into consideration the characteristics of the various media along the pathway and the transfer and bioaccumulation factors which connect those media. Radionuclides may be transported to vegetation by air and water. They may be deposited onto plants directly or through resuspension, or they may be taken up through the plant's root system from soil on which radionuclides have been deposited. Plants or their parts may be eaten by humans, or they may be consumed by animals, such as steers, sheep, or chickens, and eaten by humans indirectly in animal byproducts such as beef or milk from cows. This paper will not deal with atmospheric transport *per se*; however, when relatively insoluble materials such as long-lived radionuclides are present on the soil surface, they may in time be "resuspended" into the air and, thus, contribute significantly to the inhalation, external dose, or food chain pathway doses to people long after the source term has ceased to exist. In addition, soil from remediation activities on areas such as tailing ponds, from cleanup following nuclear accidents, and, to a lesser extent, from burial sites, may erode, thus spreading radioactivity over a larger area. Contaminated soil particles may be resuspended as a result of winds and human activities such as farming and construction. The rate of resuspension usually decreases with time as the soil weathers. A comparable mechanism is "splash-up," in which particles are transferred from the soil surface to plant surfaces by water splash during periods of rain.

The transfer of radionuclides from air and water to vegetation has usually been estimated by two general types of models: transient and steady-state. In a transient or dynamic model, the plant, air, soil and other media are considered as compartments containing various amounts of radioactivity **(Figure1).** Linear differential equations are used to describe the rate of change of the amount of radioactivity in each compartment as a function of the various transfer paths into and out of the compartment. When the equations are integrated over long times with constant input values the radionuclides in the various compartments approach constant concentrations. The system is then considered to be in equilibrium or in a steady state. Transient models give reasonable results for pulsed inputs, such as inputs from an accident, and, after a reasonable integration time, they would give results similar to the simpler, steady-state model.

The steady-state or equilibrium model is designed to predict radiological conditions at some future steady state given a continuous, constant source. These tend to be relatively simple models, which often have only two compartments **(Figure 2).** The first compartment describes the direct deposition of radionuclides onto plant surfaces from air and water (from irrigation, for example); the second compartment accounts for later uptake through the plant's roots for long-lived radionuclides previously deposited on the soil. For short-lived radionuclides such as iodine-131, the first component is generally of greatest concern. For some long-lived nuclides and long buildup times, the second compartment may control plant concentrations.

Over the years, variations in these models have been developed to better describe the radionuclide transfer processes. These model variations include an interception or retention factor, a translocation factor, a weathering factor, standing crop biomass, surface soil density, and the soil build-up time. For example, when evaluating uptake from the soil through the root system of long-lived radionuclides that have built up in soils over an extended time period, the model considers the rate of radionuclide removal from the soil through harvesting, the leaching of radionuclides out of the root zone by water, and the equilibrium distribution coefficient (K_D) for the radionuclide in the soil. If the K_D is small, the radionuclide travels with the water; if the K_D is large, the nuclide is retained in the soil for long periods of time. The radionuclide concentration in animal products, such as milk, meat, or eggs, is dependent on the amount of contaminated feed or forage eaten by the animals and their intakes of contaminated water and air. For short-lived nuclides, the seasonal availability of fresh, contaminated feed is an important factor in the rate at which it is ingested. Many site-specific and default parameters that are used in these models are described in NCRP 1984. Tritium and carbon-14 are handled as special cases because of their ubiquitous distribution once they are released into the environment; transport of tritium and carbon-14 is based on the assumption of their rapid and nearly uniform mixing with their stable element analogs in nature (NCRP 1984).

3. Modeling of Aquatic Pathways

Radionuclides enter aquatic systems through atmospheric deposition, run-off/soil erosion, ground-water discharges, or releases of liquid effluents. Regardless of the source, potential exposure through ecological pathways can occur from the ingestion of radionuclides either directly (as from drinking water) or as a result of transfer through aquatic food webs and consumption of aquatic biota. Existing pathway models, which are predominantly equilibrium or steady-state, predict the concentration of radionuclides in the water as a result of dilution, dispersion, and adsorption on sediments as a function of time. In most models, the adsorption of a radionuclide on sediments or the assimilation of a radionuclide by aquatic biota is calculated using a simple empirical relationship. For the adsorption of a radionuclide from water to sediment, the dimensionless coefficient is the distribution coefficient (K_D), which linearly relates the concentration of a constituent on sediment to its concentration in the water (**Figure 3**). For the transfer of the radionuclide from water to an organism, the bioaccumulation factor is used. This factor linearly relates the concentration in an organism or tissue to the concentration in the water (**Figure 4**). Adsorption on sediments and assimilation by aquatic organisms are complex phenomena controlled by a number of environmental factors; however, these empirical factors have been shown to be entirely adequate for assessment purposes. Site-specific and default values are given in NCRP 1984.

4. Uncertainty and Model Validation

Models are only mathematical approximations of real environmental processes and situations, and the parameters used in the models are, therefore, highly variable. The necessary amount of detailed information is rarely, if ever, available. The assessment models, as applied, are conservative enough that the results overestimate actual doses. However, with increasing emphasis on restricting release and dose to levels considered "as low as reasonable achievable" (the ALARA concept), importance is being placed on decreasing the amount of deliberate conservatism in assessment calculations. From a regulatory perspective, application of the ALARA concept makes demonstrating compliance by environmental monitoring difficult and expensive, since concentrations in the environment are extremely low (NCRP 1989). Reliance on models will therefore become mandatory; however, reliance on models brings with it the risk that decreasing the conservatism may increase the possibility of underestimating actual doses unless the magnitude of uncertainty is understood. It should be noted that most dose assessment models have been developed to estimate the outcome of some future activity as a point estimate, and some degree of conservatism is acceptable. However, when reconstructing the potential doses from past activities, such as releases from the Nevada Test Site or from releases during the early years at the Hanford Site, it is necessary to determine the uncertainty in model parameters in order to determine a realistic probable distribution of dose received by the public.

Most models used for environmental radiological assessments are deterministic; that is, they use single values for each parameter to produce a predicted quantity. This predicted quantity cannot reflect the influence of parameter variability or uncertainty. Stochastic models, on the other hand, can produce a range of distribution of predicted values as a function of parameters which are defined as random variables. In stochastic models, parameter variability can be considered explicitly.

The best method for validating a model is to test the model against accurately measured, independent sets of field or laboratory observations made over the range of conditions for which the application of the model is intended. This procedure is referred to as "model validation." However, only limited validation studies have been performed in the United States on radiological assessment models, in part because of the difficulty in measuring the low-level concentrations of radionuclides present in the environment. Where validation information is not available, a procedure referred to as "parameter imprecision" can be used to evaluate model predictions. This procedure requires estimating the variability associated with each model parameter to ascertain the influence of the combined variability of all model parameters on the model output **(Figure 5)**. Approaches to establishing the uncertainty in model predictions are described in a report by the International Atomic Energy Agency (IAEA 1989). The largest uncertainties are expected to be associated with the predictions of deposition, sedimentation, resuspension, food chain bioaccumulation, and groundwater transport.

While the validation of food chain models has been limited in the past, the accident at the Chernobyl Power Station in the USSR provided an opportunity for the Biospheric Model Validation Study (BIOMOVS), an international group organized by the Swedish National Institute of Radiation Protection, to conduct an international validation exercise. A similar model validation study (VAMP) was initiated by the IAEA in 1988.

A number of terrestrial, aquatic, and ground water scenarios have been studied by BIOMOVS; the results of the scenario on the grass-cow-milk pathway for iodine-131 will be used as an example. Data sets were assembled for iodine-131 and cesium-137 in air, vegetation, milk, beef, and grain from 13 locations in 11 countries. The purpose of the exercise was to test model predictions independently against these data. Therefore, participants were only provided with information about the daily and time-integrated radionuclide concentrations in air, the daily amount of precipitation, and the prevailing conditions in agricultural practices. The participants were asked to predict, preferably with associated uncertainties, the resultant contamination of pasture vegetation and milk for both radionuclides. In addition, the participants were asked to predict the contamination of beef and grain (barley) for cesium-137.

The model predictions for total deposition were within a factor of 2 and 1.5 of the observed values for iodine (six sites) and cesium (five sites) respectively, while the predictions for wet deposition were within an order of magnitude. In the case of the predictions for wet deposition, the differences in results reflect the different assumptions concerning washout ratios, scavenging coefficients, effective mixing heights, and, for iodine, the assumed chemical form. Most models predicted the time-integrated concentrations in forage for both radionuclides at most sites to within an order of magnitude of the observations, and approximately half of the models predicted the observations to within a factor of two. Many processes are involved in predicting the radionuclide concentrations in forage; therefore, comparison of model performance is more meaningful when particular processes such as interception and loss from vegetation are considered. The weathering half-lives for iodine and cesium on vegetation range from 6 to 14 days and 11 to 14 days, respectively. The extent of milk contamination primarily depends on the degree of forage contamination and the intake of forage by the cow. The contamination of milk after the Chernobyl accident was limited in some localities by restricting the percentage of fresh feed given to the cows. Of particular interest is that all calculated grass-milk transfer factors for iodine were well below the generally accepted value of 1×10^{-2}. The average for all locations was 2.6×10^{-3}. For cesium, the average transfer factor was calculated to be 7×10^{-3}, which is identical to the normal literature value. Some of the reasons for low transfer factors for iodine could be seasonal effects, the breed of cow, supplemental feed containing iodine, and dry-lot feeding. About 70% of the models predicted iodine milk concentrations to within a factor of 10, and a few were within a factor of two **(Figure 6).**

Overestimation resulted largely from the use of the literature value for transfer from forage to milk. The results indicate that the models performed reasonably well for the forage-milk module with considerably more uncertainty involved in predicting the air to vegetation module. The models generally predicted the iodine loss rate from milk well. For cesium the prediction of the loss rate was excellent for the first 30 days. After 30 days, the models did less well. Models which included soil ingestion predicted this portion of the slope to within a factor of 3.

Most models predicted the time-integrated concentrations of cesium in beef within a factor of 10; however, no model predicted the time-integrated concentrations in beef from all locations to within a factor of 2.5. The unknown composition of the diet, as well as unreported feeding of the animals and use of stored contaminated feed harvested shortly after the Chernobyl accident, may have contributed to the results. The results for contamination of grain indicated that further work is required on the modelling of the radionuclide transfer to grain. Only two models gave predicted/observed ratios that were reasonably accurate, i.e., a geometric mean within about a factor of 3 from unity.

5. Screening Models

In recent years, the trend has been to develop more complex models for dose assessment and to incorporate detailed modules on ecological processes; however, the increased model complexity has not necessarily improved the accuracy of estimates of dose and, in certain cases, has had the opposite effect. For many situations, such as situations in which only small quantities of radionuclides are used and the resultant concentrations and, hence, dose in the environment are too low to measure, simple models that will adequately address these situations are needed. Scientific Committee #64 was charged with the responsibility of developing such models that could be used for the preliminary evaluation of radionuclide releases. To be effective, these models needed to have a predetermined level of uncertainty and should be the only model required if the resulting dose is less than a prescribed level. A screening model for determining compliance with environmental standards was completed for releases of radionuclides to the atmosphere (NCRP 1989) and is now used by the U.S. Environmental Protection Agency (EPA) to assess compliance with the National Emission Standards for Hazardous Air Pollutants Standards for radionuclides under the Clean Air Act (NESHAPS). A more comprehensive NCRP report on screening techniques for assessing releases of radionuclides to the atmosphere, to surface waters, and to ground water is nearing completion.

If the cleanup or remediation of hazardous waste sites on federal and private property is to proceed cost effectively, a screening approach for both radionuclides and hazardous chemicals will be necessary. We cannot afford to treat all sites equally. Screening techniques will allow high-risk sites or units to be given priority over other, lower-risk sites. One of the stumbling blocks to developing these techniques is the lack of transfer data for the nonradiological materials (organic and inorganic) that might be present at these sites.

6. Ecological Problems at Remediated Sites

Of particular interest in the remediation of radioactive and mixed-waste sites, such as those present at every U.S. Department of Energy (DOE) facility, is the role plants and animals play in confounding efforts to isolate these wastes from the environment. A few years ago, the engineered barriers were covered with rip-rap (a coarse gravel) and sprayed with herbicides to prevent plant growth. It soon became apparent, especially in the arid areas of the western United States, that this kind of coverage, while it is adequate for the long-term physical stabilization of the site, resulted in increased soil moisture content; i.e., precipitation increased the water content of the burial site. Experimental work indicated that transpiration by plant material was a significant factor in controlling the rate of entry of water into the burial zone.

More recent research on engineered barriers for long-term stabilization has demonstrated that barriers should be designed not only to prevent the intrusion of water from precipitation entering the burial site by covering it with appropriately sized clay, soil, and gravel but also by including a plant cover that would enhance transpiration at the burial site and therefore moderate the soil water content. The plant crop should have a shallow rooting system that will maintain the integrity of the physical barrier. Should the deep roots enter the burial site, they may provide a pathway for water to reach the buried materials and a route for the radionuclides and chemicals to be transported back to the surface. Also, the barriers must be designed to prevent burrowing animals from reaching the buried materials.

7. Effects of Radiation on Environmental Biota

Studies on the effects of ionizing radiation on terrestrial plants and animals and on aquatic organisms were begun in the early 1900's. After the advent of the nuclear age in 1944, the production of special nuclear materials and the need to dispose of nuclear waste, the testing of nuclear weapons, and the development of strategies on the potential impacts of nuclear war, the research tempo in the area of radiation effects increased during the next two decades. In the terrestrial environment, the investigations were mainly experimental studies on individual plants and animals in the laboratory and in experimental field plots. Selected studies were conducted at nuclear weapon test sites. In the aquatic environment (freshwater and marine), investigations were conducted at the laboratory level, at nuclear tests sites in selected cases, and in areas contaminated by waste-disposal operations. Practically no work has been done on impacts at the ecosystem level. Two soon-to-be-published reviews, one by NCRP and the other by IAEA, provide a context for evaluating the effects of radiation on environmental biota at the ecosystem level. The NCRP report on the aquatic environment will indicate that a chronic dose rate of less than 10 mGy d^{-1} to the maximally exposed individual in a population of aquatic organisms would ensure protection of the population. The IAEA report reaches the same conclusion. The IAEA also addresses the terrestrial environment and implies that chronic doses of 1 mGy d^{-1} or less would provide adequate protection for the population. Both reports support the International Commission on Radiation Protection (ICRP) statement (ICRP 1977) that "if man is adequately protected then other living things are also likely to be sufficiently protected."

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