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EFFECTS OF IONIZING RADIATION ON TERRESTRIAL PLANTS AND ANIMALS: A WORKSHOP REPORT

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EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) Air, Water, and Radiation Division (EH-412) is preparing to issue protective radiological standards for aquatic and terrestrial organisms. To support this effort, the DOE sponsored a workshop to evaluate the adequacy of current approaches to radiological protection. Workshop participants reviewed and discussed a 1992 International Atomic Energy Agency (IAEA) report on radiological protection of biota for its adequacy and completeness in answering the following questions: Can DOE use these data and conclusions for promulgating radiological standards for the protection of terrestrial organisms? Are the conclusions given in this report still valid or have they been superseded by more recent data?

The consensus of the workshop participants was that the dose limits for animals and plants recommended by the IAEA are adequately supported by the available scientific information. Participants agreed, however, that better guidance on application of those dose limits is needed. Participants further agreed with the IAEA that dose limits designed to protect man generally protect biota as well, except when (1) human access is restricted without restricting access by biota, (2) unique exposure pathways exist, (3) rare or endangered species are present, or (4) other stresses are significant. To deal with these exceptions, site-specific exposures should be considered in developing secondary standards.

Existing exposure models were found to be sufficient in principle for developing secondary standards. Workshop participants concluded, however, that (1) site-specific transfer coefficients are needed for some important species and exposure routes and (2) improved methods of dosimetry for reference biota are needed to eliminate unnecessary conservatism and provide a practical approach for implementating the standards.

1. INTRODUCTION

Radiological protection of plants and animals is currently a subject of regulatory concern. On the basis of a recent published report on this topic by the International Atomic Energy Agency (IAEA 1992), the National Council on Radiation Protection is planning to reevaluate the existing information on effects of radiation on biota, and the U.S. Department of Energy (DOE) is preparing guidelines for the protection of terrestrial biota. Scientific information relevant to guideline development includes information on the movement and bioavailability of radionuclides in terrestrial environments, transfer of radionuclides in terrestrial food chains, dose calculation methods for terrestrial plants and animals, and dose-response relationships for exposed biota.

To support its guideline development effort, the DOE Air, Water, and Radiation Division (EH-412) sponsored a workshop to evaluate the adequacy of current approaches to radiological protection, as exemplified by the IAEA report. Workshop participants reviewed and discussed the 1992 IAEA report for its adequacy and completeness in answering the following questions: Can DOE use these data and conclusions for promulgating radiological standards for the protection of terrestrial organisms? Are the conclusions given in this report still valid or have they been superseded by more recent data?

The workshop, held in Oak Ridge, Tennessee, on June 14–15, 1995, was attended by 12 experts in radioecology and ecological risk assessment. The attendees heard presentations on (1) DOE's perspective and regulatory responsibilities, presented by Mr. Andrew Wallo, III, Director of the DOE Air, Water, and Radiation Division; (2) the rationale underlying the conclusions contained in IAEA 73, presented by Dr. Gordon Blaylock of the SENES Oak Ridge Center for Risk Analysis; and (3) a summary of data available from the former Soviet Union, presented by Dr. John Trabalka of Oak Ridge National Laboratory. Following these presentations, the participants discussed the adequacy of the data and models available for setting radiological protection standards for terrestrial biota. In evaluating the selection and interpretation of data on biological effects of ionizing radiation, the attendees considered

- study selection criteria,
- the adequacy of support for assumptions employed by the IAEA working group,
- the adequacy of data available for various taxonomic groups,
- the relevance of the biological endpoints included in the IAEA evaluation,
- alternative methods of analysis, and
- the potential existence of new laboratory or field data not considered by the IAEA.

In evaluating the methods for calculating radiological doses to biota, the attendees considered

- the generality of the available models,
- the adequacy of support for assumptions and parameter values used by the IAEA,

- the adequacy of validation for the models used,
- alternative methods of analysis, and
- the potential existence of new data for model parameterization or validation.

Section 2 contains summaries of the presentations given at the workshop. Section 3 summarizes the findings and conclusions regarding both the adequacy of the existing standards and the research and development activities needed to support implementation of the standards.

2. SUMMARY OF PRESENTATIONS

2.1 PRESENTATION BY ANDREW WALLO: DOE'S REGULATORY PERSPECTIVE

The U.S. Department of Energy's Office of Environmental Policy and Assistance is responsible for the interpretation of environmental regulations and for the development and issuance of DOE requirements and guidance for radiological protection of the public and the environment.

DOE's requirements for radiological protection of the public and the environment are found in DOE Order No. 5400.1, *General Environmental Protection Program* and in DOE Order 5400.5, which will eventually be promulgated as 10 CFR Part 834, *Radiation Protection of the Public and Environment* by the Air, Water, and Radiation Division. Feedback on the draft of 10 CFR Part 834 indicates a need for a holistic approach to radiological protection of the environment. The need to integrate ecological protection into these radiation programs has also been identified in various federal interagency efforts in which DOE participates. To accomplish this integration, we need to evaluate exposure pathways for aquatic and terrestrial organisms and ecosystems and to develop protective radiological standards for aquatic and terrestrial organisms.

The current Order and proposed rule include guidelines for protection of aquatic organisms. By the end of the calendar year 1995, the goal is to identify or develop radiation protection standards for the terrestrial biota that could be incorporated into DOE regulations. The objective is to have guidelines that will be useful to DOE as well as other agencies in implementing environmental protection and restoration programs. DOE believes that the recent IAEA guidance is a reasonable template for these guidelines.

The 1992 IAEA report endorses the 1977 International Commission on Radiological Protection (ICRP) report and states that chronic radiation dose rates below 1 mGy/d (0.1 rad/d) will not harm plant and animal populations and that radiation standards for human protection will also protect populations of nonhuman biota. The IAEA report concludes that specific radiation protection standards for nonhuman biota are not needed where there are protective standards for humans in place. However, DOE needs to define how broadly this guidance can be applied. Clearly, the guidance applies in situations where properties are being released without control because the stringent protection requirements for the public, which are set at a level low enough to protect individuals who reside on the site and obtain all sustenance from the site, will ensure that ecosystems are protected. In some situations, however, the public are protected by restricting access or use of property; these restrictions are not necessarily effective in controlling the movement or access of plants and animals. We must determine if special ecological guidelines are needed for these situations.

The workshop should provide DOE answers to the following questions:

- Is the recommendation by the IAEA sound?
- What, if any, guidelines are needed to protect nonhuman biota?
- How can this concept be implemented in radiation protection guidance such as DOE's 10 CFR Part 834?

Ideally, radiation protection requirements should be flexible enough to allow each facility to develop its own approaches on protection of the environment (i.e., aquatic and terrestrial biota). In addition, guidance and methodology that can be used to demonstrate compliance with ecological radiation protection requirements need to be identified or developed. The workshop participants should determine if guidance or technical documents are available that would provide sufficient information on how to protect aquatic and terrestrial organisms.

The participants should address three issues:

- Is the 1992 IAEA document the only document available for protecting plants and animals from radiation, and is this document sufficient in its recommendations regarding protective radiation standards for nonhuman biota?
- Do we have methods available to demonstrate compliance with dose limits for nonhuman biota?
- A critical aspect of protecting plants and animals from radiation is the concept of protecting a population rather than individuals of a given species; the exception is endangered species, where individuals must be protected. Is the population concept appropriate for protecting an ecosystem?

The scope of the applicability of radiation protection guidelines must also be defined. The guidelines can be stated as (1) general levels of operations or cleanup, (2) site-specific levels, (3) screening values, (4) levels requiring no detailed studies, or (5) a combination of several of these. Methods of implementing the guidelines must be clear.

In summary, we need to know if ecological radiation protection standards are needed, and, if so, we need to know the appropriate level of these standards and how they should be implemented.

2.2 PRESENTATION BY GORDON BLAYLOCK: SUMMARY OF THE IAEA REPORT

The IAEA Technical Report Series No. 332 had two objectives: (1) to determine whether the statements of the ICRP about the protection of nonhuman organisms and populations are consistent with current knowledge and (2) to determine whether or not radiation protection standards for aquatic and terrestrial biota are warranted. The ICRP concluded in 1977 that

> "Although the principal objective of radiation protection is the achievement and maintenance of appropriately safe conditions for activities involving human exposure, the level of safety required for the protection of human individuals is thought likely to be adequate to protect other species, although not necessarily individual members of those species. The Commission therefore believes that if man is adequately protected then other living things are also likely to be sufficiently protected." (ICRP 1977)

The IAEA noted that, although this assumption has generally been accepted and adopted for standard setting, it had not been rigorously evaluated. The IAEA Report Series 332 was intended to be a rigorous review of the scientific information relevant to the ICRP's earlier conclusions. The report dealt primarily with potential effects on natural plant and animal populations exposed to routine, chronic releases of radionuclides that are controlled to limit exposure of humans to specified safety standards. Accidental releases and releases to areas where human access would be controlled were not specifically considered. The IAEA report specifically evaluated situations in which (1) environmental releases are limited to levels that protect the most highly exposed humans, and (2) the biota of the natural environment share the same environment as the most exposed humans.

Underlying the report is a basic assumption concerning the difference between the way society views risks to people and the way it views risks to other organisms. Our values are strongly focused upon individual humans, and standards are designed to protect the most exposed or most sensitive individuals. In contrast, we view and value most other species as populations rather than as identifiable individuals. Hence, the focus of the IAEA was on defining standards that would protect the viability of populations of organisms, even though some individuals might be adversely affected. The IAEA report adopted the following definition of a population:

> "A population is a biological unit for study, with a number of varying statistics (e.g., number, density, birth rate, death rate, sex ratio, age distribution), and which derives a biological meaning from the fact that some direct or indirect interaction among its members are more important than those between its members and members of other populations." (1992)

The report considered two types of exposures to populations. An acute exposure is one that is delivered in a time period that is short compared with the time over which any obvious biological response develops. A chronic exposure is one that could continue over a large fraction of the natural life of the organism. The IAEA evaluated data relating to terrestrial plants, mammals, birds, reptiles, amphibians, and invertebrates. The objective of the data review was to identify acute doses and chronic dose rates "below which the likelihood of observing population level effects is remote." Both experimental (laboratory and field) and observational (areas of high natural background radiation and areas with significant anthropogenic contamination) studies were evaluated. A detailed evaluation of data relating to effects of ionizing radiation on aquatic biota was not performed because the IAEA believed that existing comprehensive reviews of these data were adequate.

For acute effects, the IAEA found that reproduction is likely to be the most limiting endpoint in terms of survival of populations. Lethal doses were judged to vary widely among different populations, with birds, mammals, and a few tree species being the most sensitive among those considered by the working group. Acute doses of 0.1 Gy/d (10 rad/d) or less were judged very unlikely to produce persistent, measurable deleterious changes in populations or communities of terrestrial plants or animals. For chronic effects, the working group found again that reproduction is likely the most limiting process. Sensitivity varies markedly among different taxa; certain mammals, birds, reptiles, and a few tree species appear to be most sensitive. For invertebrates, indirect responses caused by radiation-induced changes in vegetation appear to be more critical than direct effects of radiation on the organisms themselves. The working group concluded that irradiation at chronic dose rates of 1 mGy/d (100 mrad/d or 0.1 rad/d) to even the most radiosensitive species does not appear likely to cause observable changes in terrestrial animal populations. For aquatic biota, the working group found that a chronic dose rate of 10 mGy/d (1 rad/d) would be unlikely to adversely affect populations. IAEA cautioned, however, that reproductive effects in long-lived species with low reproductive capacity might require further consideration.

In addition to estimating a "safe" dose for biota, IAEA evaluated whether application of current radiological protection standards for human exposure would result in maintenance of doses to biota below the "safe" level. Three exposure scenarios were evaluated:

- controlled releases of radionuclides from the atmosphere,
- controlled releases of radionuclides to a freshwater aquatic system,
- and uncontrolled constant releases of radionuclides from a shallow-land nuclear waste repository.

For each scenario, steady-state environmental concentrations of selected radionuclides were calculated that would yield a radiation dose to man equal to the annual dose limit for members of the public (1 mSv/year). These concentrations were used to calculate equilibrium dose rates to reproductive or growth tissues of aquatic and terrestrial biota. The resulting doses were compared with the "safe" dose rates (1 rad/d for aquatic biota and 0.1 rad/d for terrestrial biota) recommended by the group. Fifteen isotopes were considered in at least one of the three release scenarios: ^{3}H, ^{14}C, ^{32}P, ^{60}Co, ^{90}Sr, ^{95}Zr, ^{99}Tc, ^{129}I, ^{131}I, ^{137}Cs, ^{226}Ra, ^{235}U, ^{238}U, ^{239}U, and ^{241}Am. Three approaches were employed in estimating radiological doses: the published results of the PATHWAY model (Whicker and Kirchner 1987), limits on air concentrations and annual intakes derived by the ICRP

(1979–81), and computer simulations conducted in 1987 by a class in radionuclide kinetics at Colorado State University. Parameter selection emphasized situations that would yield maximum environmental concentrations and therefore maximum doses to biota.

Evaluations of doses to plant tissue considered foliar depositions, root uptake, and external exposure. Evaluations of doses to animal tissue considered external exposure, inhalation, and ingestion. Upper-estimate dose rates to soil organisms were calculated to be ≤5 mGy/d for all radionuclides. According to the IAEA, available scientific literature supports a conclusion that this dose rate would not cause measurable perturbations in populations of soil microorganisms or soil invertebrates. Upper estimate dose rates for terrestrial plants and animals were in all cases <1 mGy/d (0.1 rad/d).

On the basis of these results, IAEA endorsed ICRP's assertion that regulation of radionuclide releases to levels that protect man will also protect biota. IAEA qualified this endorsement by noting that there may be circumstances, such as the presence of rare or endangered species, in which the generic dose calculations presented in the IAEA report may be insufficient and site-specific analyses may be required.

2.3 PRESENTATION BY J. R. TRABALKA: OVERVIEW OF RUSSIAN/CONFEDERATION OF INDEPENDENT STATES INFORMATION SOURCES, WITH EMPHASIS ON STUDIES AT THE 1957 EXPLOSION SITE IN THE URALS

A number of recent published reports have summarized data collected following three major accidental radionuclide releases in the former Soviet Union. The releases came from the Mayak reprocessing facility into the Techa River (1950–51), the 1957 explosion of stored radioactive waste at Kyshtym, and the 1986 accident at the Chernobyl Nuclear Power Plant. The reports include

- proceedings of the 1990 Luxembourg seminar entitled *Comparative Assessment of the Environmental Impact of Radionuclides Released During Three Major Nuclear Accidents: Kyshtym, Windscale, Chernobyl,* EUR 13574, Commission of the European Communities, 1991 (2 volumes);
- "Radiobiology and Radioecology in the Vicinity of Chernobyl," *Science of the Total Environment* **112,** 1992;
- *Ecological After-Effects of Radioactive Contamination at South Ural,* V. E. Solkov and D. A. Krivolutskii (eds.), Nauka Publishers, Moscow, 1992 (in Russian); and
- the report of an International Union of Radioecology working group (Task Force 5), chaired by Dr. Dennis Woodhead, on effects of enhanced radiation exposure to wild organisms in their natural environment (unpublished draft).

In addition, a workshop entitled *Radioecology: Advances and Perspectives* was held on October 3–7, 1994 at Sebastopol, Ukraine. This workshop focused on damaging effects of radionuclide contamination from accidents and waste disposal, especially the incidents at Chernobyl and Mayak. Effects examined include extensive tree mortality in pine forests, changes in thyroid activity and reduced viability of cattle near Chernobyl, impacts on small rodents near Chernobyl, and impacts on aquatic biota in water bodies near Mayak. The principal conclusions from the workshop were as follows:

- No deleterious effects of radiation could be observed in locations where radiological doses were less than or equal to 5 rad/year.
- Where doses between 5 and 400 rad/year were received, radiation effects were "ecologically masked," meaning that adverse effects on individual organisms were observed but no changes in populations or ecosystems occurred.
- Where doses were >400 rad/year, damaging effects on populations and communities occurred.
- Total destruction of ecosystems occurred where doses exceeded 10,000 rad/year.

Dr. Trabalka has performed a detailed evaluation of scientific literature published by Russian radioecologists following the Kyshtym disaster. He found a number of uncertainties and limitations that affect the interpretation of these data. For example, high spatial variability in deposition following the September, 1957 explosion led to major uncertainties concerning the true levels of radiation to which biota were exposed. Deposition of atmospherically transported particles dropped off rapidly both longitudinally and in cross section along the main deposition axis. Local effects of surface features (e.g., vegetation type and topography) caused substantial fine-scale variability in deposition. Moreover, following initial deposition, the action of wind and precipitation resulted in substantial redeposition of particles. Radionuclides initially deposited on tree crowns were rapidly washed off and deposited on the litter surface, where further migration through leaching and plant root uptake occurred. The release consisted predominantly of ^{90}Sr, decay products of ^{90}Sr, and short-lived (half-life <1 year) isotopes. The radiation that remained five years after the accident was due almost entirely to ^{90}Sr.

These uncertainties are significant because studies conducted immediately following the accident were of relatively poor quality by today's standards. Large errors existed in original measurements of radionuclide deposition; current values are based on reconstructions rather than on actual measurements. Dosimetry (measurements of the actual radiation doses received by organisms) was not attempted. All reported effects were related to levels of initial surface deposition (e.g., ^{90}Sr activity in Ci/km^2). Other concerns raised by Dr. Trabalka include the methodology and timing of the ecological studies and the failure to distinguish between direct effects of radiation and indirect effects such as successional changes in plant communities following forest die-off or altered predator-prey relationships. Potential confounding factors such as immigration of organisms from uncontaminated areas and toxicity from chemical pollutants released from nearby industrial facilities were not obtained.

Despite these uncertainties, approximate dose-response relationships can be derived from studies of "acute" effects of radiation at Kyshtym (i.e., effects resulting from the first 1 to 1.5 years of exposure following the accident):

- Where dose rates exceeded 300–500 rad/d at the soil surface (deposition 4000 Ci/km^2 ^{90}Sr), complete mortality of even the most tolerant plant species (e.g., species with renewal buds below the soil surface) occurred.
- Where dose rates exceeded 40–50 rad/d at the soil surface, complete mortality of grasses and herbs with renewal buds at or near the surface occurred. These plants were replaced by plants with renewal buds buried in the soil. Slow recovery occurred after 3–4 years,
- Where dose rates to the meristem buds of birch trees exceeded 40–50 rad/d (^{90}Sr deposition 4000 Ci/km^2), mortality to trees was complete. At lower dose rates, withered crowns, underdeveloped leaves, and phenological shifts (delay in opening of leaves and flowers, premature leaf fall) were observed over 4 years.
- Where dose rates at the soil surface were $\leq$30 rad/d, seed germination was reduced in plants with renewal buds near the soil surface; morphological changes (gigantism, chlorosis, blued and contorted leaves, lower numbers of seeds in spikes) were observed in some species over 2–3 years.
- A 1958 study demonstrated reduced nesting of birds in contaminated forests where estimated dose rates in tree crowns exceeded 20 rad/d (^{90}Sr deposition 2000 Ci/km^2). Lethal doses to resident birds and mammals would have been expected where dose rates exceeded 10 rad/d, but effects of the Kyshtym accident on birds and mammals were not evaluated until 1964.
- Pine trees were the most sensitive of the biota examined. Where dose rates to needles were 5–10 rad/d or higher, complete mortality of pines occurred within 2 years. At lower dose rates, a variety of sublethal effects were observed.

Dr. Trabalka's overall evaluation is that although a substantial quantity of radioecological data has been collected in the former Soviet Union, much of the data has probably not been evaluated by Western scientists. Those studies that have been evaluated, however, are generally consistent with other published literature. The 1994 workshop in Sebastopol included participants knowledgeable about data collected at Chernobyl and Mayak; participants at this workshop reached conclusions similar to those presented in IAEA 332.

3. SUMMARY OF WORKSHOP DISCUSSION

Following the presentations, workshop participants developed an independent evaluation of the information relevant to setting radiological protection standards for terrestrial biota. The discussion paralleled the format of IAEA 332. First, the laboratory and field data on biological effects of ionizing radiation were discussed. Then, methods and assumptions involved in radiological dose calculations were discussed.

3.1 BIOLOGICAL EFFECTS DATA

3.1.1 Laboratory Studies

Participants first identified the types of laboratory data that could be used in setting radiological protection standards. The following types of effects were discussed:

- chromosomal aberrations, defined as visually observable morphological changes in chromosome structure;
- DNA damage, defined as damage to DNA molecules, detectable through biochemical assays;
- cancer, defined as the development of tumors or other benign or malignant lesions analogous to those that occur in humans;
- growth reduction, defined as a reduction in the rate of growth of organisms, including both animals and plants;
- reproduction effects, including sterility, reduction in fecundity, and occurrence of developmental abnormalities or reduction in viability of offspring;
- reduced seed germination in plants; and
- mortality, including both acute lethality and long-term reduction in life span.

Participants identified a number of methodological problems limiting the value of laboratory studies. First, techniques employed for both external and internal dosimetry in early experimental studies were much less accurate than are those used today. Second, the species tested were, for the most part, selected either because of ease of handling or relevance to human health research. Rodents, beagles, chickens, and *Drosophila* have been the most common animals studied. Most laboratory research on radiation effects on plants has been performed with seeds and seedlings. Third, the range of sensitivities of species and life stages in nature is undoubtedly much greater than the range of sensitivities of species and life stages for which laboratory data are available. Nutritional status is known to affect responses of animals to stress; because of parasitism, disease, or variations in food availability, animals in nature are probably often more vulnerable to added stresses such as ionizing radiation than are well-fed laboratory animals. In addition to these difficulties, most of the emphasis in laboratory research has been on acute exposures, and, even for these, changes in methodology through time make it difficult to compare results of different studies.

Workshop participants compiled a list of criteria for evaluating published laboratory studies:

- Duration. Chronic studies, defined as studies in which organisms are exposed throughout most or all of their life spans, are preferred over acute studies.
- Replication. Studies should include sufficient replication for confidence limits around test endpoints such as LD50s to be reliably calculated. (Participants did not specify a minimally acceptable statistical power or other criterion for determining a required number of replicates.)
- Presence of dose-response relationship. Participants agreed that studies in which the magnitude of the measured response did not increase with increasing radiation dose should not be used for setting protection standards.
- Taxonomic distribution. Data used for standard setting should include tests on mammals, birds, reptiles, invertebrates, and plants; studies covering a wide range of taxa are preferable to those covering a narrow range.
- Ecological relevance of endpoints. Only test endpoints that have clear consequences for the abundance and persistence of populations should be considered. These endpoints include growth, reproduction, and survival. Genetic changes and morphological changes such as tumors do not have unambiguous population-level consequences and should not be used.
- Accuracy of dosimetry. Studies that use the most modern dosimetric methods are preferred; studies using less accurate methods may be used with appropriate qualifications.

3.1.2 Field Studies

The general consensus of participants was that field data are usually more valuable than laboratory data for assessing ecological effects of ionizing radiation. Two kinds of field studies have been performed: experimental studies, in which natural ecosystems have been exposed to radiation under controlled conditions, and monitoring studies, in which measurements of radiation exposures and effects have been made in contaminated environments.

The conditions in experimental studies are much more natural than in laboratory studies. The full array of natural biota are potentially available for study although, in practice, data on birds and large, mobile animals are difficult to collect. For plants, soil-dwelling invertebrates, and small mammals, population-level effects can be directly observed. Moreover, highly accurate dosimetry is possible, at least for external exposures (participants noted that early field experiments, conducted prior to the development of thermoluminescent dosimetry techniques, must be interpreted with caution). Indirect effects, notably changes in plant and animal community composition caused by reduced abundance of sensitive plant species, can also be observed.

Monitoring of contaminated ecosystems has additional advantages. Many such sites involve exposures over a much larger spatial scale than is possible in a field experiment. Sites where data relevant to radiological protection standards have been collected include Mayak, Kyshtym, Chernobyl, Windscale, the DOE reservations, nuclear-weapons testing sites throughout the world, uranium-mining sites, and regions with high natural background radiation. Because of the larger spatial extent of exposures associated with many of these sites, mobile animals can, at least in principle, be included. Moreover, the range of ecosystem types in which monitoring studies have been performed is far greater than the range for which experimental data are available. Whereas experimental studies have used primarily acute external exposures, monitoring studies involve both internal and external exposures and, in many cases, chronic exposures.

Field studies are also subject to a variety of important limitations. Almost all experimental studies, particularly those in which doses are high enough to produce detectable biological effects, have been limited to acute external exposures. In the small number of field experiments involving direct application of isotopes to plants or soils, dose rates have been below biological effects thresholds; the results, therefore, are useful primarily for estimating transfer coefficients. Experiments involving applied isotopes are also subject to significant uncertainties owing to spatial variations in isotope application and the difficulty of obtaining accurate dose measurements for internal exposures. Background environmental variability is inevitably higher in field experiments than in controlled laboratory settings, and sample sizes and numbers of replicates are usually small. Thus, the minimum detectable biological effect is much larger in field experiments than in laboratory experiments. Moreover, for practical reasons, experimental studies have emphasized effects on sedentary species, especially plants, because observed dose-response relationships are generally poor except for plants.

Monitoring studies are subject to additional uncertainties relating to the high spatial heterogeneity of radionuclide deposition rates. For some of the most important monitoring studies (e.g., Kyshtym), direct measurements of deposition rates are unavailable; for others (e.g., Chernobyl), spatial patterns in deposition must be interpolated from limited field sampling. Dose rates for monitoring studies conducted outside the former Soviet Union have generally been too low to produce measurable ecological effects. Because good principals of experimental design (e.g., replication, controls) cannot be applied in monitoring studies, it is often impossible to unambiguously distinguish between radiological effects and effects caused by chemical contamination, habitat disturbance, or natural climatic variation. This is especially true for birds, mobile mammals, and any situations in which doses were less than catastrophic. Moreover, primary effects (i.e., direct effects of radio nuclides on organisms) are difficult to distinguish from secondary or indirect effects such as those resulting from plant community succession following death of sensitive species. Finally, methods used have differed greatly among studies, making comparisons difficult.

With these limitations in mind, workshop participants developed a list of criteria for selection of field studies for use in standard setting:

- Duration. Long-term studies are preferable to short-term; this criterion applies both to the duration of the dose and the duration of the study.
- Accuracy of dosimetry. Studies that use the most modern dosimetric methods are preferred; studies using less accurate methods may be used with appropriate qualifications.
- Presence of dose-response relationship. The magnitude of the measured response should increase with increasing radiation dose; intermediate responses as well as high responses and negative responses should be observed.
- Type of effect observed. Demonstrations of impacts on populations and communities are more useful than measurements of impacts on individual organisms.
- Statistical design. Studies with good statistical designs (site selection, sample replication) for estimating doses and effects are preferred over studies with poor or no statistical designs.
- Quality of documentation. Methods used should be fully documented so that the reliability of the data can be effectively evaluated.

3.1.3 Evaluation of Data Selection Criteria Used by IAEA

Participants found that, in general, the data selection criteria used by IAEA were similar to those developed at the workshop. Field studies were used in preference to laboratory studies when good quality studies of both kinds were available. Chronic studies were preferred over acute studies. Like the workshop participants, IAEA excluded biological endpoints that are not clearly indicative of potential population-level effects. The excluded endpoints include genetic effects (chromosomal aberrations and DNA damage) and tumor induction.

3.2 DOSE CALCULATIONS

Two aspects of dose calculation were discussed at the workshop: (1) the use of environmental transport models to estimate the environmental partitioning and transport of radionuclides and (2) the use of direct measurements and dosimetric models to calculate the radiation doses received by whole organisms and specific target tissues.

3.2.1 Environmental Transport Calculations

Participants agreed that environmental transport modeling will always be necessary in radiological risk assessment, especially for assessing risks associated with new facilities for which actual monitoring data do not yet exist or for assessing doses to humans and biota from existing environmental contamination. The participants did not attempt critical evaluation of any existing environmental transport models. Recent model comparison studies have shown that the choices of assumptions and data sets for parameterization have much more influence on the accuracy of model predictions than do differences between the various models available for performing dose calculations. Hence, it is unlikely that the use by IAEA of a model other than PATHWAY would have altered the conclusions reached by IAEA.

A fundamental principal of environmental pathways modeling is that the fewer steps in model extrapolation required, the more accurate the predictions. Hence, measurements should be made as close to the target organism as possible. For example, in estimating internal radiological doses to herbivorous wildlife such as deer, measurements of radiological activity in vegetation browsed by deer are preferable to estimates of vegetation activity extrapolated from measured activity in soil. However, in the IAEA study, all dose calculations were made on the basis of assumed deposition rates on soil. IAEA attempted to minimize the impact of uncertainties in soil-to-plant-to-herbivore transfer coefficients by using the same set of assumptions to estimate both doses to humans and doses to biota. IAEA argued that the ratio of these two doses, which was the quality of interest, would be insensitive to uncertainties in transfer coefficients.

Workshop participants agreed in general with IAEA's argument. Participants noted, however, that the validity of the argument is dependent on high similarity of transfer processes in human vs biotic food chains and that circumstances exist in which these processes may be substantially different, resulting in unusually efficient transfer to biota. Some ecosystems contain unique environmental pathways, such as the lichen-to-reindeer pathway, that differ qualitatively from the soil-to-plant-to-animal transfers simulated by PATHWAY and other similar models. Moreover, high soil acidity and low soil clay content promote uptake of radionuclides and other contaminants by plants. Such soils are poor sites for agriculture but can support diverse natural ecosystems. In addition, some organisms may have unusual life histories that lead to anomalously high exposures to environmental radionuclides. Participants suggested that site-specific assessments should evaluate the potential existence of these kinds of circumstances.

3.2.2 Dosimetry for Biota

Workshop participants found that the greatest single uncertainty affecting radiological dose calculations for biota is in dosimetry; the calculation of the total radiation dose received by an organism from both external and internal sources. Three types of doses must be considered:

1. radiated external dose, the dose received from radioactive particles not in direct contact with the organism itself;
2. deposited external dose, the dose received from radioactive particles deposited directly on the surface of the organism; and
3. internal dose, the dose received from radionuclides ingested or inhaled by the organism.

Only one of these three doses, the radiated external dose, can be reliably measured in the field. For the other two sources, dosimetric models are needed to relate measurements of radionuclide activity to the dose absorbed by target tissue. The geometry of the organism, the ability of different radioactive particles to penetrate various tissues, and the partitioning of radionuclides within the organism all influence the dose received by target tissues. Through years of research, reliable dosimetric models have been developed for man and for well-studies laboratory animals such as mice and rats. However, similar models do not exist for most kinds of terrestrial biota. The importance of uncertainty in dosimetry for terrestrial organisms is currently unknown. Although the participants briefly discussed the issue of using weighting factors to account for differences in the damage-causing potential of different types of radiation, they reached no conclusion. They did agree that models are needed for the following kinds of terrestrial biota:

- mammals (large and small),
- birds (large and small),
- plants (evergreens, deciduous trees, shrubs/grass), and
- soil invertebrates (earthworm).

4. CONCLUSIONS AND RECOMMENDATIONS

The consensus of workshop participants was that the 0.1 rad/d limit for animals and the 1 rad/d limit for plants recommended by IAEA are adequately supported by the available scientific information. However, they concluded that

- guidance on implementing the limits is needed, and
- the existing data support application of the 0.1 rad/d limit for populations of terrestrial and aquatic fauna to *representative* rather than *maximally exposed* individuals. A dose not exceeding 0.1 rad/d to representative members of a population of terrestrial or aquatic fauna would not cause adverse effects at the population level. Therefore, application of such a screening criterion would ensure protection of terrestrial and aquatic fauna and would be consistent with the NCRP and IAEA recommendations.

Participants further agreed with IAEA that protecting humans generally protects biota except when (1) human access is restricted but access by biota is not restricted, (2) unique exposure pathways exist, (3) rare or endangered species are present, or (4) other stresses are significant. To deal with these exceptions, site-specific exposures should be considered in developing secondary standards. The participants concluded that existing exposure models are sufficient in principle for developing secondary standards. However, transfer coefficients must be developed for some important species and exposure routes that have not been adequately studied, and improved dosimetric models for reference biota are needed to eliminate unnecessary conservatism and provide a practical approach to implementation of the standards.

ERRATA

The second item of the bullet list in Chapter 4 incorrectly states that:

- the existing data support application of the 0.1 rad/d limit for populations of terrestrial and aquatic fauna to *representative* rather than *maximally exposed* individuals. A dose not exceeding 0.1 rad/d to representative members of a population of terrestrial or aquatic fauna would not cause adverse effects at the population level. Therefore, application of such a screening criterion would ensure protection of terrestrial and aquatic fauna and would be consistent with the NCRP and IAEA recommendations.

It should read as follows:

- the existing data support application of the recommended limits for populations of terrestrial and aquatic organisms to *representative* rather than *maximally exposed* individuals. A dose not exceeding 0.1 rad/d to representative members of a population of terrestrial fauna, or 1 rad/d to representative members of populations of terrestrial flora and aquatic fauna, would not cause adverse effects at the population level. Therefore, application of such screening criteria would ensure protection of terrestrial and aquatic organisms and would be consistent with the NCRP and IAEA recommendations.

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Appendix A

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