FINAL REPORT

GUIDANCE FOR ASSESSING ECOLOGICAL RISKS POSED BY RADIONUCLIDES: SCREENING-LEVEL RADIOECOLOGICAL RISK ASSESSMENT

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LIST OF ACRONYMS

ALARA - As Low As Reasonably Achievable
ANL - Argonne National Laboratory
ATP - Adenosine Tri-phosphate
BEIR - Biological Effects of Ionizing Radiation
BNL - Brookhaven National Laboratory
CEQ - Council on Environmental Quality
CERCLA - Comprehensive Environmental Restoration, Compensation, and Liability Act
Ci - Curie
DCLs - Derived Concentration Levels
DOE - Department of Energy
E - Emission Energies
EDE - Effective Whole Body Dose Equivalent
EPA - Environmental Protection Agency
FGR - Federal Guidance Report
HRMB - Hazardous and Radioactive Materials Bureau
HSWA - Hazardous and Solid Waste Amendments
HTO - Tritiated Water
IAEA - International Atomic Energy Agency
ICRP - International Commission on Radiological Protection
LD50 - Lethal Dose 50
LET - Linear Energy Transfer
TLD - Thermoluminescent Dosimetry
LOAEL - Lowest Observed Adverse Effect Level
LORELs - Lowest Observed Radiation Effect Levels
MeV - Million electron volts
MCLs - Maximum Concentration Levels
NAS - National Academy of Sciences
NCRP - National Council on Radiation Protection and Measurements
NESHAPS - National Emissions Standards for Hazardous Air Pollutants
NMED - New Mexico Environmental Department
NOAEL - No Observed Adverse Effect Level
NORELs - No Observed Radiation Effect Levels
NRC - National Research Council
NRDL - United States Naval Radiological Defense Laboratory
NUREG - Nuclear Regulatory Commission Regulations
OSWER - Office of Solid Waste and Emergency Response
R - Roentgen
Rem - Roentgen equivalent man
RESLs - Radioecological Screening Levels
RBE - Relative Biological Effectiveness
RCRA - Resource Conservation and Recovery Act
RESG - Radioecological Screening Guidance

LIST OF ACRONYMS (continued)

RFI - RCRA Facility Investigation
RI/FS - Remedial Investigation/Feasibility Study
ROD - Record of Decision
RESRAD - Residual Radioactivity
ORNL - Oak Ridge National Laboratory
USAEC - United States Atomic Energy Commission
UT-AEC - University of Tennessee-Atomic Energy Commission

1.0 INTRODUCTION

1.1 Purpose

The Hazardous and Radioactive Materials Bureau (HRMB) of the New Mexico Environmental Department (NMED) has issued screening level ecological risk assessment guidance for chemicals. The guideline is entitled "Guidance for Assessing Risks Posed by Chemicals: Screening Level Ecological Risk Assessment," March/April 2000. The guide is a multi-phase tool for conducting consistent ecoscreens by RCRA hazardous waste permitted facilities and corrective action/remediation projects under Hazardous and Solid Waste Amendments (HSWA). This document is designed to supplement that guide by providing screening guidance for sites contaminated with radioactive material, referred to as Radioecological Screening Guidance (RESG).

Radioecological Screening Guidance (RESG) is a tool that NMED developed to help standardize and accelerate the evaluation and cleanup of soils, water, and sediment contaminated with radioactive materials. This guidance provides a methodology for environmental science/ engineering professionals with a background in radiological risk assessment to calculate radioecologically-based, site-specific screening levels for radionuclides in soil, water, and sediment that may be used to identify areas needing further investigation. The guide does not address scenarios where organisms are contaminated directly from radioactive fallout, such as the contamination of grass and trees. The guide is limited to screening sites where the soil, water, and/or sediment has been contaminated and cleanup decisions are required, such as at sites undergoing RCRA corrective actions, sites on the National Priorities List, sites undergoing decontamination and decommissioning, and sites with elevated levels of naturally occurring radioactivity.

The purpose of this guide is to provide generic radioecological screening levels (RESLs), along with a method for deriving site-specific screening levels. The RESLs will serve as a tool to screen radioactively contaminated sites to determine the need for an action, but not necessarily cleanup. Possible actions can range from re-evaluation of likely risks using site-specific data to interim actions to mitigate risks to ecological receptors. The RESLs are not intended for use in determining compliance with as low as reasonably achievable (ALARA) levels or serve as remediation standards.

1.2 Background

Past practices of discharging radioactive effluents either directly to the atmosphere, to rivers, lakes, and oceans or storage and shallow land burial of wastes have the potential for contaminating the terrestrial and aquatic environments. Many radionuclide contaminants may enter the food chain and concentrate in select species. Other radionuclides may remain or concentrate in abiotic compartments of an ecosystem (e.g., silt). Radiation exposure to terrestrial and aquatic organisms may, therefore, result from internal and external sources involving multiple exposure pathways.

Radiation protection standards, including those involving natural resources, have been developed principally to protect human health. The underlying philosophy has been that radiation standards that adequately protect humans also protect the environment and all other life forms. The National Academy of Sciences (NAS 1972) Biological Effect of Ionizing Radiation (BEIR) I Committee stated that:

> *Evidence to date indicates that probably no other living organisms are very much more radiosensitive than man so that if man as an individual is protected, then other organisms as populations would be most unlikely to suffer harm.*

A similar viewpoint was expressed by the International Commission on Radiological Protection (ICRP) in its 1977 Report No. 26:

> *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 is thought likely to be adequate to protect other species, although not necessarily individual members of those species.*

The last sentence reflects a qualitative difference in how we perceive risks for humans compared to other species. For humans, radiation standards reflect the high value that is placed on the individual. The risk of injury or death of any humans is considered highly undesirable and/or unacceptable. For non-humans, the loss of a few or many (provided that there is a large overall population) is not considered a limiting factor for setting standards; rather, the standards are set based on the response and maintenance of endemic populations.

Except for the paper by Thompson (1988), the NAS and ICRP positions have not been seriously challenged. More recently the International Atomic Energy Agency (IAEA, 1992) examined the validity of the 1972 NAS and 1977 ICRP assumptions as they relate to radioactive releases to both the terrestrial and freshwater environments and also solid waste disposal underground. The IAEA Technical Series No. 332, *Effects of Ionizing Radiation on Plants and Animals at Levels Implied by Current Radiation Protection Standards* was prepared by an *ad hoc* committee of scientific experts who reviewed, analyzed, and interpreted the existing body of literature. The report covered effects of ionizing radiation on aquatic organisms, terrestrial populations, and communities. In this report, the IAEA concurred with the earlier NAS and ICRP positions. The IAEA concluded:

> *There is no convincing evidence from the scientific literature that chronic radiation doses below 1 mGy/d^{-1} (0.1R/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 mSv/a^{-1} will lead to dose rates to plants and animals in the same area of less than 0.1 mGy/d^{-1}. Therefore specific radiation protection standards for non-human biota are not needed.*

This position has been somewhat controversial because it is well documented that radionuclides in the environment can be expected to produce substantially higher doses to certain organisms than to people inhabiting and/or deriving sustenance from the same environment. This document has been prepared in recognition of this observation and, as such, takes a more stringent position than the earlier IAEA, NCRP, and ICRP positions regarding the need for separate and distinct ecologically oriented radiation protection standards. In so doing, this document recognizes, for example, that burrowing animals and sediment dwelling aquatic organisms are in intimate contact with radionuclides that deposit in soil and sediment at relatively high concentrations. In addition, unique feeding habits have been shown to result in the reconcentration of radionuclides through the food chain. (Kevern 1971; Mauro, 1973). It must also be recognized that contaminant-induced radiation exposure is but one of many stresses that human activities place on terrestrial and aquatic populations. However, the mode of interaction of radiation (i.e., antagonistic, additive, or synergistic) with other environmental contaminants or stressors is difficult to assess under conditions of chronic exposure. In addition, experimental studies to date have shown that fertility and fecundity[1] of the organisms and embryonic development are the most sensitive stages of the radiation response. It is precisely these attributes which are

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[1] Fecundity is a measure of the production of viable eggs.

important in determining the viability of the population and, in turn, the homeostasis of the ecosystem at large. These biological endpoints are difficult to discern in the natural setting. For these reasons, we have adopted a conservative approach to deriving RESLs.

1.3 Issues Related to Critical Organ, Relative Biological Effectiveness (RBE), and Microdosimetry of Alpha Particles

The methods used in this guide to derive RESLs differ from those employed by others (i.e., DOE 1998 and IAEA Technical Series No. 332) because of unresolved issues related to critical organ, relative biological effectiveness, and microdosimetry of alpha emitters. This section provides an overview of these issues and how they have been addressed in the derivation of the RESLs.

1.3.1 Critical Organ

Many of the models used to derive the radionuclide concentrations in organisms other than man address the concentrations of radionuclides in the edible portions of organisms, such as beef, sheep meat, goat meat, and fish and invertebrate muscle. Models focused on radionuclide concentrations in the muscles of these animals because there was concern that man would be exposed to them through ingestion. For example, the accumulation of radionuclides in beef is derived using empirically determined transfer factors expressed in units of pCi/kg beef per pCi/day ingested by cattle. Similarly, the radionuclide concentrations in fish and shellfish, given the radionuclide concentrations in water, are typically determined using empirically determined bioaccumulation factors (or concentration factors) expressed in terms of pCi/kg edible portions of fish and shellfish per pCi/L of the radionuclide in the water in which the organism resides.

This approach to predicting the accumulation of radionuclides in organisms is appropriate for modeling the doses to man through the food chain, but, for some radionuclides, primarily alpha emitters, it is inappropriate when evaluating the doses and adverse effects of the exposures on the organisms. As is the case for man, the radionuclides taken into the body of organisms other than man are transferred to various organs, and it is the doses to these critical organs that are of concern, not necessarily the doses to muscle tissue, which is typically addressed in the food chain models. Hence, when deriving the doses to organisms other than man, consideration must be given to the doses to the critical organs, which may often be significantly higher than the dose to muscle or the average dose to the organism as a whole.

Pentreath (1979) discusses this issue, explaining that the effects of radiation on aquatic organisms are often determined using external uniform whole body exposures to gamma emitters. The adverse effect experienced by the organism is likely due to the exposures received by specific organs and tissues, which, in the case of external gamma exposures, would be the same for all tissues and organs. However, for internal emitters, many radionuclides are not uniformly distributed and deliver their doses to specific organs and tissues, which may differ markedly from the average whole body exposure. This is especially true for alpha and pure beta emitters, where the energy is deposited locally. For example, Pentreath reports that, in the crab, the concentration of plutonium taken up from water in various tissues relative to muscle tissue is as follows:

Muscle = 1
Hepatopancreas = 3.75
Gills = 27
Exoskeleton = 92

Similarly, the concentration distribution of uranium in mullet is as follows:

Muscle = 1
Bone = 41
Liver = 8
Gonad and eggs = 1.7

In the case of Cs-137, which goes to muscle, the disparity is much less:

Muscle = 1
Gill = 0.5
Bone = 0.3
Liver = 0.5

The implication is that if adverse effects are observed in an organism from a given dose of uniform external exposure to gamma radiation, what is the dose to specific organs from internal emitters that will have comparable adverse effects? One method that can be used to address this issue is to use the bioaccumulation or transfer factor approach to obtain the radionuclide concentration in the muscle of the organism, and then apply a multiplier to determine the radionuclide concentration in the critical organ using empirically determined distributions, such as those summarized above. The next steps would include determining the dose to the various organs using standard dosimetry methods, applying weighting factors, and then summing the weighted doses to the individual organs. This is the method used to derive the effective whole body dose equivalent (EDE) in humans. Unfortunately, we are not in a position to perform the assessment at this level of sophistication for all radionuclides and organisms. However, this issue is given explicit consideration in the derivation of the RESLs.

1.3.2 Relative Biological Effectiveness (RBE)

Many questions have been raised regarding issues related to the relative biological effectiveness (RBE) of internally deposited alpha emitters. For example, in a paper submitted for publication to the Journal of the Health Physics Society by David Kocher and J.R. Trabalka,[2] issues related to the relative biological effectiveness of internally deposited alpha emitters are explored. They point out that many radioecological models estimate the body burden of internal emitters and then derive the average dose to the organism based on the average concentration of the radionuclide in the organism. However, like man, many radionuclides deposit in specific organs and tissues, resulting in higher absorbed doses to those organs and tissues. In addition, the relative biological effectiveness of the deposited energy from alpha emitters for particular biological endpoints may be greater than that of gamma and beta emitters. Kocher points out that the conventional RBE of 20 for alpha emitters for humans may be overly conservative as applied to the deterministic effects of radiation on organisms other than man because the RBE of 20 for alpha emitters was developed considering the stochastic effects of radiation on humans. Based on their review of the literature, Kocher and Trabalka concluded that an RBE of 5 to 10 may be more appropriate for deriving screening levels for organisms other than man. (Kocher and Trabalka, unpublished, personal communication, February 29, 2000). The review found that most of the research on RBEs for deterministic effects was limited to the effects of neutrons and heavy ions on lung tissue. In most cases, the RBEs were about 7-10. The applicability of these results to animal or plant survivability, impaired gonadal development, lowered organ weights, and sterility for both acute and chronic exposures is uncertain, but it appears that an RBE of 20 may be overly conservative.

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[2] We would like to express our appreciation to Dr. David Kocher for kindly allowing us to cite material contained in his draft publication.

In 1957, a comprehensive, systematic study of RBEs in mammalian systems was published by a team of researchers from Los Alamos Scientific Laboratory[3] under the direction of John B. Storer et al (1957). The study used gamma irradiation from Ra-226 as the baseline for investigating a broad range of biological endpoints and types of radiation exposure in mice and rats. The following types of biological endpoints were evaluated:

Table 1-1. Biological Endpoints

Biological Endpoints in Mice and Rats	**Dose Range (rads)**
LD50	400-800
median survival times	200-1500
splenic and thymic atrophy	100-1000
testicular atrophy	50-300
intestinal atrophy	100-400
whole body weight loss	100-200
depression of Fe-59 uptake by red blood cells	50-250
incidence of lense opacity	10-500
incidence of successful tumor implants	100-500
duration of depression of mitotic activity	5-55

The experimental apparatus for all gamma and X-ray exposures consisted of external exposure of the animals in cages specially designed to ensure uniform whole body exposure. Exposure to tritium beta particles was achieved through the injection and ingestion of tritiated water. Neutron and alpha exposures were administered externally through the use of an accelerator. Fission and thermal neutrons were administered through the use of a critical assembly. Proton and alpha exposures were delivered internally by the interaction of the thermal neutrons with elements in the tissue. The alpha exposures resulted from $B(n,\alpha)Li$ interaction with boron injected into the animals. The energies of the protons and alpha particles generated in this manner were 0.6 and 2.4 MeV, respectively. Exposure to fission fragments was produced by injecting the animals with plutonium followed by exposure to thermal neutrons. Internal alpha exposure was also achieved by injection with Pu-238. Determination of the doses, dose rates, and linear energy

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[3] Now Los Alamos National Laboratory (LANL)

transfer (LET) for individual tissues and types of particles was too complex to describe here. Suffice it to say that great care was taken to determine doses and measures of biological endpoints.

The following biological endpoints were investigated and RBEs observed:

Table 1-2. RBE versus LET

Types of Radiation	LET (kev/micron)	Range of RBEs Observed Relative to Ra-226 Gamma Exposures
250 kvp X-rays	3	1.2 to 2.0
Co-60 gamma rays	0.3	0.9 to 1.0
4 MeV gamma rays from graphite capture of thermal neutrons	0.3	0.6 to 0.8
6 kev beta particles from tritium	5.5	1.3 to 1.6
thermal neutrons		
14 MeV neutrons and 7 MeV protons	10	0.8 to 1.7
recoil protons from fission neutrons	45	1.0 to 2.3
0.6 MeV protons from N(np)C reactions	65	1.6 to 4.9
fission neutrons	43-48	2.0 to 4.4
alpha particles and lithium recoils	190	1.3 to 3.5
fission fragments	4000-9000	0.7 to 0.9
heavy recoils from 14 MeV neutrons	850	1 to 2
fast neutrons	8.5-24	1.2 to 4.4
Radon alpha particles	110	1.4
1 MeV neutrons	70	2.8

The important findings here relative to this investigation are that the highest RBE from alpha particles was 3.5, and this included 30-day lethality, testicular atrophy, acute lethality, and splenic and thymic atrophy as the biological endpoints.

Storer (1957) also reviewed the literature and showed that the highest RBE reported for mammalian cell lethality was about 3.5 and occurs as the LET passes through a value of about

40 kev/micron. Lower RBEs were associated with both lower and higher LET values. Bear in mind that the LET of a typical 5.3 MeV alpha particle in tissue is about 110 kev/micron (Casarette 1968) but varies along its path length, increasing as the alpha particle comes to a full stop at the end of its path length.

Zirkle (1954) also reviewed the literature on RBE versus LET. The review covered 86 studies of a broad range of chemical and biological endpoints for organisms ranging from viruses to small mammals exposed to gamma rays, X-rays, beta and alpha particles, and neutrons. Of particular relevance to this study are the results of the investigations of the RBE of alpha exposure to plants and small mammals, as follows:

- Mouse LD50 - RBE 2.2
- Reduction in root growth of Vicua (bean plant) - RBE 11 to 21
- Death of root of Vicua (bean plant) - RBE 9
- Inhibition of root growth of Vicua (bean plant) - RBE 0.6
- Chromatid breaks on division of generative nucleus in Tradescantia pollen tubes-RBE 2.0 to 4.2

Based on this review of the literature, it is difficult to justify an RBE for alpha emitters greater than 5 for a broad range of biological endpoints in mammalian systems. The RBEs for alpha exposure of plant systems appear to be more variable. We have elected to use an RBE of 5 for plant systems and the internal dose conversion factors for humans for mammalian systems, which incorporate an RBE of 20 for internally deposited alpha emitters. This approach is expected to bound the effective dose from alpha emitters.

1.3.3 Microdosimtery of Alpha Particles

Several articles contained in IAEA 1979 also address issues related to the microdosimetry of internal and external alpha emitters, particularly in fish eggs and larvae. The issue has to do with uncertainty regarding the actual dose experienced by eggs and larvae in radioecological studies and the ability to discern adverse effects in-situ. For example, adherence of alpha emitters to the surface of fish eggs or developing embryos can cause relatively high localized doses. Woodhead (1979) calculates the energy deposition pattern to range from 0 to 1.25e-03 Gy per hour per Bq/cm^2 of Pu-239 on the surface of fish eggs over a distance of 35 microns. For Pu-239 uniformly distributed within a fish egg, the dose rate ranges from about 1.6e-06 to 3.5e-06 Gy/hr per Bq/cm^3 (Woodhead 1979). The implication is that empirically determined bioaccumulation factors which are used to estimate the average radionuclide concentrations in aquatic organisms may not reliably represent the dose rate experienced by individual tissues and organs to localized energy deposition from alpha emitters.

In this guideline, we have explicitly tried to address these issues by identifying doses that have little or no effect on organisms other than man, and the radionuclide concentrations in soil, water, and sediment that are associated with those doses. However, it is clear that these are complex matters, especially for alpha emitters. Where uncertain, we tended to err on the side of conservatism. For this reason, failure of a site to meet the screening levels reported in this guide does not necessarily mean that there is a significant radioecological issue at the site. However, compliance with the screening levels would provide a fairly high level of assurance that radioecological issues are not a significant concern at the site.

1.4 Scope

This guidance:

- Provides a simple (generic) approach to deriving screening level radionuclide concentrations that are protective of the ecosystem from potential radiological harm, referred to as Radioecological Screening Levels (RESLs), but not necessarily protective of individual organisms comprising the ecosystem
- Considers four trophic levels
- Employs commonly accepted methods to assess external and internal doses for a broad range of radionuclides, with consideration given to RBE and microdosimetric issues
- Specifies target radiation dose levels for the no-observed-radiation-effect-level (NOREL) and lowest-observed-radiation-effect-level (LOREL) at the population level
- Includes algorithms to calculate radionuclide-specific (including progeny) concentrations in various environmental media (e.g., soil, sediment, and water) corresponding to NOREL and LOREL target doses, using a simple approach
- Provides generic RESLs for soil, sediment, and water for 60 radionuclides for different terrestrial and aquatic trophic levels
- Provides methodologies for deriving generic and site-specific RESLs for sites contaminated with multiple radionuclides

1.5 Approach

This document presents the radioecological risk assessment guidance in a user-friendly manner. It has been designed in a form similar to "Soil Screening Guidance: User's Guide," (EPA 1996). It contains generic, simple equations for deriving radionuclide concentrations in soil, sediment, and water (referred to as RESLs expressed in units of pCi/g of soil and sediment dry weight, and pCi/L of water) that correspond to the no-observed radiological effect level (NOREL) and lowest-observed radiological effect level (LOREL) (which are expressed in units of rem per day[4]) for the most sensitive aquatic and terrestrial organisms. The equations contain a set of default parameters for use in deriving generic LORELs and NORELs for each radionuclide in water, soil, and sediment for terrestrial and aquatic organisms. The generic, default parameters can be replaced by site-specific parameters when site-specific data become available.

The objective of the guide is the derivation of the concentrations of specified radionuclides in the accessible environment (i.e., soil, sediment, and water). This guide does not provide models for simulating the performance of engineered waste disposal systems (such as high-level or low-level radioactive waste storage or disposal facilities), nor does it provide models to simulate the transport of radionuclides in ground water or surface water. These types of models, which are referred to as "performance assessment models," are used to support the siting and design of waste repositories with respect to performance objectives, which, in turn, are intended primarily to protect public health and safety. These models are being developed under separate programs and are not addressed here.

RESLs are not cleanup standards. RESLs alone do not trigger the need for response actions or define "unacceptable" levels of radionuclides in the environment. In this guidance, "screening" refers to the process of identifying and defining areas, radionuclides, and conditions, at a particular site that do not require further radioecological evaluation. This guidance complements the human health screening guidance by ensuring that in the process of protecting human health, the environment and sensitive members of the ecosystem are also protected. Generally, at sites where radionuclide concentrations fall below RESLs, no further action or study is warranted based on radioecological considerations. Generally, where radionuclide concentrations equal or exceed RESLs, further study or investigation, but not necessarily cleanup, is warranted.

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[4] The convention is to express dose to organisms other than man in units of rad per day. However, in this guide, we attempt to explicitly consider the RBE of internally deposited alpha emitters. For this reason, we express the doses in units of rem/day.

1.6 Role of Radioecological Screening Levels

NMED anticipates the use of RESLs as a tool to facilitate prompt identification of radionuclides and exposure areas of radioecological concern. However, the application of this or any screening methodology is not mandatory. The framework leaves discretion to the site manager and technical experts (e.g., risk assessors, hydrogeologists) to determine whether a screening approach is appropriate for the site and, if screening is to be used, the proper method of implementation. If comments are received at individual sites questioning the use of the approaches recommended in this guidance, the comments should be considered and an explanation provided as part of a RCRA site's Statement of Basis or a CERCLA site's Record of Decision (ROD). The decision to use a screening approach should be made early in the process of investigation at the site.

NMED developed the RESLs to be consistent with and to enhance the current site investigation process. They do not replace the Remedial Investigation/Feasibility Study (RI/FS) under Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) or the Resource Conservation and Recovery Act (RCRA) Facility Investigation (RFI). Screening out sites or areas of sites where radioecological issues are not of concern should simplify corrective action decision-making.

Unlike human health screening levels, knowledge of background radionuclide concentrations at the site is not critical for radioecological screening, because, as will be demonstrated, the concentration of the radionuclides of concern in background and the variability of the background concentrations can never be greater than the screening level, unless the site is contaminated with elevated levels of naturally occurring radionuclides.

This guidance provides the information needed to calculate RESLs for the 60 radionuclides addressed in EPA 1994. These 60 radionuclides were selected because of their relatively long half-lives and relative abundance in the nuclear industry. Sufficient information may not be available to develop soil screening levels for additional radionuclides. Additional radionuclides should not be screened out, but should be addressed in the site-specific risk assessment for the site. In addition, the site-specific risk assessment should address the radionuclides, exposure pathways, and areas at the site that are not screened out.

To calculate RESLs, the exposure equations and pathway models are run in reverse to back-calculate an "acceptable level" of radionuclides in soil, water, and sediment for each trophic level. Radioecological toxicity criteria are used to define an acceptable level of contamination in soil, based on the LORELs and NORELs, for each trophic level.

One exception to the above approach is uranium, which presents both chemical and radiological hazards. RESLs for uranium must consider both of these types of hazards. As a general rule, for higher organisms (mammals), the radiological hazard dominates inhalation of insoluble forms of uranium, while the chemical toxicity is the major hazard from intake of soluble forms of uranium. Chemical toxicity of uranium in the kidney has been a concern in establishing health protection standards for humans, and these same concerns extend to other mammals. Accordingly, uranium toxicity could be an issue in establishing ecological screening levels. However, this guide is limited to the assessment of the radiological toxicity of uranium.

1.7 Organisms of Concern And Exposure Pathways

The guidance addresses aquatic and terrestrial organisms separately, and within each group, the guidance addresses four trophic levels. A range of trophic levels is addressed because radionuclides, such as ^{137}Cs, are reconcentrated up the food chain. In addition, different ecological niches are of interest because of differences in proximity to contaminated media. For example, burrowing animals and sediment dwellers have a much greater potential for intimate contact with contaminated soil and sediment than arboreal and pelagic organisms. In addition, higher forms of life are generally more sensitive than lower forms of life. One reason for this is the chromosomes of higher organisms are larger and contain more genetic information, and a radiation induced break in a large chromosome is likely to cause greater damage to the cell. In addition, higher organisms are more vulnerable to DNA damage caused by radiation because they require more biochemical machinery to function. (Whicker and Schultz 1982) By evaluating four trophic levels, some of the variability in radiosensitivity of different organisms and variability in exposure potential due to differences in ecological niches can be captured.

The pathways of exposure include external exposure from immersion in water, soil, and sediment, and internal exposure from the uptake of radionuclides in food and water, ingestion of soil, and inhalation of airborne radionuclides.[5] For alpha and beta emitters, direct contact of contaminated soil and sediment with the surface of the organism is also of concern. As will become apparent later in the report, highly radiosensitive plant tissue, such as root tips, have the potential to receive relatively high direct-contact, surface-contamination exposures, including exposures to alpha and beta emitters. Similarly, alpha emitters may adhere to the surface of eggs and reconcentrate in eggs in the aquatic environment, thereby delivering relatively high localized doses. Consideration was given to these issues, within the limits of our understanding of them, in the development of the RESLs.

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[5] External exposure to airborne radionuclides was not explicitly addressed because exposures from this pathway are extremely small as compared to external exposures from radioactivity in soil.

2.0 TERRESTRIAL ORGANISMS

2.1 No Observed Adverse Effect Level (NOAEL) and Lowest Observed Adverse Effect Level (LOAEL)

The concept of the "No Observed Adverse Effect Level" (NOAEL) and the "Lowest Observed Adverse Effect Level" (LOAEL) is used in Council on Environmental Quality (CEQ) 1989 as target points for chronic and subchronic tests of animals which are used, in part, to establish toxicity limits for human beings. In this report, we use the terms "No Observed Radiological Effect Level" (NOREL) and the "Lowest Observed Radiological Effect Level" (LOREL). Appendix A presents a review of the literature on the radiosensitivity of terrestrial organisms with the objective of defining NORELs and LORELs. This section provides a brief summary of the material provided in Appendix A. As will be seen, most studies emphasize LD50s, but it was possible to develop preliminary LORELs and NORELs from the literature. Specifically, a NOREL of 0.1 rad/day for aquatic and terrestrial organisms is a useful benchmark that can be employed for all organisms representing the more sensitive members of each trophic level. This differs from IAEA guidelines which recommend a NOREL of 0.1 rad/day for terrestrial organisms but 1.0 rad/day for aquatic organisms. We have adopted the more conservative strategy as a means of accommodating many of the uncertainties associated with such relationships.

For many species of insects, amphibians, reptiles, and birds, these NORELs may be overly protective. As will be demonstrated, these organisms appear to be less radiosensitive than mammals and higher plants. In addition, the ecological niche occupied by root tips and burrowing mammals place these organisms in more intimate contact with radionuclides in soil. As a result, this guide focuses on protection of these organisms, and, in doing so, should be protective of all organisms other than man.

Appendix A also shows that most terrestrial radioecological sensitivity studies employed uniform exposure to external sources of gamma radiation to establish a dose-response relationship. Care was taken in extrapolating these results to localized exposure of sensitive tissues to less penetrating radiation. For example, the exposure of plants to Co-60 sources and the associated doses and observed effects reported in the literature do not take into consideration that the root tips of the plants were likely shielded from the exposures by the overlying soil. The implication is that, if the root tips were also exposed to the same doses received by the above-ground portions of the plants, the damage caused by a given radiation dose might have been greater. Therefore, the conclusions drawn from external exposure experiments using highly penetrating gamma emitters must be carefully applied to exposure settings where localized, radiosensitive tissues may be exposed to both penetrating and non-penetrating radiation.

In this guide, we presume that the NOREL for plants is 0.1 rad/day for exposure to root tips. However, there is limited direct evidence to support this conclusion. Nevertheless, a broad range of investigations into the effects of radiation on all terrestrial and aquatic organisms at all developmental stages seems to support a NOREL of 0.1 rad/day. For this reason, we feel justified in using a NOREL of 0.1 rad/day for plant root tips. With respect to root tip exposure to internal and external alpha emitters, we employed an RBE of 5 based on our review of the RBE literature on the effects of alpha emitters on mammalian and plant systems. It should be recognized, however, that, based on our review of the literature, direct empirical data on the NOREL for root tip exposure to alpha emitters is limited and warrants additional research.

Great differences exist among the terrestrial species in regard to radiosensitivity and effects resulting from both acute, high-intensity and low dose-rate exposures to ionizing radiation. Relative to mammals and vascular plants, invertebrates and non-vascular plants appear to be more resistant to ionizing radiation. For example, O'Brian and Wolfe (1964) report that lethality among insects occurs at doses that are about 100 times greater than that in vertebrates. Franz and Woodwell (1968) found that algae were highly radio-resistant as compared to higher plants.

Among the plants, the forest vascular plants and, in particular, the coniferous species have the highest radiosensitivity. Indeed, several well-conducted field studies have clearly demonstrated that certain pines (e.g., Jack pine, longleaf pine, and pitch pine) are as radiosensitive as many mammals. Whicker and Fraley (1974) estimated that an 8-30 day exposure with a total dose of 2000 R[6] might cause mortality in nearly all coniferous forest plants. The dose rates would be ~66-250 R/day in this case. Whicker and Fraley concluded that, at 1000 R, there would be substantial changes in species composition through selective mortality of the more radiosensitive components of the coniferous forest community. Recovery was estimated to require one to several generations. The IAEA (1992) concluded that even lower doses would eliminate some pine trees, giving as an example the death of *P. elliotti* after receiving 300 R in a 200-hour period (~1.5 R/hour).

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[6] For the purposes of this document, 1 R can be considered equivalent to 1 rad.

Based on several comparative radiosensitivity studies of mammals, it is clear that man, while falling within the range of mammals, may not be the most radiosensitive mammalian species. The larger mammals, such as the burro (donkey), cow, dog, sheep, and swine, are at least as radiosensitive to acute radiation exposure as man, and in some cases, they have very slow recovery rates so that they are unusually radiosensitive to lower dose rate or chronic exposures. For example, the lethality for burros receiving a dose of 300 rads in 1 hour appears to be about the same as if the 300 rad exposure was protracted over a 1000-hour exposure period. Thus, based on both acute and chronic exposures, several species of large mammals appear to be equally as sensitive (and perhaps more so) as humans. Unfortunately, most chronic studies of irradiated ecosystems measured only population dynamics of small animals (such as rodents) and did not study deer, bears, or other large wild animals. Thus, it seems to be a reasonable assumption that the radiosensitivity of the large wild animals (except during periods of hibernation) is comparable to the radiosensitivity of the large domestic animals (Page 1968).

Birds are generally less radiosensitive than most mammals, with LD50s ranging from ~400 to >1000 R. Although it has been stated that wild birds are more radio resistant than domesticated birds, this review does not support that conclusion. The LD50 for white leghorn chickens was 900 R at a dose-rate of 5 R/minute. The LD50 for many wild birds was <900, although none were lower than the estimated LD50 for man (~400 R). Very little information is available on the chronic radiation sensitivity, although certain species of birds disappeared from the irradiated ecosystems at doses not much higher than the acute LD50s (Mellinger and Schultz 1975).

While no acute LD50s were found for reptiles and amphibians, the lethal range must be rather high (>2000 R) at low dose rates, based on the lack of mortality or apparent organ injury (except for reproduction) after 5 years of exposure at 1-5 R/day (IAEA 1992). Adult invertebrates, especially insects, are particularly radio resistant with survival at doses of 10,000 - 300,000 R (O'Brian and Wolfe 1964).

Effects on reproduction have clearly been demonstrated at dose rates slightly greater than 1 R/day in several species of terrestrial organisms, including mice, trees, and lizards. Other effects, including lethality, may be manifest at dose rates < 5 R/day, especially in species with slow recovery rates such as the burro and primate. Unfortunately, studies in the range of 1 R/day or lower have not been conducted to adequately define low dose-rate effects (see Appendix A).

The IAEA and ICRP assumptions that the level of safety that protects man will adequately protect all other species may very well be appropriate, based on our current knowledge of low dose rate radiation effects. However, the data base on low dose rate effects on terrestrial mammals is quite inadequate to support such an evaluation with confidence. The IAEA states that "there is no convincing evidence *from the scientific literature* that chronic radiation doses below 1 $mGy\bullet d^{-1}$ (0.1 R/day) will harm animal or plant populations." However, no data are presented to back up the statement. One might just as well state that there is no evidence that chronic radiation doses below 0.1 R/day will **not** harm animal or plant populations. While induction of reproductive effects has been observed at dose rates of ~ 1 R/day, data are not available to make definitive statements as to whether dose rates of 0.1 rad/day are a concern.

In light of these findings, a preliminary NOREL of 0.1 rad/day has been selected for the more sensitive members of terrestrial ecosystems, including vascular plants and large mammals. In addition, we believe that this approach will be protective of all organisms other than man since other organisms appear to be less radiosensitive than large mammals and vascular plants and also have less or comparable potential for exposure due to their ecological niche.

2.2 Derivation of Radioecological Screening Levels (RESLs) For The First Trophic Level

In this section, RESLs for soil are derived that correspond to the NOREL for the first trophic level. Pine trees were selected as the most appropriate representative of the first trophic level for New Mexico. As discussed in Section 2.1 and Appendix A, vascular plants, particularly pine forests, are the most radiosensitive plant species. In addition, pine trees (Pinus edulis) are extremely common in New Mexico. Among the various parts of the plant, the root tips appear to be among the most radiosensitive tissues of plants, primarily due to their high growth rates. Casarette (1968) cites studies that demonstrated that irradiation of the root tips (meristematic region) of Vicia faba caused growth inhibition by inhibiting cell division and growth-stimulating auxins. Root tips are also of special interest due to their close proximity to contaminated soil, creating the potential for greater external exposure to both penetrating (gamma) and non-penetrating (alpha and beta) radiation. The RESLs are expressed in terms of pCi/g of dry soil that corresponds to a dose of 0.1 rad /day. Screening criteria that are protective of the root tips of vasular plants will provide a high level of assurance that the entire first trophic level is protected from the potential harmful effects of elevated levels of radionuclides in soil.

In this section, RESLs are derived for individual exposure pathways and radionuclides. Explicit consideration is given to RBE and microdosimetric issues pertaining to radio-sensitive tissues. Then the sum of fractions rule is described for use in evaluating compliance with the RESLs for multiple radionuclides and pathways.

2.2.1 External Exposures

Plants growing on a contaminated site will be exposed to radiation emitted by radionuclides in the soil. A definitive analysis of the external exposures would take into account each of the following processes and considerations:

- Radioactive decay and progeny (i.e., radioactive daughters) ingrowth
- Correction factors for the non-uniformity of the contaminated soil
- Depletion of the contaminated soil horizon by environmental processes, such as leaching, erosion, or plant uptake
- Limitations in the depth and aerial extent of the contamination

In determining whether the screening models should explicitly consider these processes, the authors took guidance from the Environmental Protection Agency's (EPA) human health risk assessment guidance (EPA 1989, 1991a, and 1991b), ecological risk assessment guidance (EPA 1997), and the NMED guidance (NMED 1999). These guidelines do not explicitly account for these processes or conditions, and, when ingrowth of progeny is expected to be of importance, the progeny are included at the outset of the calculations. In this way, the screening analysis is kept relatively simple and provides a high level of assurance of protectiveness. Should site-specific conditions demand a more focused analysis that explicitly considers these processes and conditions, a site-specific analysis may be performed.

The RESLs are based on the assumption that the plants are exposed to a source geometry that is effectively an infinite slab. The concept of an "infinite slab" means that the thickness of the contaminated zone and its aerial extent are so large that it behaves as if it were infinite in its physical dimensions. In practice, soil contaminated to a depth greater than about 15 cm and with an aerial extent greater than about 1,000 m^2 will create a radiation field comparable to that of an infinite slab.

The models used to derive the RESLs assume that the contaminated zone is a constant, non-depleting source of radioactivity. This assumption provides an upper bound estimate of exposure to radionuclides in soil. The vast majority of sites in the U.S. that contain soil with elevated levels of radionuclides are contaminated with relatively long-lived radionuclides (uranium, radium, thorium, transuranics, ^{137}Cs, and tritium). In addition, high level and low level radioactive waste also consist primarily of relatively long-lived radionuclides. As a result, this assumption is realistic and applicable to most sites and postulated transportation accidents. However, contamination of soil that may occur following an accident at a nuclear facility, such as nuclear power plant, or from local fallout associated with weapons testing, may contain relatively large amounts of short-lived radionuclides. Under these conditions, the RESLs may be overly conservative.

The following equation is used to derive the normalized external dose rate expressed in units of rem/day to the root tips per pCi/g of a given radionuclide in soil.

$$\mathrm{NDP_{ext}}\ (\text{rem/day per pCi/g}) = 0.037\ \text{dis/sec-pCi} \times [E_\gamma + E_\beta + (5 \times 0.75E_\alpha)]\ \text{MeV/dis} \times 24\ \text{hr/day} \times 3600\ \text{sec/hr} \times 0.01\ \text{rem-g/erg} \times 1.6\text{E-6}\ \text{erg/MeV}$$

$$\mathrm{NDP_{ext}} = 5.1\text{E-05} \times [E_\gamma + E_\beta + (5 \times 0.75E_\alpha)]$$

where:

$\mathrm{NDP_{ext}}$ is the normalized external dose to plants (rem/day per pCi/g)
E_γ is total gamma per disintegration for a given radionuclide (see Table 2-1)
E_β is total beta energy per disintegration for a given radionuclide (see Table 2-1)
E_α is total alpha energy per disintegration for a given radionuclide (see Table 2-1)
0.75 adjusts for the shielding of alpha emissions by soil particles
5 is the assumed radiobiological effectiveness of exposure to alpha emitters

The external screening levels for plants ($\mathrm{RESLP_{ext}}$) are derived using the following equation:

$$\mathrm{RESLP_{ext}}\ (\text{pCi/g}) = 0.1\ \text{rad per day}/\mathrm{NDP_{ext}}$$

Table 2-1. Parameters Used to Derive RESLs - Decay Energy*

Nuclide	MeV/disintegration					
	Total	α	β^-	β^+	e^-	γ
Ac-227	33.8	32.3	0.96	0	0.129	0.403
Ag-108m	1.69	0.000	5.668E-2	8.184E-5	1.419E-2	1.62
Ag-110m	2.82	0.000	8.121E-2	0.000	2.892E-3	2.73
Am-241	5.54	5.48	0.000	0.000	2.940E-2	2.810E-2
Am-243	5.76	5.26	0.115	0.000	0.153	0.230
Bi-207	1.65	0.000	0.000	0.000	0.110	1.54
C-14	4.947E-2	0.000	4.947E-2	0.000	0.000	0.000
Cd-109	0.107	0.000	0.000	0.000	8.044E-2	2.616E-2
Ce-144	1.35	0.000	1.29	0.000	9.906E-3	5.136E-2
Cl-36	0.249	0.000	0.249	0.000	1.763E-5	1.586E-6
Cm-243	6.09	5.83	0.000	0.000	0.123	0.133
Cm-244	5.80	5.80	0.000	0.000	6.439E-3	1.490E-3
Cm-248	4.66	4.65	0.000	0.000	4.772E-3	1.054E-3
Co-57	0.143	0.000	0.000	0.000	1.827E-2	0.125
Co-60	2.60	0.000	9.579E-2	0.000	0.000	2.51
Cs-134	1.72	0.000	0.157	0.000	5.169E-3	1.56
Cs-135	5.630E-2	0.000	5.630E-2	0.000	0.000	0.000
Cs-137	0.796	0.000	0.171	0.000	6.023E-2	0.566
Eu-152	1.28	0.000	8.369E-2	0.000	4.028E-2	1.15
Eu-154	1.53	0.000	0.225	0.000	4.847E-2	1.25
Eu-155	0.122	0.000	4.544E-2	0.000	1.635E-2	6.058E-2
Fe-55	5.664E-3	0.000	0.000	0.000	4.003E-3	1.661E-3
Gd-153	0.152	0.000	0.000	0.000	4.186E-2	0.110
H-3	5.685E-3	0.000	5.685E-3	0.000	0.000	0.000
I-129	7.894E-2	0.000	4.090E-2	0.000	1.340E-2	2.464E-2
Mn-54	0.840	0.000	0.000	0.000	3.820E-3	0.836
Na-22	2.39	0.000	0.000	0.194	7.544E-5	2.19
Nb-94	1.72	0.000	0.146	0.000	1.108E-3	1.57
Pa-231	5.45	5.38	0	0	0.0355	0.0372
Pb-210	5.73	5.3	0.396	0	0.0279	0.005
Pm-147	6.196E-2	0.000	6.196E-2	0.000	0.000	3.456E-6
Pu-238	5.50	5.49	0.000	0.000	8.260E-3	1.600E-3
Pu-239	5.15	5.15	0.000	0.000	4.880E-3	6.540E-4
Pu-240	5.16	5.15	0.000	0.000	8.332E-3	1.526E-3

Table 2-1. Parameters Used to Derive RESLs - Decay Energy* (continued)

Nuclide	MeV/disintegration					
	Total	α	β^-	β^+	e^-	γ
Pu-241	5.230E-3	0.000	5.230E-3	0.000	0.000	0.000
Pu-242	4.92	4.91	0.000	0.000	6.839E-3	1.267E-3
Pu-244	7.30	4.59	0.956	0.000	0.250	1.50
Ra-226	26.7	24	0.851	0	0.0851	1.77
Ra-226-ser**	32.4	29.3	1.247	0	0.113	1.775
Ra-228	1.37	0	0.375	0	0.0659	0.927
Ru-106	1.63	0	1.42	0	0	0.207
Sb-125	0.690	0.000	8.644E-2	0.000	0.136	0.468
Sm-147	2.25	2.25	0.000	0.000	0.000	0.000
Sm-151	1.979E-2	0.000	1.963E-2	0.000	1.428E-4	1.260E-5
Sr-90	1.13	0.000	1.13	0.000	0.000	0.000
Tc-99	8.460E-2	0.000	8.460E-2	0.000	0.000	5.183E-7
Th-228	34.4	31.9	0.759	0	0.116	1.56
Th-229	33.6	32.4	0.725	0.000	0.162	0.341
Th-230	4.69	4.68	0	0	0.0129	0.001
Th-232	4.02	4.00	0	0	0.0109	0.001
Th-232-ser**	39.8	35.9	1.134	0	0.193	2.49
Tl-204	0.239	0.000	0.238	0.000	1.221E-4	1.136E-3
U-232	5.32	5.31	0.000	0.000	1.438E-2	1.782E-3
U-233	4.82	4.81	0.000	0.000	3.004E-3	7.181E-4
U-234	4.78	4.76	0	0	0.0113	0.001
U-235	4.75	4.38	0.08	0	0.117	0.176
U-236	4.50	4.49	0.000	0.000	9.564E-3	1.373E-3
U-238	5.11	4.19	0.864	0	0.0265	0.0248
U-sep**	10.1	9.16	0.868	0	0.0433	0.0341
U-series**	49.1	44.9	2.16	0	0.177	1.83
Zn-65	0.590	0.000	0.000	2.023E-3	4.561E-3	0.584

* See Appendix B for a description of how these values were derived.

** These radionuclides include the energy of decay of all their progeny. They are to be used when the radionuclide has been detected in the environment and it is known that all of their progeny are also present. For example, "U-series" means that U-238 was measured, but it is known that all its progeny, both long-lived and short lived, are also present.

Inherent in this method for deriving the $\text{RESLP}_{\text{ext}}$ is the assumption that the radiation field experienced by the sensitive tissues of the root tip is uniform and is unperturbed by the presence of the root tip or the soil containing the contamination. Plate No. 118 of the Handbook of Biological Data (Spector,1956) indicates that the diameter of pine tree root hairs is 22 to 26 microns and the length ranges from 140 to 240 microns. For gamma emitters, the validity of this assumption is apparent since the range of gamma emitters in soil is large compared to the thickness of a root tip. For example, the linear attenuation coefficient for 1 MeV photons in water is about 10% per cm (Shleien et al. 1998). For beta emitters, the following rule of thumb from the Radiological Health Handbook (Shleien et al. 1998) shows that the range of most beta emitters is large compared to the dimensions of a root tip.

$$R(\text{g/cm}^2) \approx E_{\text{max}}/2$$

where:

R = Range in g/cm^2 (range in cm times the density of the material in g/cm^3)
E_{max} = maximum energy in MeV (1-4 MeV energy range)

For example, for a typical 1 MeV beta particle in soil, the range is 0.5 g/cm^2. Assuming a gross density of 1.5 g/cm^3, the range is 0.33 cm or 3.3 mm, 3300 micron. Hence, the range of a beta particle is large compared to the thickness of a root hair. The only exception to this rule of thumb is tritium, which has a very weak 18 keV (max) beta, which will not entirely penetrate the root hair. As a result, this approach is conservative as applied to tritiated water in soil.

The upper end range of an alpha particle in tissue is about 0.07 mm or 70 microns (Shleien et al. 1998). This range is about three times greater than the thickness of pine tree root hairs. Hence, the assumption of uniform energy deposition, though not appropriate for the root itself, is appropriate for evaluating the external dose to the growing root hairs. We also considered the fact that the alpha emitters will be bound to the surface of soil particles. The size of soil particles range from less than 2 microns for clay, 2 to 20 microns for silt, 20 to 200 microns for fine sand, and 200 to 2000 microns for coarse sand (Marshall 1988). Typical 5 MeV alpha particles in soil with a particle density of 2.5 g/cm3 will have a range of about 25 microns. As result, some soil particles will fully attenuate the alpha emissions, but clay particles will not. Hence, the attenuation factor will range from 1.0 to 0.5 depending on the size of the soil particles. On this basis, we elected to use a correction factor of 0.75 to account for shielding of alpha emissions by soil particles. In addition, a relative biological effectiveness of 5 was applied to the alpha dose.

The basis for this RBE, as discussed above, are studies summarized by Kocher and Trabalka (2000), Storer (1957), and Zirkle (1954).

One more issue that needs to be explored is the possibility that the radionuclides will adsorb to the root hairs so that the root hairs experience localized radionuclide concentrations and associated energy depositions that are higher than the concentrations and energy depositions of the radionuclides in soil. This issue applies primarily to alpha emitters because the short range of alpha particles creates the potential for localized areas of higher energy deposition. For this to occur, the concentration of radionuclides in a gram of root hairs due to surface adsorption would need to be higher than the concentration of the radionuclides in soil. Given the high distribution coefficients for most radionuclides in soil, it would seem unlikely that the concentration of radionuclides would be higher than in roots. Notwithstanding this issue, the bioaccumulation factors for plants, which are used later for deriving internal doses, likely account for sorption. Hence, this issue does not appear to be significant and no adjustments were made to the models to account for enhanced external exposure due to sorption.

It is clear that issues related to the microscopic distribution of alpha emitters and the microscopic distribution of the energy deposition patterns of alpha emitters in soil and in the vicinity of the root tips, along with issues related to RBE, represent significant challenges to the development of screening criteria. We have attempted to give due consideration to these issues, but acknowledge the uncertainties attendant to these issues.

2.2.2 Internal Exposures

Higher plants take up nutrients and organic and inorganic material in soil, including radionuclides, through elaborate root systems. Radionuclides taken into plant tissue are a source of internal radiation exposure.

The radionuclide concentration in plants is determined using empirically determined soil-to-plant transfer factors. Soil-to-plant transfer factors are expressed in units of pCi/kg fresh weight of plant material per pCi/kg dry weight of soil for a given radionuclide after the plant has had an opportunity to come into equilibrium with the nutrients and other materials in the soil. They are used to estimate the radionuclide concentration in plants given the radionuclide concentration in the soil in which the plant is growing. Appendix C presents tabulations of soil-to-plant transfer factors recommended or used by EPA (1989a), the Nuclear Regulatory Commission (NRC)

(Kennedy 1992), Residual Radioactivity Model (RESRAD) (Yu 1993), Peterson (1983), the National Council on Radiation Protection and Measurements (NCRP 1996), the International Atomic Energy Agency (IAEA 1994) and others. Among the soil-to-plant transfer factors presented in Appendix C, we selected the values in Table 2-2 for comparison, and, among these values, we selected the largest for use in deriving the RESLs.

We have taken this conservative approach because the soil-to-plant factors for a given type of plant and for a given radionuclide can vary considerably from site to site with season and time after contamination. These variations depend on such factors as the physical and chemical properties of the soil, environmental conditions, and chemical form of the radionuclide in the soil. Furthermore, soil management practices such as ploughing, liming, fertilizing, and irrigation can also affect the uptake of radionuclides by vegetation.

Estimates of this parameter are often based on an analysis of literature references which require subjective evaluation of the experimental techniques, reliability of reported data, and appropriateness of reported values to the parameters. It should also be noted that estimates of plant uptake parameters are often based on the assumption of equilibrium. Some studies have indicated that concentration factors for radionuclides change with time. If equilibrium or near-equilibrium conditions are achieved, they occur late in plant development. Taking all these factors into consideration, and considering that our objective is the development of RESLs, we elected to use the high end values reported in the literature. This approach also takes into consideration the possibility that roots may have higher transfer factors than the whole plant or edible portions of plants.

Once the radionuclides have accumulated in the plants, the plants will receive internal radiation exposures due to the decay of the radionuclides. Not all of the energy of radioactive decay of each radionuclide, as listed in Table 2-1, will be absorbed by the plant. For example, the mass absorption coefficient for a 0.1 to a 1 MeV gamma emitter in tissue is about 0.03 cm^2/g. This means that only 3% of the energy of the photon is absorbed per cm of plant tissue. In other words, unless the plant is very thick, only a very small fraction of the gamma energy emitted by internally deposited radionuclides will be absorbed in the plant. The rest will escape. Conversely, except for the root hairs, virtually all of the energy of beta and alpha emitters will be deposited within the plant tissue. Because the root hairs have a diameter of about 25 micron, most of the energy of alpha and beta particles emitted from within the cells will escape. However, due to the proximity of the root hairs to the root tips, we can assume that the entire

Table 2-2. Comparison of Selected Soil-to-Plant Transfer Factors *

Element	RESRAD (Yu 1993) (pCi/g fresh per pCi/g dry)	IAEA (1994) (fresh wt, mean of the median values)	IAEA (1994) (fresh wt, mean of upper 95th percentile level)	NCRP (1996) for fresh vegetables	Values Selected for Screening
Ac	2.5E-3			.001	0.0025
Ag	1.5E-1	.0375	6.22E-4	.004	0.15
Am	1.0E-3	9.72e-05	.12	.001	0.12
Ar	0			0	0
As	8.0E-2			.08	0.08
At	-			.2	0.2
Ba	5.0E-3			.01	0.01
Be	4.0E-3			.004	0.004
Bi	1.0E-1			.1	0.1
Br	7.6E-1			.4	0.76
C	5.5			-	5.5
Ca	5.0E-1			.5	0.5
Cd	3.0E-1			.5	0.5
Ce	2.0E-3			.002	0.002
Cf	1.0E-3			.001	0.001
Cl	20.0			20.0	20.0
Cm	1.0E-3	1.09e-04	1.10e-03	.001	0.0011
Co	8.0E-2	.028	.316	.08	0.316
Cr	2.5E-4			.01	0.01
Cs	4.0E-2	.034	.365	.2	0.365
Cu	1.3E-1			.05	0.13
Eu	2.5E-3			.002	0.0025
F	2.0E-2			.02	0.02
Fe	1.0E-3			.001	0.001
Fr	-			.03	0.03
Ga	-			.003	0.003
Gd	2.5E-3			.002	0.0025
H	4.8			-	4.8
Hf	-			.003	0.003
Hg	3.8E-1			.3	0.38
Ho	2.6E-3			.002	0.0026

Table 2-2. Comparison of Selected Soil-to-Plant Transfer Factors (continued)

Element	RESRAD (Yu 1993) (pCi/g fresh per pCi/g dry)	IAEA (1994) (fresh wt, mean of the median values)	IAEA (1994) (fresh wt, mean of upper 95th percentile level)	NCRP (1996) for fresh vegetables	Values Selected for Screening
I	2.0E-2	1.02E-2		.02	0.02
In	3.0E-3			.003	0.003
Ir	3.0E-2			.03	0.03
K	3.0E-1			.3	0.3
Kr	0			0	0
La	-	2.27e-04	1.48e-03	.002	0.002
Mn	3.0E-1	.276	2.31	.3	2.31
Mo	1.3E-1			.1	0.13
N	7.5			7.5	7.5
Na	5.0E-2			.05	0.05
Nb	1.0E-2	5.13E-3		.01	0.01
Nd	2.4E-3			.002	0.0024
Ni	5.0E-2	.047	.475	.05	0.475
Np	2.0E-2	4.15e-03	4.69e-02	.02	0.0469
O	-			.6	0.6
P	1.0			1	1.
Pa	1.0E-2			.01	0.01
Pb	1.0E-2	.0019	.020	.004	0.02
Pd	1.0E-1			.1	0.1
Pm	2.5E-3			.002	0.0025
Po	1.0E-3	3.15E-3		.001	0.00315
Pr	2.5E-3			.002	0.0025
Pu	1.0E-3	9.41e-05	.0738	.001	0.0738
Ra	4.0E-2	3.63e-03	.0278	.04	0.04
Rb	1.3E-1			.2	0.2
Re	-			.2	0.2
Rh	1.3E-1			.03	0.13
Rn	0			0	0
Ru	3.0E-2	2.28E-2		.03	0.03
S	6.0E-1			.6	0.6
Sb	1.0E-2			.01	0.01

Table 2-2. Comparison of Selected Soil-to-Plant Transfer Factors (continued)

Element	RESRAD (Yu 1993) (pCi/g fresh per pCi/g dry)	IAEA (1994) (fresh wt, mean of the median values)	IAEA (1994) (fresh wt, mean of upper 95th percentile level)	NCRP (1996) for fresh vegetables	Values Selected for Screening
Sc	2.0E-3			.002	0.002
Se	1.01E-1			.1	0.101
Sm	2.5E-3			.002	0.0025
Sn	2.5E-3			.3	0.3
Sr	3.0E-1	.177	.987	.3	0.987
Tb	2.6E-3			.002	0.0026
Tc	5.0	27.1	111	5	111
Te	6.0E-1			.1	0.6
Th	1.0E-3	7.21e-04	.0126	.001	0.0126
Tl	2.0E-1			.2	0.2
U	2.5E-3	1.89e-03	.020	.002	0.02
W	1.8E-2			.8	0.8
Xe	0			0	0
Y	2.5E-3			.002	0.0025
Zn	4.0E-1			.4	0.4
Zr	1.0E-3			.001	0.001

* See Appendix C for a more complete tabulation of the soil-to-plant transfer factors included in the review.

root ball will experience an approximately uniform dose from the uptake of alpha and beta emitters which reflects the soil-to-plant transfer factor.

On this basis, the following equation is used to derive the normalized internal doses to plants NDP_{int} :

$$NDP_{int} \text{ (rem/day per pCi/g)} = RF \times 0.037 \text{ dis/sec-pCi} \times (E_\beta + 5\ E_\alpha) \text{ MeV/dis} \times 24 \text{ hr/day} \times 3600 \text{ sec/hr} \times 0.01 \text{ rad-g/erg} \times 1.6E\text{-}6 \text{ erg/MeV}$$

$$NDP_{int} = 5.1E\text{-}5 \times RF \times (E_\beta + 5\ E_\alpha)$$

where:

NDP_{int} is the normalized dose to plants from internal exposures (rem/day per pCi/g)

RF= soil-to-plant transfer (or reconcentration) factor
E_β is the beta energy per disintegration for a given radionuclide (MeV) (see Table 2-1)
E_α is the alpha energy per disintegration for a given radionuclide (MeV) (see Table 2-1)
5 is the assumed RBE for alpha emitters in plants

The screening levels for plants from internal exposures ($RESLP_{int}$) are derived using the following equation:

$$RESLP_{int}\ (pCi/g) = 0.1\ \text{rem per day}/NDP_{int}$$

2.3 Derivation of Radioecological Screening Levels (RESLS) for Mammals in the 2nd, 3rd, and 4th Trophic Levels

This section presents external and internal RESLs for mammals representing the 2nd, 3rd, and 4th trophic levels. The criteria for selecting mammals representative of each trophic level are (1) the animals are common to New Mexico, (2) they capture the three trophic levels, and (3) they have ecological niches that tend to result in high-end doses. For example, burrowing animals would tend to receive high-end doses from contaminated soil due to their prolonged and intimate contact with the contaminated soil. Table 2-3 was used to screen the three representative trophic levels:

The following three categories of animals were selected to represent the three trophic levels and varied living habits:

1. Small burrowing mammals, such as the ground squirrel, muskrat, chipmunk, and prairie dog, that feed primarily on herbs and grasses (trophic level 2)
2. Large grazing animals, such as deer and elk (trophic level 2)
3. Large predatory carnivores that feed on deer (trophic level 3/4)

If these categories of organisms are protected, then all organisms other than man are likely to be protected.

Table 2-3. Common Mammals in New Mexico

Common Mammals in New Mexico	**Feeding Habits (Trophic Level)**
Coati	omnivore (2/3)
Black Bear	omnivore (2/3)
Mountain Lion	carnivore (3/4)
Mule Deer	herbivore/browser (2)
White-tailed Deer	herbivore/browser (2)
Pronghorn Antelope	herbivore/grazer (2)
Elk	herbivore/grazer (2)
Fox	omnivore (2/3)
Chipmunk	omnivore (2/3)
Bushy-Tailed Woodrat	herbivore/grazer (2)
Muskrat	herbivore/grazer (2)
Abert's and Fox Squirrel	herbivore/browser (2)
Yellow Bellied Marmot	herbivore/grazer (2)
Bobcat	carnivore (3/4)
Beaver	herbivore/browser (2)
Pocket Gopher	herbivore/grazer (2)
Ground Squirrel	herbivore/browser (2)
Porcupine	herbivore/browser (2)
Desert Bighorn Sheep	herbivore/grazer (2)

2.3.1 Small Burrowing Mammals

External Exposures

Burrowing animals have the highest potential for external exposure to radionuclides in soil because, while in their burrow, they are surrounded by the contaminated soil and are exposed to a 4 pi geometry (i.e., 360 degrees of exposure), as opposed to 180 degrees, or 2 pi exposure geometry, for animals that nest/sleep on the land surface. Thus, burrowing animals have a two-fold higher external exposure potential than animals on the land surface.

The equation used to derive the normalized dose for external exposure of burrow-dwelling mammals (NDB_{ext}) is as follows:

NDB_{ext} (rem/day per pCi/g) = 0.037 dis/sec-pCi x Eγ MeV/dis x 24 hr/day x 3600 sec/hr x 0.01 rad-g/erg x 1.6E-6 erg/MeV

$$NDB_{ext} = 5.1\text{E-}5 \times E\gamma$$

where:

NDB_{ext} is the normalized dose (rem/day per pCi/g)
Eγ is the energy per disintegration for a given radionuclide (see Table 2-1)

The radionuclide screening levels for external exposure to burrowing animals ($RESLB_{ext}$) are derived using the following equation:

$$RESLB_{ext}\ (\text{pCi/g}) = 0.1 \text{ rem per day}/NDB_{ext}$$

Inherent in this method for deriving the $RESLB_{ext}$ is the assumption that the radiation field experienced by the burrow-dwelling animal is uniform and is unperturbed by the presence of the animal or the burrow. Gamma emitters are attenuated in water at a rate of about 0.1 per cm. Hence, for large burrows, this approach may overestimate the external gamma exposure, but not by more than a factor of two. External exposures from beta emitters can be ignored since they represent only a skin dose and will not impact sensitive tissues. External exposures for alpha emitters can also be ignored because of insufficient penetrating power.

Internal Exposures

The internal exposure of all organisms feeding on the first or higher trophic level is best derived based on knowledge of the amount of radioactive material inhaled and ingested, the transport of the radionuclides to the various tissues and organs in the body, the amount of energy of radioactive decay deposited in the tissues and organs, including an appropriate RBE, and the retention time of these radionuclides in the tissues and organs. This information has been developed for man but not for organisms other than man. In approaching this problem, we considered two alternatives. The first was to attempt to develop this information for organisms other than man from the literature. The second was to use the dose conversion factors (i.e., rem effective dose equivalent (EDE) per pCi inhaled or ingested) provided for man. Both approaches have significant limitations. The first approach would require an enormous level of effort and, in the end, would likely result in dose conversion factors which are difficult to defend due to limited information on the RBE, uptake, and clearance of radionuclides for the types of organisms of concern here. The second approach is limited because the application of human uptake, RBEs, clearance rates, and internal dosimetry may be overly conservative for small mammals. For larger mammals, this approach may be somewhat more appropriate. In addition, as discussed above, the use of an RBE of 20 for alpha emitters, which are inherent in the dose conversion factors for man, is likely to be overly conservative for assessing deterministic effects in organisms other than man.

Given this dilemma, we elected to use the internal dose conversion factors for man as tabulated by the EPA in Federal Guidance Report (FGR) No. 11 (EPA 1988). Table 2-4 presents the dose conversion factors. These were compiled from data files furnished by Oak Ridge National Laboratory (ORNL), which are the basis of FGR 11 and 12. The derived dose concentration factors (DCFs) for each radionuclide include the contributions of progeny with half-lives of six months or less, except as noted.

We felt justified in using this approach, and its inherent conservatism, since our objective is the derivation of screening levels. However, the reader is cautioned that, for smaller organisms especially, the absorption fractions may be different (perhaps smaller due to a shorter gastrointestinal tract), the absorbed doses will be less due to the smaller size of the organs, and the clearance rate is likely to be greater due to the higher metabolism of smaller organisms.

Some sense of the magnitude of the conservatism inherent in these modeling parameters, as applied to mammals other than man, include a factor of two to ten in the alpha dose due to the use of a quality factor of 20 and an underestimate of the clearance rate that is proportional to the difference in the body weights and surface area of humans versus the mammal of interest. A good measure of the difference in clearance rates are the differences in the respiratory rates among different animals, as indicated in Table 2-5. Hence, the dose rate per unit activity ingested may be inversely proportional to the respiratory rate.

The differences in dose due to differences in organ size between man and organisms other than man are likely to be small since most of the internal dose is delivered by the beta and alpha emissions which are generally close to 100% absorbed even for relatively small organs. As discussed previously, the range of alpha particles in tissue is about 70 microns and the range of beta particles in tissue is about 3.3 mm. The attenuation of gamma emitters in tissue is about

Table 2-4. Dose Conversion Factors*

Radionuclide	External (mrem/hr per pCi/g or pCi/cm^2)					Internal (mrem per pCi)							
						Inhalation				Ingestion			
	Surface	1 cm	5 cm	15 cm	Infinite	Highest	Lowest	Fastest	Slowest	Highest	Lowest	High f_1	Low f_1
Ac-227+D	5.15e-05	5.23e-05	1.47e-04	2.15e-04	2.30e-04	6.72e+00	1.31e+00	6.72e+00	1.32e+00	1.48e-02	1.48e-02	1.48e-02	1.48e-02
Ag-108m+D	2.13e-04	2.18e-04	6.29e-04	9.83e-04	1.10e-03	2.83e-04	2.53e-05	3.01e-05	2.83e-04	7.62e-06	7.62e-06	7.62e-06	7.62e-06
Ag-110m+D	3.53e-04	3.64e-04	1.06e-03	1.69e-03	1.96e-03	8.03e-05	3.09e-05	3.96e-05	8.03e-05	1.08e-05	1.08e-05	1.08e-05	1.08e-05
Am-241	3.66e-06	2.45e-06	4.65e-06	4.99e-06	4.99e-06	4.44e-01	4.44e-01	4.44e-01	4.44e-01	3.64e-03	3.64e-03	3.64e-03	3.64e-03
Am-243+D	2.88e-05	2.80e-05	7.35e-05	9.93e-05	1.02e-04	4.40e-01	4.40e-01	4.40e-01	4.40e-01	3.63e-03	3.63e-03	3.63e-03	3.63e-03
Bi-207	1.97e-04	2.02e-04	5.84e-04	9.25e-04	1.07e-03	2.00e-05	3.23e-06	3.23e-06	2.00e-05	5.48e-06	5.48e-06	5.48e-06	5.48e-06
C-14	2.14e-09	9.16e-10	1.44e-09	1.53e-09	1.53e-09	2.09e-06	2.90e-09	2.09e-06	2.35e-08	2.09e-06	2.09e-06	2.09e-06	2.09e-06
Cd-109+D	4.29e-06	1.45e-06	2.60e-06	3.03e-06	3.03e-06	1.14e-04	3.96e-05	1.14e-04	4.51e-05	1.31e-05	1.31e-05	1.31e-05	1.31e-05
Ce-144+D	7.77e-06	7.62e-06	2.11e-05	3.22e-05	3.70e-05	3.74e-04	2.16e-04	2.16e-04	3.74e-04	2.11e-05	2.11e-05	2.11e-05	2.11e-05
Cl-36	8.96e-08	7.52e-08	1.89e-07	2.60e-07	2.73e-07	2.19e-05	2.24e-06	2.24e-06	2.19e-05	3.03e-06	3.03e-06	3.03e-06	3.03e-06
Cm-243	1.67e-05	1.66e-05	4.56e-05	6.44e-05	6.65e-05	3.07e-01	3.07e-01	3.07e-01	3.07e-01	2.51e-03	2.51e-03	2.51e-03	2.51e-03
Cm-244	1.17e-07	1.39e-08	1.44e-08	1.44e-08	1.44e-08	2.48e-01	2.48e-01	2.48e-01	2.48e-01	2.02e-03	2.02e-03	2.02e-03	2.02e-03
Cm-248	7.99e-08	9.63e-09	1.00e-08	1.00e-08	1.00e-08	1.65e+00	1.65e+00	1.65e+00	1.65e+00	1.36e-02	1.36e-02	1.36e-02	1.36e-02
Co-57	1.53e-05	1.58e-05	4.24e-05	5.67e-05	5.71e-05	9.07e-06	2.63e-06	2.63e-06	9.07e-06	1.18e-06	7.44e-07	7.44e-07	1.18e-06
Co-60	3.13e-04	3.24e-04	9.48e-04	1.54e-03	1.85e-03	2.19e-04	3.31e-05	3.31e-05	2.19e-04	2.69e-05	1.02e-05	1.02e-05	2.69e-05
Cs-134	2.02e-04	2.08e-04	6.03e-04	9.53e-04	1.08e-03	4.62e-05	4.62e-05	4.62e-05	4.62e-05	7.33e-05	7.33e-05	7.33e-05	7.33e-05
Cs-135	4.44e-09	2.24e-09	3.94e-09	4.37e-09	4.37e-09	4.55e-06	4.55e-06	4.55e-06	4.55e-06	7.07e-06	7.07e-06	7.07e-06	7.07e-06
Cs-137+D	7.39e-05	7.58e-05	2.20e-04	3.45e-04	3.89e-04	3.19e-05	3.19e-05	3.19e-05	3.19e-05	5.00e-05	5.00e-05	5.00e-05	5.00e-05
Eu-152	1.47e-04	1.50e-04	4.33e-04	6.86e-04	7.99e-04	2.21e-04	2.21e-04	2.21e-04	2.21e-04	6.48e-06	6.48e-06	6.48e-06	6.48e-06
Eu-154	1.59e-04	1.62e-04	4.71e-04	7.50e-04	8.76e-04	2.86e-04	2.86e-04	2.86e-04	2.86e-04	9.55e-06	9.55e-06	9.55e-06	9.55e-06
Eu-155	7.86e-06	7.18e-06	1.69e-05	2.08e-05	2.08e-05	4.14e-05	4.14e-05	4.14e-05	4.14e-05	1.53e-06	1.53e-06	1.53e-06	1.53e-06
Fe-55	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	2.69e-06	1.34e-06	2.69e-06	1.34e-06	6.07e-07	6.07e-07	6.07e-07	6.07e-07
Gd-153	1.41e-05	1.10e-05	2.32e-05	2.79e-05	2.79e-05	2.38e-05	9.47e-06	2.38e-05	9.47e-06	1.17e-06	1.17e-06	1.17e-06	1.17e-06
H-3	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	6.40e-08	6.40e-08	6.40e-08	6.40e-08	6.40e-08	6.40e-08	6.40e-08	6.40e-08

Table 2-4. Dose Conversion Factors (continued)

Radionuclide	External (mrem/hr per pCi/g or pCi/cm^2)					Internal (mrem per pCi)							
						Inhalation				Ingestion			
	Surface	1 cm	5 cm	15 cm	Infinite	Highest	Lowest	Fastest	Slowest	Highest	Lowest	High f_1	Low f_1
I-129	3.44e-06	1.27e-06	1.47e-06	1.48e-06	1.48e-06	1.74e-04	1.74e-04	1.74e-04	1.74e-04	2.76e-04	2.76e-04	2.76e-04	2.76e-04
Mn-54	1.08e-04	1.11e-04	3.22e-04	5.11e-04	5.88e-04	6.70e-06	5.25e-06	5.25e-06	6.70e-06	2.77e-06	2.77e-06	2.77e-06	2.77e-06
Na-22	2.80e-04	2.90e-04	8.42e-04	1.34e-03	1.56e-03	7.66e-06	7.66e-06	7.66e-06	7.66e-06	1.15e-05	1.15e-05	1.15e-05	1.15e-05
Nb-94	2.04e-04	2.10e-04	6.09e-04	9.65e-04	1.10e-03	4.14e-04	3.61e-05	3.61e-05	4.14e-04	7.14e-06	7.14e-06	7.14e-06	7.14e-06
Pa-231	5.42e-06	4.90e-06	1.38e-05	2.05e-05	2.17e-05	1.28e+00	8.58e-01	1.28e+00	8.58e-01	1.06e-02	1.06e-02	1.06e-02	1.06e-02
Pb-210+D	4.71e-07	2.95e-07	5.72e-07	6.81e-07	6.96e-07	2.32e-02	2.22e-02	2.30e-02	2.24e-02	7.27e-03	7.27e-03	7.27e-03	7.27e-03
Pm-147	4.54e-09	2.54e-09	4.88e-09	5.69e-09	5.71e-09	3.92e-05	2.58e-05	2.58e-05	3.92e-05	1.05e-06	1.05e-06	1.05e-06	1.05e-06
Pu-238	1.12e-07	1.35e-08	1.62e-08	1.72e-08	1.73e-08	3.92e-01	2.88e-01	3.92e-01	2.88e-01	3.20e-03	4.96e-05	3.20e-03	4.96e-05
Pu-239	4.89e-08	1.20e-08	2.45e-08	3.24e-08	3.37e-08	4.29e-01	3.08e-01	4.29e-01	3.08e-01	3.54e-03	5.18e-05	3.54e-03	5.18e-05
Pu-240	1.07e-07	1.32e-08	1.59e-08	1.67e-08	1.67e-08	4.29e-01	3.08e-01	4.29e-01	3.08e-01	3.54e-03	5.18e-05	3.54e-03	5.18e-05
Pu-241	2.57e-10	2.05e-10	5.20e-10	6.71e-10	6.73e-10	8.25e-03	4.96e-03	8.25e-03	4.96e-03	6.84e-05	7.66e-07	6.84e-05	7.66e-07
Pu-242	8.88e-08	1.11e-08	1.37e-08	1.46e-08	1.46e-08	4.11e-01	2.93e-01	4.11e-01	2.93e-01	3.36e-03	4.92e-05	3.36e-03	4.92e-05
Pu-244+D	4.42e-05	4.45e-05	1.29e-04	2.03e-04	2.30e-04	4.03e-01	2.89e-01	4.03e-01	2.89e-01	3.32e-03	6.28e-05	3.32e-03	6.29e-05
Ra-226+D	2.21e-04	2.29e-04	6.69e-04	1.08e-03	1.28e-03	8.60e-03	8.60e-03	8.60e-03	8.60e-03	1.33e-03	1.33e-03	1.33e-03	1.33e-03
Ra-226-ser	2.21e-04	2.29e-04	6.70e-04	1.08e-03	1.28e-03	3.18e-02	3.08e-02	3.16e-02	3.10e-02	8.60e-03	8.60e-03	8.60e-03	8.60e-03
Ra-228+D	1.24e-04	1.27e-04	3.69e-04	5.88e-04	6.82e-04	5.08e-03	4.86e-03	5.08e-03	4.90e-03	1.44e-03	1.44e-03	1.44e-03	1.44e-03
Ru-106+D	2.82e-05	2.90e-05	8.37e-05	1.31e-04	1.47e-04	4.77e-04	5.62e-05	5.62e-05	4.77e-04	2.74e-05	2.74e-05	2.74e-05	2.74e-05
Sb-125+D	5.77e-05	5.72e-05	1.64e-04	2.52e-04	2.80e-04	1.39e-05	3.41e-06	3.41e-06	1.39e-05	3.65e-06	3.64e-06	3.65e-06	3.64e-06
Sm-147	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	7.47e-02	7.47e-02	7.47e-02	7.47e-02	1.85e-04	1.85e-04	1.85e-04	1.85e-04
Sm-151	6.70e-10	1.11e-10	1.12e-10	1.12e-10	1.12e-10	3.00e-05	3.00e-05	3.00e-05	3.00e-05	3.89e-07	3.89e-07	3.89e-07	3.89e-07
Sr-90+D	7.46e-07	6.89e-07	1.83e-06	2.64e-06	2.81e-06	1.31e-03	2.47e-04	2.47e-04	1.31e-03	1.53e-04	2.27e-05	1.53e-04	2.27e-05
Tc-99	1.04e-08	6.22e-09	1.22e-08	1.43e-08	1.43e-08	8.32e-06	1.02e-06	1.02e-06	8.32e-06	1.46e-06	1.46e-06	1.46e-06	1.46e-06
Th-228+D	1.87e-04	1.96e-04	5.73e-04	9.39e-04	1.16e-03	3.45e-01	2.53e-01	2.53e-01	3.45e-01	8.08e-04	8.08e-04	8.08e-04	8.08e-04
Th-229+D	4.24e-05	4.18e-05	1.15e-04	1.68e-04	1.82e-04	2.16e+00	1.74e+00	2.16e+00	1.74e+00	4.03e-03	4.03e-03	4.03e-03	4.03e-03

Table 2-4. Dose Conversion Factors (continued)

Radionuclide	External (mrem/hr per pCi/g or pCi/cm^2)					Internal (mrem per pCi)							
						Inhalation				Ingestion			
	Surface	1 cm	5 cm	15 cm	Infinite	Highest	Lowest	Fastest	Slowest	Highest	Lowest	High f_1	Low f_1
Th-230	9.99e-08	4.97e-08	1.11e-07	1.36e-07	1.38e-07	3.26e-01	2.62e-01	3.26e-01	2.62e-01	5.48e-04	5.48e-04	5.48e-04	5.48e-04
Th-232	7.34e-08	2.47e-08	5.03e-08	5.92e-08	5.95e-08	1.64e+00	1.15e+00	1.64e+00	1.15e+00	2.73e-03	2.73e-03	2.73e-03	2.73e-03
Th-232-ser	2.83e-05	2.90e-05	8.38e-05	1.31e-04	1.47e-04	1.64e+00	1.15e+00	1.64e+00	1.15e+00	2.76e-03	2.76e-03	2.76e-03	2.76e-03
Tl-204	1.97e-07	1.71e-07	3.86e-07	4.58e-07	4.62e-07	2.41e-06	2.41e-06	2.41e-06	2.41e-06	3.36e-06	3.36e-06	3.36e-06	3.36e-06
U-232	1.35e-07	4.01e-08	8.25e-08	1.02e-07	1.03e-07	6.59e-01	1.27e-02	1.27e-02	6.59e-01	1.31e-03	6.92e-05	1.31e-03	6.92e-05
U-233	9.54e-08	4.60e-08	1.13e-07	1.54e-07	1.59e-07	1.35e-01	2.79e-03	2.79e-03	1.35e-01	2.89e-04	2.65e-05	2.89e-04	2.65e-05
U-234	9.96e-08	2.15e-08	3.88e-08	4.56e-08	4.58e-08	1.32e-01	2.73e-03	2.73e-03	1.32e-01	2.83e-04	2.61e-05	2.83e-04	2.61e-05
U-235+D	2.22e-05	2.17e-05	5.99e-05	8.40e-05	8.64e-05	1.23e-01	2.54e-03	2.54e-03	1.23e-01	2.67e-04	2.81e-05	2.67e-04	2.81e-05
U-236	8.66e-08	1.39e-08	2.15e-08	2.43e-08	2.45e-08	1.25e-01	2.59e-03	2.59e-03	1.25e-01	2.69e-04	2.47e-05	2.69e-04	2.47e-05
U-238+D	3.61e-06	3.41e-06	9.21e-06	1.35e-05	1.51e-05	1.18e-01	2.48e-03	2.48e-03	1.18e-01	2.68e-04	3.74e-05	2.68e-04	3.74e-05
U-sep	4.75e-06	4.45e-06	1.21e-05	1.75e-05	1.92e-05	2.56e-01	5.33e-03	5.33e-03	2.56e-01	5.64e-04	6.48e-05	5.64e-04	6.48e-05
U-series	2.29e-04	2.36e-04	6.89e-04	1.11e-03	1.31e-03	9.66e-01	3.78e-01	7.16e-01	6.29e-01	3.64e-03	3.14e-03	3.64e-03	3.14e-03
Zn-65	7.37e-05	7.61e-05	2.22e-04	3.58e-04	4.22e-04	2.04e-05	2.04e-05	2.04e-05	2.04e-05	1.44e-05	1.44e-05	1.44e-05	1.44e-05

* Dose conversion factors were compiled from data files furnished by ORNL, which are the basis of FGR 11 and 12. The DCFs for each nuclide include the contributions of progeny with half-lives of six months or less, normalized to the specific activity of the parent—such nuclides bear the suffix "+D". Nuclides with the suffix "-ser" include the contributions of the entire radioactive decay chain in full secular equilibrium, also normalized to the specific activity of the parent. "U-sep" refers to the three uranium isotopes in the ratios of their natural abundance, separated from the long-lived progeny, normalized to the specific activity of U-238. "U-ser" refers to the three uranium isotopes in the ratios of their natural abundance, in secular equilibrium with their entire decay chains, normalized to the specific activity of U-238. These factors were compiled through a program written by Keith Eckerman and modified by SC&A. The decay scheme is listed in FGR 12, Table A.1, but has been corrected for Cd-109 and Th-234.

10% per cm. Hence, a large portion of the gamma energy escapes even relatively large organs, e.g., an organ with a diameter of 10 cm (4 inches) will absorb about half of the energy of a 1 MeV gamma ray.

Taking these different factors into consideration, use of human dose conversion factors for assessing the doses to small mammals may overestimate the dose by a factor of perhaps 2 to 50 depending on the radionuclide (i.e., 5-fold for the RBE for alpha emitters, 2-to 10-fold for the metabolic rate, and two-fold for the organ size for gamma emitters).

Table 2-5. Respiratory Rates for Different Animals

Organism	Body Weight (kg) (from Spector, 1956)	Respiratory Rate (cm^3 per kg body weight per hour) (from Spector, 1956) Resting
Mammals		
Man (resting)	76	200
Dog	13	580
Mouse	0.023	3500
Guinea pig	0.43	1250
Horse	770	130
Fox	4.6	505
Rabbit	2.5	460-580
Racoon	5.2	3950

Based on the above, the internal radionuclide screening levels ($RESLB_{int}$) for a small burrowing animal (a rabbit was used as a surrogate) are derived using a two-step process. First, the normalized dose is derived in units of rem/day per pCi/g in soil. Then, the internal $RESLB_{int}$ is derived based on a NOREL of 0.1 rem/day.

The normalized internal dose (NDB_{int}) from the ingestion of food and soil is derived as follows:

$$NDB_{int} = [(I_{bv} \text{ x RF}) + I_{bs}] \text{ x } DCF_{int} \text{ x } .001$$

where:

NDB_{int} = normalized internal dose (rem/day EDE per pCi/g in soil)
RF = the soil-to-plant transfer or reconcentration factor (see Table 2-2)
I_{bv}= ingestion rate of vegetation (g/day). 120 g/day based DOE 1999 for a rabbit as a surrogate for burrow dwelling animals

I_{bs}= ingestion rate of soil (g/day). 3 g/day based DOE 1999 for a rabbit as a surrogate for burrow dwelling animals.
DCF_{int}= internal dose conversion factor for ingestion (mrem EDE/pCi ingested) from Federal Guidance Report No. 11 (EPA 1988)
.001 = rem/mrem

The $RESLB_{int}$ is derived as follows:

$$RESLB_{int} = 0.1 \text{ rem per day}/\ NDB_{int}$$

In order to ensure that inhalation of particlates is not a significant contributor to dose, we also evaluated the normalized inhalation dose, as follows:

$$NDB_{inh} = DL \times I_h \times DCF_{inh} \times 0.001$$

where:

NDB_{inh} = normalized inhalation dose to burrowing animals (rem/day EDE per pCi/g in soil)
DL = dust loading (g/m^3). Assumed to be 2e-04 g/m^3 based on high end recommendation in Yu 1993.
I_h= inhalation rate (m^3/day). Assumed 505 cm^3 per hr per kg body weight. For a fox, body weight is about 4.6 kg. Therefore, respiration rate is 0.056 m^3/day (Spector 1956).
DCF_{inh}= inhalation dose conversion factor (mrem EDE/pCi inhaled) from Federal Guidance Report No. 11 (EPA 1988)
0.001 rem/mrem

2.3.2 Deer

External Exposures

The normalized external dose for deer (NDD_{ext}) is derived in the same manner as it is for humans, as follows:

$$NDD_{ext} = DCF_{ext} (\text{mrem/hr per pCi/g}) \times .001 \text{ rem/mrem} \times 24 \text{ hrs/day}$$

The radionuclide screening levels for external exposure to deer ($RESLD_{ext}$) is derived as follows:

$$RESLD_{ext} = 0.1 \text{ rem per day}/\ NDD_{ext}$$

where:

NDD_{ext} = normalized dose for deer for external exposures (rem/day per pCi/g)

DCF_{ext} = external dose conversion factor for an effectively infinite slab derived from Federal Guidance Report No. 12 (Sv/s per Bq/m^3) (EPA 1993), as presented in Table 2-4 (mrem/hr per pCi/g)

All other terms in the equation are unit conversion factors.

Internal Exposures

The normalized internal dose to deer (NDD_{int}) from the ingestion of food and soil is derived as follows:

$$NDD_{int} = [(I_{dv} \text{ x } RF) + I_{ds}] \text{ x } DCF_{int} \text{ x } .001$$

where:

NDD_{int} = normalized internal dose for deer (rem/yr EDE per pCi/g)

RF = the soil-to-plant transfer factor (see Table 2-2)

I_{dv}= ingestion rate of vegetation for deer (g/day). 20,000 g/day derived from equations in Wildlife Exposure Factors Handbook (EPA 1993) and body weights in Handbook of Biological Data (Spector 1956)

I_{ds}= ingestion rate of soil for deer (g/day). 400 g/day based on the assumption that soil ingestion is 2% of food ingestion

DCF_{int}= internal dose conversion factor for ingestion (mrem EDE/pCi ingested) derived from Federal Guidance Report No. 11 (EPA 1988) (see Table 2-4)

.001 = rem/mrem

The $RESLD_{int}$ is then derived as follows:

$$RESLD_{int} = 0.1 \text{ rem per day}/ NDD_{int}$$

2.3.3 Mountain Lion

External Exposures

The external exposures for the mountain lion can be assumed to be comparable to those derived above for deer.

Internal Exposures

The internal RESLs are derived using a three-step process. First, the normalized body burden for deer is derived, expressed in terms of pCi/g of muscle per pCi/g of a radionuclide in soil. The normalized body burden is derived using empirically determined transfer factors as follows:

$$NBB_D = [(RF \times I_{dv})+I_{ds}] \times TF_d$$

where:

NBB_D = normalized body burden for deer (pCi/kg meat per pCi/g soil)
RF = the soil-to-plant transfer factor (see Table 2-2)
I_{dv}= ingestion rate of vegetation for deer (g/day). 20,000 g/day derived from equations in Wildlife Exposure Factors Handbook (EPA 1993) and body weights in Handbook of Biological Data (Spector 1956)
I_{ds}= ingestion rate of soil for deer (g/day). 400 g/day based on the assumption that soil ingestion is 2% of food ingestion.
TF_d is the food to meat transfer factor (d/kg) from Table 2-6

The food to meat transfer factors for deer were obtained from the high end values listed for cattle from the different sources listed in Table 2-6.

The normalized ingestion dose (NDL_{int}) for the mountain lion from the ingestion of food and soil is derived as follows:

$$NDL_{int} = [(I_{ld} \times NBB_D) + I_{ls}] \times DCF_{int} \times .001 \text{ rem/mrem}$$

where:

NDL_{int} = normalized internal dose for lion (rem/day EDE per pCi/g in soil)
I_{ld} = ingestion rate of deer meat by lion (kg/day). Assumed to be 3.6 kg/day based on equations in Wildlife Exposure Factors Handbook (EPA 1993) and a body weight of 125 kg from Handbook of Biological Data (Spector 1956)
I_{ls}= ingestion rate of soil by lion (86 g/day based on 2.4% of diet from Wildlife Exposure Factors Handbook)
DCF_{int} = internal dose conversion factor for ingestion (mrem EDE/pCi ingested) from Federal Guidance Report No. 11 (EPA 1988)
.001 = rem/mrem

The $RESLL_{int}$ is then derived as follows:

$$RESLL_{int} = 0.1 \text{ rem per day} / ND_{int}$$

Table 2-6. Food to Meat Transfer Factors (day/kg)

Element	NCRP (1996)	EPA (1989)	NRC R.G. 1.109 (NRC 1977)	RESRAD	IAEA (1994)			Selected Value
					Expected Value	Min.	Max.	
H		0	1.2e-02	1.2e-02				1.2e-02
C		0	3.1e-02	3.1e-02				3.1e-02
Na	8.0e-02	5.5e-02	3.0e-02	8.0e-02	8.0E-02			8.0E-02
Mg	3.0e-03				2.0E-02			2.0E-02
P	5.0e-02	5.5e-02	4.6e-02	5.0e-02	5.0E-02	4.0E-02	6.0E-02	6.0E+02
Cl	4.0e-02			6.0e-02	2.0E-02			2.0E-02
K	2.0e-02	2.0e-02		2.0e-02	2.0E-02			2.0E-02
Ca	2.0e-03	7.0e-04		1.6e-03	2.0E-03	7.0E-04	3.0E-03	3.0E-03
Cr	3.0e-02	5.5e-03	2.4e-03	9.0e-03	9.0E-03			9.0E-03
Mn	1.0e-03	4.0e-04	8.0e-04	5.0e-04	5.0E-04	4.0E-04	7.0E-04	7.0E-04
Fe	3.0e-02	2.0e-02	4.0e-02	2.0e-02	2.0E-02	2.0E-03	5.0E-02	5.0E-02
Co	3.0e-02	2.0e-02	1.3e-02	2.0e-02		4.0E-05	7.0E-02	7.0E-02
Ni	5.0e-03	6.0e-03	5.3e-02	5.0e-03	5.0E-03			5.0E-03
Cu	1.0e-02	1.0e-02	8.0e-03	1.0e-02	9.0E-03	5.0E-03	1.0E-02	1.0E-02
Zn	1.0e-01	1.0e-01	3.0e-02	1.0e-01	1.0E-01	4.0E-02	2.0E-01	2.0E-01
Rb	3.0e-02	1.5e-02	3.1e-02	1.5e-02	1.0E-02			1.0E-02
Sr	1.0e-02	3.0e-04	6.0e-04	8.0e-03	8.0E-03	3.0E-04	8.0E-03	8.0E-03
Y	2.0e-03	3.0e-04	4.6e-03	2.0e-03	1.0E-03			1.0E-03
Zr	1.0e-06	5.5e-03	3.4e-02	1.0e-06	1.0E-06			1.0E-06
Nb	3.0e-07	2.5e-01	2.8e-01	3.0e-07	3.0E-07			3.0E-07
Mo	1.0e-03	6.0e-03	8.0e-03	1.0e-03	1.0E-03			1.0E-03
Tc-95m	1.0e-04	8.5e-03	4.0e-01	1.0e-04	1.0E-04			1.0E-04
Tc-99m	1.0e-04	8.5e-03	4.0e-01	1.0e-04	1.0E-06			1.0E-06
Ru	2.0e-03	2.0e-03	4.0e-01	2.0e-03	5.0E-02	1.0E-04	5.0E-02	5.0E-02
Ag	3.0e-03	3.0e-03	1.7e-02	3.0e-03	3.0E-03	2.0E-03	6.0E-03	6.0E-03
Cd	1.0e-03	5.5e-04		4.0e-04	4.0E-04			4.0E-04
Sb	1.0e-03	1.0e-03		1.0e-03	4.0E-05	4.0E-05	5.0E-03	5.0E-03
Te	7.0e-03	1.5e-02	7.7e-02	7.0e-03	7.0E-03			7.0E-03
I	4.0e-02	7.0e-03	2.0e-03	7.0e-03	4.0E-02	7.0E-03	5.0E-02	5.0E-02
Cs	5.0e-02	2.0e-02	4.0e-03	3.0e-02	5.0E-02	1.0E-02	6.0E-02	6.0E-02
Ba	2.0e-04	1.5e-04	3.2e-03	2.0e-04	2.0E-04			2.0E-04
Ce	2.0e-05	7.5e-04	1.2e-03	2.0e-05	2.0E-05			2.0E-05
Pm	2.0e-03	5.0e-03		2.0e-03				5.0e-03

Table 2-6. Food to Meat Transfer Factors (day/kg) (continued)

Element	NCRP (1996)	EPA (1989)	NRC R.G. 1.109 (NRC 1977)	RESRAD	IAEA (1994)			Selected Value
					Expected Value	Min.	Max.	
Sm	2.0e-03	5.0e-03		2.0e-03				5.0e-03
Eu	2.0e-03	5.0e-03		2.0e-03				5.0e-03
Gd	2.0e-03	3.5e-03		2.0e-03				3.5e-03
W	4.0e-02	4.5e-02	1.3e-03	4.0e-02	4.0E-02			4.0E-02
Tl	2.0e-02	4.0e-02		2.0e-03				4.0e-02
Pb	8.0e-04	3.0e-04		8.0e-04	4.0E-04	1.0E-04	7.0E-04	7.0E-04
Bi	2.0e-03	4.0e-04		2.0e-03				2.0e-03
Po	5.0e-03	3.0e-04		5.0e-03	5.0E-03	6.0E-04	5.0E-03	5.0E-03
Ra	1.0e-03	2.5e-04		1.0e-03	9.0E-04	5.0E-04	5.0E-03	5.0E-03
Ac	2.0e-05	2.5e-05		2.0e-05				2.5e-05
Th	1.0e-04	6.0e-06		1.0e-04				1.0e-04
Pa	5.0e-06	1.0e-05		5.0e-03				5.0e-03
U	8.0e-04	2.0e-04		3.4e-04	3.0E-04			3.0E-04
Np	1.0e-03	5.0e-07	2.0e-04	1.0e-03	1.0E-03			1.0E-03
Pu	1.0e-04	5.5e-05		1.0e-04	1.0E-05	2.0E-07	2.0E-04	2.0E-04
Am	5.0e-05	3.5e-06		5.0e-05	4.0E-05	4.0E-06	1.0E-04	1.0E-04
Cm	2.0e-05	3.5e-06		2.0e-05				2.0e-05

Federal Guidance Report No. 11 (EPA 1988)

Table 2-7. Normalized Doses (Rem/d per pCi/g)

Nuclide	Plants		Burrowing Animals				Deer			Mountain Lion		
	Ext	Int	Ext	Int (food)	Int (soil)	Inh	Ext	Int (food)	Int (soil)	Ext	Int (food)	Int (soil)
Ac-227	6.25E-03	2.09E-05	2.08E-05	4.44E-06	4.44E-05	7.53E-08	5.52E-06	7.40E-04	5.92E-03	5.52E-06	5.99E-07	1.27E-03
Ag-108m	8.62E-05	5.48E-07	8.34E-05	1.37E-07	2.29E-08	3.17E-12	2.64E-05	2.29E-05	3.05E-06	2.64E-05	5.60E-07	6.55E-07
Ag-110m	1.44E-04	6.50E-07	1.41E-04	1.94E-07	3.24E-08	8.99E-13	4.70E-05	3.24E-05	4.32E-06	4.70E-05	7.93E-07	9.29E-07
Am-241	1.05E-03	1.70E-04	1.45E-06	5.24E-05	1.09E-05	4.97E-09	1.20E-07	8.74E-03	1.46E-03	1.20E-07	3.67E-06	3.13E-04
Am-243	1.03E-03	1.64E-04	1.18E-05	5.23E-05	1.09E-05	4.93E-09	2.45E-06	8.71E-03	1.45E-03	2.45E-06	3.66E-06	3.12E-04
Bi-207	8.42E-05	5.67E-07	7.93E-05	6.58E-08	1.64E-08	2.24E-13	2.57E-05	1.10E-05	2.19E-06	2.57E-05	9.47E-08	4.71E-07
C-14	2.52E-06	1.40E-05	0.00E+00	1.38E-06	6.27E-09	2.34E-14	3.67E-11	2.30E-04	8.36E-07	3.67E-11	2.58E-05	1.80E-07
Cd-109	5.44E-06	2.07E-06	1.35E-06	7.86E-07	3.93E-08	1.28E-12	7.27E-08	1.31E-04	5.24E-06	7.27E-08	1.96E-07	1.13E-06
Ce-144	6.89E-05	1.34E-07	2.65E-06	5.06E-09	6.33E-08	4.19E-12	8.88E-07	8.44E-07	8.44E-06	8.88E-07	6.68E-10	1.81E-06
Cl-36	1.27E-05	2.56E-04	8.17E-11	0.00E+00	9.09E-09	2.45E-13	6.55E-09	1.21E-03	1.21E-06	6.55E-09	8.74E-05	2.61E-07
Cm-243	1.13E-03	1.66E-06	6.85E-06	3.31E-07	7.53E-06	3.44E-09	1.60E-06	5.52E-05	1.00E-03	1.60E-06	7.63E-08	2.16E-04
Cm-244	1.11E-03	1.64E-06	7.67E-08	2.67E-07	6.06E-06	2.78E-09	3.46E-10	4.44E-05	8.08E-04	3.46E-10	6.14E-08	1.74E-04
Cm-248	8.90E-04	1.32E-06	5.43E-08	1.80E-06	4.08E-05	1.85E-08	2.40E-10	2.99E-04	5.44E-03	2.40E-10	4.13E-07	1.17E-03
Co-57	7.31E-06	2.97E-07	6.44E-06	4.47E-08	3.54E-09	1.02E-13	1.37E-06	7.46E-06	4.72E-07	1.37E-06	2.00E-06	1.01E-07
Co-60	1.33E-04	1.56E-06	1.29E-04	1.02E-06	8.07E-08	2.45E-12	4.44E-05	1.70E-04	1.08E-05	4.44E-05	4.56E-05	2.31E-06
Cs-134	8.78E-05	3.05E-06	8.03E-05	3.21E-06	2.20E-07	5.17E-13	2.59E-05	5.35E-04	2.93E-05	2.59E-05	1.22E-04	6.30E-06
Cs-135	2.87E-06	1.06E-06	0.00E+00	3.10E-07	2.12E-08	5.10E-14	1.05E-10	5.16E-05	2.83E-06	1.05E-10	1.18E-05	6.08E-07
Cs-137	4.07E-05	4.35E-06	2.91E-05	2.19E-06	1.50E-07	3.57E-13	9.34E-06	3.65E-04	2.00E-05	9.34E-06	8.32E-05	4.30E-06
Eu-152	6.50E-05	1.60E-08	5.92E-05	1.94E-09	1.94E-08	2.48E-12	1.92E-05	3.24E-07	2.59E-06	1.92E-05	5.25E-08	5.57E-07
Eu-154	7.77E-05	3.52E-08	6.44E-05	2.87E-09	2.87E-08	3.20E-12	2.10E-05	4.78E-07	3.82E-06	2.10E-05	7.74E-08	8.21E-07
Eu-155	6.24E-06	7.96E-09	3.12E-06	4.59E-10	4.59E-09	4.64E-13	4.99E-07	7.65E-08	6.12E-07	4.99E-07	1.24E-08	1.32E-07
Fe-55	2.89E-07	2.06E-10	8.55E-08	7.28E-11	1.82E-09	3.01E-14	0.00E+00	1.21E-08	2.43E-07	0.00E+00	4.59E-08	5.22E-08
Gd-153	7.74E-06	5.39E-09	5.67E-06	3.51E-10	3.51E-09	2.67E-13	6.70E-07	5.85E-08	4.68E-07	6.70E-07	6.63E-09	1.01E-07
H-3	2.90E-07	1.41E-06	0.00E+00	3.69E-08	1.92E-10	7.17E-16	0.00E+00	6.14E-06	2.56E-08	0.00E+00	2.67E-07	5.50E-09
I-129	4.03E-06	5.59E-08	1.27E-06	6.62E-07	8.28E-07	1.95E-12	3.55E-08	1.10E-04	1.10E-04	3.55E-08	3.97E-05	2.37E-05
Mn-54	4.28E-05	4.54E-07	4.31E-05	7.68E-07	8.31E-09	7.50E-14	1.41E-05	1.28E-04	1.11E-06	1.41E-05	3.25E-07	2.38E-07
Na-22	1.22E-04	5.00E-07	1.13E-04	6.90E-08	3.45E-08	8.58E-14	3.74E-05	1.15E-05	4.60E-06	3.74E-05	4.64E-06	9.89E-07
Nb-94	8.76E-05	7.58E-08	8.09E-05	8.57E-09	2.14E-08	4.64E-12	2.64E-05	1.43E-06	2.86E-06	2.64E-05	4.63E-12	6.14E-07
Pa-231	1.03E-03	1.39E-05	1.92E-06	1.27E-05	3.18E-05	1.43E-08	5.21E-07	2.12E-03	4.24E-03	5.21E-07	1.14E-04	9.12E-04
Pb-210	1.04E-03	2.77E-05	2.58E-07	1.74E-05	2.18E-05	2.60E-10	1.67E-08	2.91E-03	2.91E-03	1.67E-08	1.47E-05	6.25E-04
Pm-147	3.16E-06	7.98E-09	1.78E-10	3.15E-10	3.15E-09	4.39E-13	1.37E-10	5.25E-08	4.20E-07	1.37E-10	8.51E-09	9.03E-08
Pu-238	1.05E-03	1.04E-04	8.24E-08	2.83E-05	9.60E-06	4.39E-09	4.15E-10	4.72E-03	1.28E-03	4.15E-10	4.32E-06	2.75E-04

Table 2-7. Normalized Doses (Rem/d per pCi/g) (continued)

Nuclide	Plants		Burrowing Animals				Deer			Mountain Lion		
	Ext	Int	Ext	Int (food)	Int (soil)	Inh	Ext	Int (food)	Int (soil)	Ext	Int (food)	Int (soil)
Pu-239	9.85E-04	9.79E-05	3.37E-08	3.14E-05	1.06E-05	4.80E-09	8.09E-10	5.23E-03	1.42E-03	8.09E-10	4.78E-06	3.04E-04
Pu-240	9.85E-04	9.79E-05	7.86E-08	3.14E-05	1.06E-05	4.80E-09	4.01E-10	5.23E-03	1.42E-03	4.01E-10	4.78E-06	3.04E-04
Pu-241	2.67E-07	1.99E-08	0.00E+00	6.06E-07	2.05E-07	9.24E-11	1.62E-11	1.01E-04	2.74E-05	1.62E-11	9.24E-08	5.88E-06
Pu-242	9.39E-04	9.33E-05	6.53E-08	2.98E-05	1.01E-05	4.60E-09	3.50E-10	4.96E-03	1.34E-03	3.50E-10	4.54E-06	2.89E-04
Pu-244	1.02E-03	9.18E-05	7.73E-05	2.94E-05	9.96E-06	4.51E-09	5.52E-06	4.90E-03	1.33E-03	5.52E-06	4.48E-06	2.86E-04
Ra-226	4.73E-03	2.49E-04	9.12E-05	6.38E-06	3.99E-06	9.63E-11	3.07E-05	1.06E-03	5.32E-04	3.07E-05	2.87E-05	1.14E-04
Ra-226-ser**	5.76E-03	3.05E-04	9.14E-05	4.13E-05	2.58E-05	3.56E-10	3.07E-05	6.88E-03	3.44E-03	3.07E-05	1.86E-04	7.40E-04
Ra-228	6.98E-05	9.08E-07	4.77E-05	6.91E-06	4.32E-06	5.69E-11	1.64E-05	1.15E-03	5.76E-04	1.64E-05	3.11E-05	1.24E-04
Ru-106	8.30E-05	2.19E-06	1.07E-05	0.00E+00	8.22E-08	5.34E-12	3.53E-06	1.64E-05	1.10E-05	3.53E-06	4.93E-06	2.36E-06
Sb-125	3.52E-05	1.15E-07	2.41E-05	4.38E-09	1.10E-08	1.56E-13	6.72E-06	7.30E-07	1.46E-06	6.72E-06	3.94E-08	3.14E-07
Sm-147	4.30E-04	1.45E-06	0.00E+00	5.55E-08	5.55E-07	8.37E-10	0.00E+00	9.25E-06	7.40E-05	0.00E+00	1.50E-06	1.59E-05
Sm-151	1.01E-06	2.55E-09	6.49E-10	1.17E-10	1.17E-09	3.36E-13	2.69E-12	1.95E-08	1.56E-07	2.69E-12	3.15E-09	3.35E-08
Sr-90	5.76E-05	5.74E-05	0.00E+00	1.81E-05	4.59E-07	1.47E-11	6.74E-08	3.02E-03	6.12E-05	6.74E-08	8.87E-05	1.32E-05
Tc-99	4.31E-06	4.84E-04	2.67E-11	1.94E-05	4.38E-09	9.32E-14	3.43E-10	3.24E-03	5.84E-07	3.43E-10	1.17E-08	1.26E-07
Th-228	6.23E-03	1.04E-04	8.03E-05	1.22E-06	2.42E-06	3.86E-09	2.78E-05	2.04E-04	3.23E-04	2.78E-05	1.90E-07	6.95E-05
Th-229	6.26E-03	1.06E-04	1.76E-05	6.09E-06	1.21E-05	2.42E-08	4.37E-06	1.02E-03	1.61E-03	4.37E-06	9.46E-07	3.47E-04
Th-230	8.96E-04	1.52E-05	5.15E-08	8.29E-07	1.64E-06	3.65E-09	3.31E-09	1.38E-04	2.19E-04	3.31E-09	1.29E-07	4.71E-05
Th-232	7.66E-04	1.30E-05	5.15E-08	4.13E-06	8.19E-06	1.84E-08	1.43E-09	6.88E-04	1.09E-03	1.43E-09	6.41E-07	2.35E-04
Th-232-ser**	7.06E-03	1.17E-04	1.28E-04	4.17E-06	8.28E-06	1.84E-08	3.53E-06	6.96E-04	1.10E-03	3.53E-06	6.48E-07	2.37E-04
Tl-204	1.22E-05	2.45E-06	5.85E-08	8.06E-08	1.01E-08	2.70E-14	1.11E-08	1.34E-05	1.34E-06	1.11E-08	2.13E-06	2.89E-07
U-232	1.02E-03	2.74E-05	9.18E-08	3.14E-06	3.93E-06	7.38E-09	2.47E-09	5.24E-04	5.24E-04	2.47E-09	1.13E-06	1.13E-04
U-233	9.20E-04	2.48E-05	3.70E-08	6.94E-07	8.67E-07	1.51E-09	3.82E-09	1.16E-04	1.16E-04	3.82E-09	2.50E-07	2.49E-05
U-234	9.11E-04	2.45E-05	5.15E-08	6.79E-07	8.49E-07	1.48E-09	1.10E-09	1.13E-04	1.13E-04	1.10E-09	2.45E-07	2.43E-05
U-235	8.57E-04	2.28E-05	9.06E-06	6.41E-07	8.01E-07	1.38E-09	2.07E-06	1.07E-04	1.07E-04	2.07E-06	2.31E-07	2.30E-05
U-236	8.59E-04	2.31E-05	7.07E-08	6.46E-07	8.07E-07	1.40E-09	5.88E-10	1.08E-04	1.08E-04	5.88E-10	2.32E-07	2.31E-05
U-238	8.48E-04	2.25E-05	1.28E-06	6.43E-07	8.04E-07	1.32E-09	3.62E-07	1.07E-04	1.07E-04	3.62E-07	2.32E-07	2.30E-05
U-sep**	1.80E-03	4.81E-05	1.76E-06	1.35E-06	1.69E-06	2.87E-09	4.61E-07	2.26E-04	2.26E-04	4.61E-07	4.87E-07	4.85E-05
U-series**	8.80E-03	2.34E-04	9.42E-05	8.74E-06	1.09E-05	1.08E-08	3.14E-05	1.46E-03	1.46E-03	3.14E-05	3.14E-06	3.13E-04
Zn-65	3.01E-05	1.36E-07	3.01E-05	6.91E-07	4.32E-08	2.28E-13	1.01E-05	1.15E-04	5.76E-06	1.01E-05	8.71E-05	1.24E-06

Table 2-8. RESLs (p/Ci soil dry wt.)

Nuclide	Plants			Burrowing Animals					Deer				Mountain Lion				
	Ext	Int	Combo	Ext	Int (food)	Int (soil)	Inh	Combo	Ext	Int (food)	Int (soil)	Combo	Ext	Int (food)	Int (soil)	Combo	Limiting
Ac-227	1.60E+01	4.78E+03	1.60E+01	4.82E+03	2.25E+04	2.25E+03	1.33E+06	1.44E+03	1.81E+04	1.35E+02	1.69E+01	1.50E+01	1.81E+04	1.67E+05	7.86E+01	7.82E+01	1.50E+01
Ag-108m	1.16E+03	1.82E+05	1.16E+03	1.20E+03	7.29E+05	4.37E+06	3.15E+10	1.20E+03	3.79E+03	4.37E+03	3.28E+04	1.91E+03	3.79E+03	1.79E+05	1.53E+05	3.62E+03	1.16E+03
Ag-110m	6.97E+02	1.54E+05	6.97E+02	7.11E+02	5.14E+05	3.09E+06	1.11E+11	7.10E+02	2.13E+03	3.09E+03	2.31E+04	1.19E+03	2.13E+03	1.26E+05	1.08E+05	2.05E+03	6.97E+02
Am-241	9.51E+01	5.90E+02	9.51E+01	6.91E+04	1.91E+03	9.16E+03	2.01E+07	1.54E+03	8.35E+05	1.14E+01	6.87E+01	9.81E+00	8.35E+05	2.73E+04	3.19E+02	3.16E+02	9.81E+00
Am-243	9.70E+01	6.09E+02	9.70E+01	8.44E+03	1.91E+03	9.18E+03	2.03E+07	1.33E+03	4.08E+04	1.15E+01	6.89E+01	9.84E+00	4.08E+04	2.73E+04	3.20E+02	3.14E+02	9.84E+00
Bi-207	1.19E+03	1.77E+05	1.19E+03	1.26E+03	1.52E+06	6.08E+06	4.46E+11	1.26E+03	3.89E+03	9.12E+03	4.56E+04	2.58E+03	3.89E+03	1.06E+06	2.12E+05	3.81E+03	1.19E+03
C-14	3.96E+04	7.14E+03	3.96E+04		7.25E+04	1.59E+07	4.27E+12	7.22E+04	2.72E+09	4.35E+02	1.20E+05	4.33E+02	2.72E+09	3.88E+03	5.56E+05	3.86E+03	4.33E+02
Cd-109	1.84E+04	4.83E+04	1.84E+04	7.42E+04	1.27E+05	2.54E+06	7.83E+10	4.60E+04	1.38E+06	7.63E+02	1.91E+04	7.34E+02	1.38E+06	5.10E+05	8.88E+04	7.17E+04	7.34E+02
Ce-144	1.45E+03	7.47E+05	1.45E+03	3.78E+04	1.97E+07	1.58E+06	2.39E+10	3.69E+04	1.13E+05	1.18E+05	1.18E+04	9.83E+03	1.13E+05	1.50E+08	5.51E+04	3.70E+04	1.45E+03
Cl-36	7.87E+03	3.90E+02	7.87E+03	1.22E+09		1.10E+07	4.08E+11	1.09E+07	1.53E+07	8.25E+01	8.25E+04	8.24E+01	1.53E+07	1.14E+03	3.84E+05	1.14E+03	8.24E+01
Cm-243	8.86E+01	6.03E+04	8.86E+01	1.46E+04	3.02E+05	1.33E+04	2.91E+07	6.80E+03	6.27E+04	1.81E+03	9.96E+01	9.43E+01	6.27E+04	1.31E+06	4.63E+02	4.60E+02	8.86E+01
Cm-244	9.01E+01	6.09E+04	9.01E+01	1.30E+06	3.75E+05	1.65E+04	3.60E+07	1.56E+04	2.89E+08	2.25E+03	1.24E+02	1.17E+02	2.89E+08	1.63E+06	5.76E+02	5.75E+02	9.01E+01
Cm-248	1.12E+02	7.59E+04	1.12E+02	1.84E+06	5.57E+04	2.45E+03	5.41E+06	2.34E+03	4.17E+08	3.34E+02	1.84E+01	1.74E+01	4.17E+08	2.42E+05	8.55E+01	8.55E+01	1.74E+01
Co-57	1.37E+04	3.36E+05	1.37E+04	1.55E+04	2.23E+06	2.82E+07	9.84E+11	1.54E+04	7.30E+04	1.34E+04	2.12E+05	1.08E+04	7.30E+04	5.00E+04	9.85E+05	2.88E+04	1.08E+04
Co-60	7.52E+02	6.41E+04	7.52E+02	7.74E+02	9.80E+04	1.24E+06	4.08E+10	7.67E+02	2.25E+03	5.88E+02	9.29E+03	4.44E+02	2.25E+03	2.20E+03	4.32E+04	1.08E+03	4.44E+02
Cs-134	1.14E+03	3.28E+04	1.14E+03	1.24E+03	3.11E+04	4.55E+05	1.93E+11	1.19E+03	3.86E+03	1.87E+02	3.41E+03	1.69E+02	3.86E+03	8.20E+02	1.59E+04	6.49E+02	1.69E+02
Cs-135	3.48E+04	9.45E+04	3.48E+04		3.23E+05	4.71E+06	1.96E+12	3.02E+05	9.53E+08	1.94E+03	3.54E+04	1.84E+03	9.53E+08	8.50E+03	1.64E+05	8.09E+03	1.84E+03
Cs-137	2.46E+03	2.30E+04	2.46E+03	3.43E+03	4.57E+04	6.67E+05	2.80E+11	3.18E+03	1.07E+04	2.74E+02	5.00E+03	2.54E+02	1.07E+04	1.20E+03	2.33E+04	1.03E+03	2.54E+02
Eu-152	1.54E+03	6.27E+06	1.54E+03	1.69E+03	5.14E+07	5.14E+06	4.04E+10	1.69E+03	5.21E+03	3.09E+05	3.86E+04	4.53E+03	5.21E+03	1.91E+06	1.79E+05	5.05E+03	1.54E+03
Eu-154	1.29E+03	2.84E+06	1.29E+03	1.55E+03	3.49E+07	3.49E+06	3.12E+10	1.55E+03	4.76E+03	2.09E+05	2.62E+04	3.95E+03	4.76E+03	1.29E+06	1.22E+05	4.56E+03	1.29E+03
Eu-155	1.60E+04	1.26E+07	1.60E+04	3.21E+04	2.18E+08	2.18E+07	2.16E+11	3.20E+04	2.00E+05	1.31E+06	1.63E+05	8.42E+04	2.00E+05	8.07E+06	7.60E+05	1.55E+05	1.60E+04
Fe-55	3.46E+05	4.85E+08	3.46E+05	1.17E+06	1.37E+09	5.49E+07	3.32E+12	1.14E+06		8.24E+06	4.12E+05	3.92E+05		2.18E+06	1.92E+06	1.02E+06	3.46E+05
Gd-153	1.29E+04	1.86E+07	1.29E+04	1.77E+04	2.85E+08	2.85E+07	3.75E+11	1.76E+04	1.49E+05	1.71E+06	2.14E+05	8.36E+04	1.49E+05	1.51E+07	9.94E+05	1.29E+05	1.29E+04
H-3	3.45E+05	7.12E+04	3.45E+05		2.71E+06	5.21E+08	1.40E+14	2.70E+06		1.63E+04	3.91E+06	1.62E+04		3.75E+05	1.82E+07	3.68E+05	1.62E+04
I-129	2.48E+04	1.79E+06	2.48E+04	7.88E+04	1.51E+05	1.21E+05	5.13E+10	3.62E+04	2.82E+06	9.06E+02	9.06E+02	4.53E+02	2.82E+06	2.52E+03	4.21E+03	1.57E+03	4.53E+02
Mn-54	2.33E+03	2.20E+05	2.33E+03	2.32E+03	1.30E+05	1.20E+07	1.33E+12	2.28E+03	7.09E+03	7.81E+02	9.03E+04	6.98E+02	7.09E+03	3.07E+05	4.20E+05	6.81E+03	6.98E+02
Na-22	8.22E+02	2.00E+05	8.22E+02	8.87E+02	1.45E+06	2.90E+06	1.17E+12	8.86E+02	2.67E+03	8.70E+03	2.17E+04	1.87E+03	2.67E+03	2.16E+04	1.01E+05	2.32E+03	8.22E+02
Nb-94	1.14E+03	1.32E+06	1.14E+03	1.24E+03	1.17E+07	4.67E+06	2.16E+10	1.24E+03	3.79E+03	7.00E+04	3.50E+04	3.26E+03	3.79E+03	2.16E+10	1.63E+05	3.70E+03	1.14E+03
Pa-231	9.68E+01	7.21E+03	9.68E+01	5.22E+04	7.86E+03	3.14E+03	6.98E+06	2.15E+03	1.92E+05	4.72E+01	2.36E+01	1.57E+01	1.92E+05	8.74E+02	1.10E+02	9.74E+01	1.57E+01
Pb-210	9.66E+01	3.61E+03	9.66E+01	3.88E+05	5.73E+03	4.59E+03	3.85E+08	2.53E+03	5.99E+06	3.44E+01	3.44E+01	1.72E+01	5.99E+06	6.82E+03	1.60E+02	1.56E+02	1.72E+01
Pm-147	3.16E+04	1.25E+07	3.16E+04	5.62E+08	3.17E+08	3.17E+07	2.28E+11	2.74E+07	7.30E+08	1.90E+06	2.38E+05	2.12E+05	7.30E+08	1.18E+07	1.11E+06	1.01E+06	3.16E+04

Table 2-8. RESLs (p/Ci soil dry wt.) (continued)

Nuclide	Plants			Burrowing Animals					Deer				Mountain Lion				
	Ext	Int	Combo	Ext	Int (food)	Int (soil)	Inh	Combo	Ext	Int (food)	Int (soil)	Combo	Ext	Int (food)	Int (soil)	Combo	Limiting
Pu-238	9.52E+01	9.58E+02	9.52E+01	1.21E+06	3.53E+03	1.04E+04	2.28E+07	2.63E+03	2.41E+08	2.12E+01	7.81E+01	1.67E+01	2.41E+08	2.31E+04	3.63E+02	3.58E+02	1.67E+01
Pu-239	1.02E+02	1.02E+03	1.02E+02	2.97E+06	3.19E+03	9.42E+03	2.08E+07	2.38E+03	1.24E+08	1.91E+01	7.06E+01	1.51E+01	1.24E+08	2.09E+04	3.28E+02	3.23E+02	1.51E+01
Pu-240	1.01E+02	1.02E+03	1.01E+02	1.27E+06	3.19E+03	9.42E+03	2.08E+07	2.38E+03	2.50E+08	1.91E+01	7.06E+01	1.51E+01	2.50E+08	2.09E+04	3.28E+02	3.23E+02	1.51E+01
Pu-241	3.75E+05	5.03E+06	3.75E+05		1.65E+05	4.87E+05	1.08E+09	1.23E+05	6.19E+09	9.91E+02	3.65E+03	7.79E+02	6.19E+09	1.08E+06	1.70E+04	1.67E+04	7.79E+02
Pu-242	1.06E+02	1.07E+03	1.06E+02	1.53E+06	3.36E+03	9.92E+03	2.17E+07	2.51E+03	2.85E+08	2.02E+01	7.44E+01	1.59E+01	2.85E+08	2.20E+04	3.46E+02	3.41E+02	1.59E+01
Pu-244	9.84E+01	1.09E+03	9.84E+01	1.29E+03	3.40E+03	1.00E+04	2.22E+07	8.58E+02	1.81E+04	2.04E+01	7.53E+01	1.60E+01	1.81E+04	2.23E+04	3.50E+02	3.38E+02	1.60E+01
Ra-226	2.12E+01	4.01E+02	2.12E+01	1.10E+03	1.57E+04	2.51E+04	1.04E+09	9.85E+02	3.26E+03	9.40E+01	1.88E+02	6.15E+01	3.26E+03	3.48E+03	8.74E+02	5.75E+02	2.12E+01
Ra-226-ser**	1.74E+01	3.28E+02	1.74E+01	1.09E+03	2.42E+03	3.88E+03	2.81E+08	6.31E+02	3.26E+03	1.45E+01	2.91E+01	9.66E+00	3.26E+03	5.38E+02	1.35E+02	1.05E+02	9.66E+00
Ra-228	1.43E+03	1.10E+05	1.43E+03	2.09E+03	1.45E+04	2.31E+04	1.76E+09	1.70E+03	6.11E+03	8.68E+01	1.74E+02	5.73E+01	6.11E+03	3.22E+03	8.07E+02	5.84E+02	5.73E+01
Ru-106	1.21E+03	4.56E+04	1.21E+03	9.38E+03		1.22E+06	1.87E+10	9.31E+03	2.83E+04	6.08E+03	9.12E+03	3.23E+03	2.83E+04	2.03E+04	4.24E+04	9.25E+03	1.21E+03
Sb-125	2.84E+03	8.73E+05	2.84E+03	4.15E+03	2.28E+07	9.13E+06	6.42E+11	4.15E+03	1.49E+04	1.37E+05	6.85E+04	1.12E+04	1.49E+04	2.54E+06	3.19E+05	1.41E+04	2.84E+03
Sm-147	2.32E+02	6.90E+04	2.32E+02		1.80E+06	1.80E+05	1.20E+08	1.64E+05		1.08E+04	1.35E+03	1.20E+03		6.67E+04	6.29E+03	5.74E+03	2.32E+02
Sm-151	9.91E+04	3.93E+07	9.91E+04	1.54E+08	8.57E+08	8.57E+07	2.98E+11	5.17E+07	3.72E+10	5.14E+06	6.43E+05	5.71E+05	3.72E+10	3.17E+07	2.99E+06	2.73E+06	9.91E+04
Sr-90	1.74E+03	1.74E+03	1.74E+03		5.52E+03	2.18E+05	6.82E+09	5.38E+03	1.48E+06	3.31E+01	1.63E+03	3.25E+01	1.48E+06	1.13E+03	7.60E+03	9.81E+02	3.25E+01
Tc-99	2.32E+04	2.07E+02	2.32E+04	3.75E+09	5.14E+03	2.28E+07	1.07E+12	5.14E+03	2.91E+08	3.09E+01	1.71E+05	3.08E+01	2.91E+08	8.57E+06	7.96E+05	7.27E+05	3.08E+01
Th-228	1.61E+01	9.61E+02	1.61E+01	1.24E+03	8.19E+04	4.13E+04	2.59E+07	1.19E+03	3.59E+03	4.91E+02	3.09E+02	1.80E+02	3.59E+03	5.27E+05	1.44E+03	1.03E+03	1.61E+01
Th-229	1.60E+01	9.46E+02	1.60E+01	5.69E+03	1.64E+04	8.27E+03	4.13E+06	2.80E+03	2.29E+04	9.85E+01	6.20E+01	3.80E+01	2.29E+04	1.06E+05	2.89E+02	2.84E+02	1.60E+01
Th-230	1.12E+02	6.58E+03	1.12E+02	1.94E+06	1.21E+05	6.08E+04	2.74E+07	3.96E+04	3.02E+07	7.24E+02	4.56E+02	2.80E+02	3.02E+07	7.77E+05	2.12E+03	2.12E+03	1.12E+02
Th-232	1.31E+02	7.70E+03	1.31E+02	1.94E+06	2.42E+04	1.22E+04	5.44E+06	8.07E+03	7.00E+07	1.45E+02	9.16E+01	5.62E+01	7.00E+07	1.56E+05	4.26E+02	4.25E+02	5.62E+01
Th-232-ser**	1.42E+01	8.52E+02	1.42E+01	7.80E+02	2.40E+04	1.21E+04	5.44E+06	7.11E+02	2.83E+04	1.44E+02	9.06E+01	5.55E+01	2.83E+04	1.54E+05	4.21E+02	4.14E+02	1.42E+01
Tl-204	8.20E+03	4.08E+04	8.20E+03	1.71E+06	1.24E+06	9.92E+06	3.70E+12	6.70E+05	9.02E+06	7.44E+03	7.44E+04	6.76E+03	9.02E+06	4.70E+04	3.46E+05	4.12E+04	6.76E+03
U-232	9.84E+01	3.65E+03	9.84E+01	1.09E+06	3.18E+04	2.54E+04	1.35E+07	1.39E+04	4.05E+07	1.91E+02	1.91E+02	9.54E+01	4.05E+07	8.84E+04	8.88E+02	8.79E+02	9.54E+01
U-233	1.09E+02	4.04E+03	1.09E+02	2.70E+06	1.44E+05	1.15E+05	6.61E+07	6.25E+04	2.62E+07	8.65E+02	8.65E+02	4.33E+02	2.62E+07	4.00E+05	4.02E+03	3.98E+03	1.09E+02
U-234	1.10E+02	4.08E+03	1.10E+02	1.94E+06	1.47E+05	1.18E+05	6.76E+07	6.32E+04	9.10E+07	8.83E+02	8.83E+02	4.42E+02	9.10E+07	4.09E+05	4.11E+03	4.07E+03	1.10E+02
U-235	1.17E+02	4.39E+03	1.17E+02	1.10E+04	1.56E+05	1.25E+05	7.26E+07	9.52E+03	4.82E+04	9.36E+02	9.36E+02	4.64E+02	4.82E+04	4.33E+05	4.36E+03	3.96E+03	1.17E+02
U-236	1.16E+02	4.32E+03	1.16E+02	1.41E+06	1.55E+05	1.24E+05	7.14E+07	6.56E+04	1.70E+08	9.29E+02	9.29E+02	4.65E+02	1.70E+08	4.30E+05	4.32E+03	4.28E+03	1.16E+02
U-238	1.18E+02	4.45E+03	1.18E+02	7.83E+04	1.55E+05	1.24E+05	7.57E+07	3.67E+04	2.76E+05	9.33E+02	9.33E+02	4.66E+02	2.76E+05	4.32E+05	4.34E+03	4.23E+03	1.18E+02
U-sep**	5.56E+01	2.08E+03	5.56E+01	5.69E+04	7.39E+04	5.91E+04	3.49E+07	2.08E+04	2.17E+05	4.43E+02	4.43E+02	2.21E+02	2.17E+05	2.05E+05	2.06E+03	2.02E+03	5.56E+01
U-series**	1.14E+01	4.28E+02	1.14E+01	1.06E+03	1.14E+04	9.16E+03	9.24E+06	8.78E+02	3.18E+03	6.87E+01	6.87E+01	3.40E+01	3.18E+03	3.18E+04	3.19E+02	2.88E+02	1.14E+01
Zn-65	3.32E+03	7.37E+05	3.32E+03	3.32E+03	1.45E+05	2.31E+06	4.38E+11	3.25E+03	9.87E+03	8.68E+02	1.74E+04	7.63E+02	9.87E+03	1.15E+03	8.07E+04	1.02E+03	7.63E+02

2.5 Site-Specific RESLs

The generic RESLs presented in Table 2-8 were derived using simple models and generic environmental constants. The result is a set of RESLs that may be overly conservative for some sites. Should a more site-specific analysis be required, the analyst may elect to employ the same equations described above, but take into consideration the types of organisms that may be at risk, use site specific environmental constants, or employ kinetic models that take into consideration the time varying nature of the contamination.

The generic RESLs presume that the exposed organisms include vascular plants, burrowing animals, and large mammals. If these organisms are not present at the site, the NOREL of 0.1 rad/day may be overly conservative. For example, a NOREL of 0.1 rad/day applies to higher plants and large mammals. If such organisms are not present at a site, a different, less restrictive NOREL may be appropriate. Appendix A can be used to select site-specific NORELs.

The generic values for the environmental parameters used in the RESL equations can also be replaced by site-specific parameter values, if the data are available. Examples of specific parameters for each trophic level are presented below.

For plants, the average radionuclide concentration in soil down to the depth of the root zone can be taken into consideration. For example, if the contaminated soil is limited to the top few centimeters of soil, but the root zone extends down to 15 cm, compliance with the RESLs should be assessed with respect to the average radionuclide concentration in the root zone. Similar consideration can also be given to external exposure of burrowing animals.

For external exposure to the above ground portion of plants and to animals, consideration can be given to the actual radiation field created by the soil contamination. The RESLs were derived based on the assumption that the contaminated zone is an effective infinite slab. If the extent of the contamination is limited to only a few centimeters of depth and an aerial extent of less than 1000 square meters, the radiation field caused by the contamination will be substantially smaller than that assumed in the RESL models. As such, site-specific values of the radiation field should be used to assess compliance with the 0.1 rad/day NOREL. The best approach would be to measure the actual radiation field in micro R per hour and convert this exposure rate to dose rate based on the relationship that 1 R equals 0.7 rem.

The RESLs due to internal exposures for all trophic levels are based on generic, high-end environmental transfer factors. If site-specific information is available on the actual concentrations of radionuclides in plants and animals, compliance with the 0.1 rad/day RESL can be determined directly, as opposed to using the RESL models. The example derivations of the RESLs provided in the following section can be used to derive site-specific RESLs using site-specific data.

2.6 Examples of RESL Derivations

The following presents examples of how the normalized doses and RESL values were derived for specific radionuclides.

External RESL for plants from ^{137}Cs

Assuming the ^{137}Cs concentration in the soil is 1 pCi/g, it can also be assumed that all of the energy of disintegration (E_T = 0.796 MeV/dis) emitted by ^{137}Cs in a gram of soil is absorbed by the gram of soil. Therefore, the external dose to the roots (D_{ext}) is derived as follows:

D_{ext} (rem/day) = 1 pCi/g x 0.796 MeV/dis x 0.037 dis/sec-pCi x 1.6E-6 erg/MeV x 0.01 rad-g/erg x 3600 sec/hr x 24 hr/day

where:

D_{ext} is the external dose to plant roots from Cs-137 in soil (rad/day)
Ds = 4.07E-05 rem/day per pCi/g of ^{137}Cs in soil

Because the dimensions of the root hairs are small compared to the range of all the radionuclide emissions, it can be assumed that the plant root tips and root hairs receive the same external dose. Hence, the RESL is derived as follows:

$RESL_{ext}$ = 0.1 rem/day ÷ 4.07E-05 rad/day per pCi/g
$RESL_{ext}$ = 2456 pCi/g

Internal RESL for Plants from ^{239}Pu

Assuming the ^{239}Pu concentration in soil is 1 pCi/g, and using a soil-to-plant transfer factor (RF) of 0.0738, the ^{239}Pu concentration in the plant is .0783 pCi/g. Because of the small dimensions of the plant, it is assumed that only the alpha and beta energy will be absorbed within the plant (Eα and Eβ). In addition, an RBE of 5 for the alpha is assumed. Therefore, the internal dose to the plant per pCi/g of ^{239}Pu in soil is derived as follows:

D_{int}(rem/d) = 1 pCi/g x .0738 x .037 dis/sec-pCi x [(5.15 MeV x 5) + (4.88E-03 MeV/dis)] x 1.6E-06 erg/MeV x .01 rad-g/erg x 3600 sec/hr x 24 hr

D_{int}(rad/d) = 9.7E-05
$RESL_{int}$ = 0.1/9.7E-05 = 1.03E3 pCi/g

External RESL for Burrowing Animals from ^{137}Cs

Assuming the ^{137}Cs concentration in the soil is 1 pCi/g, it can also be assumed that all of the gamma energy of disintegration (E_γ = 0.566 MeV/dis) emitted by ^{137}Cs in a gram of soil is absorbed by the gram of soil. Therefore:

Ds (rad/day) = 1 pCi/g x 0.566 MeV/dis x 0.037 dis/sec-pCi x 1.6E-6 erg/MeV x 0.01 rad-g/erg x 3600 sec/hr x 24 hr/day

Ds = 2.9E-05 rad/day per pCi/g of ^{137}Cs in soil

Because the dimensions of the burrow are small compared to the range of the gamma ray, it can be assumed that the burrow-dwelling animal receives the same external dose. Hence, the RESL is derived as follows:

$RESL_{ext}$= 0.1 rad/day ÷ 2.9E-05 rad/day per pCi/g
$RESL_{ext}$= 3.5E3 pCi/g

External RESL for Deer from ^{137}Cs

The external dose to deer from standing on contaminated soil is not unlike the exposure of man. The external dose conversion factors from Federal Guidance Report No. 12 for an infinite slab were used, assuming all progeny with half-lives less than 6 months are in equilibrium . On this basis, the external dose to deer per pCi/g of ^{137}Cs in soil is derived as follows:

$$D_{ext}\ (\text{rad/day}) = 1\ \text{pCi/g} \times 3.89\text{E-04 mrem/hr per pCi/g} \times 24\ \text{hr/day} \times 1\text{E-3 rad/mrem}$$

$$D_{ext}\ (\text{rad/day}) = 9.3\text{E-6 rad/day}$$

$$RESL_{ext} = 0.1\ \text{rad/d} \div 9.3\text{E-6 rad/day per pCi/g}$$

$$RESL_{ext} = 1.1\text{E4 pCi/g}$$

Internal Dose for Deer from ^{239}Pu

Assuming the soil contains 1 pCi/g of ^{239}Pu, the grass growing in the soil is assumed to contain .0738 pCi/g. This is based on the empirically determined, upper end soil-to-plant transfer factor of .0738 pCi/g of vegetation (fresh wt) per pCi/g of soil (dry wt). It is also assumed that a large deer ingests 20 kg per day of fresh grass (derived from the Wildlife Exposures Factors Handbook, EPA 1993), and, along with the grass, the deer ingests 400 g/day of soil. This is based on the assumption that soil ingestion is 2% of the grass ingested, based on information in the EPA 1993. The effective dose equivalent is then derived using the internal dose conversion factor for humans in Federal Guidance Report No. 11 (EPA 1988).

For vegetation:

$$D_{int} = 1\ \text{pCi/g} \times .0738 \times 20{,}000\ \text{g/day} \times 3.54\text{e-03 mrem/pCi} \times .001\ \text{rem/mrem}$$
$$= 5.2\text{e-03 rem/day}$$

For soil:

$$D_{int} = 1\ \text{pCi/g} \times 400\ \text{g/day} \times 3.54\text{e-03 mrem/pCi} \times .001\ \text{rem/mrem} =$$
$$= 1.4\text{e-03 rem/day}$$

RESL for External Exposure of a Mountain Lion to ^{137}Cs

The external RESLs for mountain lions are assumed to be the same as those for deer.

Internal Dose to a Mountain Lion from ^{137}Cs in Soil

Assuming that the internal exposure to a mountain lion is entirely due to the radionuclides it ingests from a diet which consists entirely of deer meat, plus some soil, the internal dose to the lion is determined as follows.

First, the body burden for deer (BB_D) is derived based on an upper end soil to grass transfer factor of 0.365 pCi/kg fresh grass per pCi/kg of soil and 20,000 g of grass ingested per day. In addition, we assume that the deer also ingests 400 g/day of soil along with the grass. This intake is converted to the radionuclide concentration in deer meat using an upper end feed-to-meat transfer factor of 0.06 pCi/kg meat per pCi per day ingested:

$$BB_D \text{ (pCi/kg)} = [(1 \text{ pCi/g x .365 pCi/kg veg per pCi/kg soil x 20,000 g/d}) + 1 \text{ pCi/g x 400 g/day})] \text{ x .06 pCi/kg deer per pCi/d ingested}$$

$$BB_D = 462 \text{ pCi/kg deer meat per pCi/g in soil}$$

Then, the effective dose equivalent to the lion is derived based on the Cs-137 intake by the mountain lion from food and soil ingestion. Soil ingestion is assumed to be 2.4% of its diet based on information provided in EPA 1993:

$$D_{int} = [(462 \text{ pCi/kg x 3.6 kg/day}) + (1 \text{ pCi/g x 86 g/day})] \text{ x 5E-05 mrem/pCi x .001 rem/mrem} = 8.7\text{e-05 rem/day}$$

3.0 AQUATIC ORGANISMS

This section addresses RESLs for aquatic organisms (fresh water). The section is divided into three parts following this introduction. The first part presents the LORELs and NORELs for aquatic organisms. We have elected to adopt a NOREL of 0.1 rad/day. The second part presents mathematical models for deriving radiation doses to aquatic organisms and the third part presents recommended RESLs.

3.1 Estimates of LORELs and NORELs

The biological effects of both acute and chronic exposure on aquatic organisms have been documented in numerous scientific journals, reports, and reviews. Adverse biological end-points in these studies include mortality, histopathological changes, and effects on reproduction, development, and genetic material. An overview of these reports and data is provided in Appendix D of this document and will only be summarized below for the purpose of identifying LORELs and NORELs.

For human population groups, exposure limits and regulatory standards are uniquely based on acceptable doses to individuals. These dose limits are based on probabilistic health risks that primarily address the concern for cancer induction of the exposed individual(s). In contrast, for endemic aquatic organisms, it is not the individual but the collective response of the population that is of concern; in particular, it is the capacity of the population to maintain itself through adequate reproduction and competition in the presence of stress imposed by chronic radiation exposure.

Thus, effects on the individual aquatic organism may be considered acceptable if there are no consequences at the population level. Correspondingly, the primary concern for the protection of aquatic life is the maintenance of indigenous populations and the effect of radiation on reproductive success. Reduced reproductive success may result from premature mortality and effects on reproductive tissues from adverse alterations during development and from dominant and recessive lethal mutations resulting from damage to the genetic material of germ cells.

This section provides a limited review of the literature on the sensitivity of aquatic organisms with the objective of quantifying LORELs ("lowest observed radiation effect levels") and NORELs ("no observed radiation effect levels").

Mortality and Histopathology. Research on the histopathological effects of radiation exposure in aquatic organisms shows that the basic mechanism(s) of radiation-induced mortality are similar to those observed in mammals. Cellular and tissue manifestations of lethal doses/dose-rates are those affecting the hemopoietic system, gastrointestinal tract, and immune system.

The effects of chronic radiation on mortality of fishes and higher invertebrates have been examined in a few studies. Donaldson and Bonham (1964) reported no significant difference in mortality between the salmon *Oncorhynchus tschawytscha* embryos irradiated at about 0.5 rad d^{-1} for approximately 20 days (total dose about 10 rads) and the control salmon embryos; observations were conducted up to the time of release of the smolts. Erickson (1973) also reported no increase in mortality of the guppy *Poecilia reticulata* exposed to 0.05 to 1 mCi/mL of tritium (total doses of 340 to 4,700 rads). Adults of the blue crab *Callinectes sapidus* subjected to chronic gamma irradiation required dose rates greater than about 29.9 rads h^{-1} for 70 days to cause death (Engel 1967), and juveniles of the clam *Mercenaria mercenaria* exposed to about 0.14 to 888 rads per day for 14 months exhibited decreases in survival and growth only at the highest dose rates between 384 to 888 rads per day (Baptist, et al. 1976).

In summary, effects on mortality of fish and invertebrates from chronic radiation exposures have not been reported at dose rates of less than 10 rads per day in carefully designed experiments conducted under controlled conditions (NCRP 1991).

Reproduction and Fecundity. Anderson and Harrison (1986) summarized the available data from the viewpoint of determining whether there were adverse responses to radiation exposure in aquatic organisms which could be used to monitor effects in contaminated environments. In their review, the chronic, low-level effects on germ tissues in fishes and invertebrates were evaluated for a limited number of species. Analysis of data indicated that the dose rate range 0.5-10 rad d^{-1} would encompass the level at which some low-level effects on reproduction, development, and genetic integrity are detectable in sensitive tissues and organisms.

Several species of aquatic organisms were studied at White Oak Lake at the Oak Ridge National Laboratory (ORNL). Trabalka and Allen (1977) compared exposed populations of the mosquito fish *Gambusia affinis* with those from a matched control site. Fish from White Oak Lake that were exposed to 0.6 rad per day showed no decrease in fecundity but an increase in embryo mortality.

Other species investigated at White Oak Lake included populations of the midge (*Chironomus tentans)* and the snail (*Physa heterostropha*). Researchers found an increased frequency of chromosome aberrations in the salivary gland chromosome of *Chironomus* larvae when exposed to about 0.6 rad per day (Mitani 1982a, 1982b); similarly, researchers found a reduced fecundity among the snail population at the chronic exposure rate of 0.6 rad per day (Cooly 1973).

ORNL researchers also measured population fecundity in the guppy *P. reticulata* at exposure dose rates of 3.8 rad per day to about 30 rads per day (Woodhead 1977). Total fecundity was significantly reduced at all dose rates. This finding was thought to be the result of both the effects on reproductive tissue (i.e., damage to germ cells) and the induction of dominant lethal mutations in gametes.

The results of laboratory and field studies of aquatic organisms cited above have shown that some observable effects may occur at dose rates as low as 0.6 rad per day. However, such effects are not necessarily detrimental when evaluated in the context of population dynamics. In most aquatic organisms in which reproductive rates are generally very high and on which selective pressures are strong, the value of a few (or even thousands of individual organisms) to the population is likely to be insignificant insofar as the long term structure and fate of the population is concerned.

Thus, in aquatic populations where less than one percent of the viable zygotes are normally expected to mature and reproduce, it would be incorrect to view developmental and reproductive effects observed at doses of less than 1 rad per day as harmful to the exposed population. In most instances, recruitment in fish populations is not related to the total number of eggs and offspring produced, but more typically to the availability of food. For these reasons, the National Council on Radiation Protection and Measurements (NCRP 1991) stated the following conclusion:

> Deleterious effects of chronic irradiation have not been observed in natural populations at dose rates $\leq$ 10 mGy d^{-1} [$\leq$ 1 rad d^{-1}] over the entire history of exposure to ionizing radiation. [Emphasis added.]

This conclusion was also reached by the International Atomic Energy Agency (IAEA 1992), which stated the following:

> The conclusion of the first IAEA review that appreciable effects in aquatic populations would not be expected at dose rates lower than 10 mGy d^{-1} [or 1 rad d^{-1}] has not been challenged by subsequent studies or reviews. Thus, it appears that limitation of the dose rate to the maximally exposed individuals in the population to < 10 mGy d^{-1} would provide adequate protection for the population.

Based on these and other scientific data, a conservative assumption is to assign the dose rate of ≥ 1 rad per day to the lowest observed radiological effect level (LOREL), and the dose rate of ≤ 0.1 rad per day to the no observed radiological effect level (NOREL).

3.2 Mathematical Models and Assumptions

When radionuclide contaminants enter aquatic environments, organisms that live and derive their food within that environment may be exposed to radiation both internally and externally. Organisms that represent the aquatic ecosystem are commonly categorized as either fully aquatic (e.g., water weeds, molluscs, crustacea, and fish) or semi-aquatic (e.g., ducks, herons, muskrats, and racoons).

The calculation of internal and external dose rates per unit concentration of radioactivity in water for aquatic biota is extremely complex and is highly dependent on numerous factors. These include (1) the physical characteristics of the individual radionuclide in terms of the emission (α, β, γ), emission energies, and physical half-life; (2) the chemical and biological behavior of the radionuclide that determines its distribution in water, sediment, and target species; and (3) the interactions of species representing various trophic levels of the food web. For example, a predator may consume several different types of prey from several different trophic levels. Moreover, many species in the aquatic food chain are highly mobile and can move over considerable distances. In turn, this mobility may introduce the species to environments and food sources with significantly different radionuclide concentrations.

These factors mandate the use of models for predicting radiological impacts to the aquatic environment and for the estimation of radiation dose rates to selected targets from radionuclides external to and within the assessed species. In order to derive the doses from the internal uptake of radionuclides, it is common practice to use empirically determined bioaccumulation or concentration factors. Bioaccumulation factors are the observed ratio of the radionuclide concentration in an aquatic organism to that in the water in which the organisms live. It assumes the organism has achieved equilibrium with the radionuclides in the water, and is a convenient metric because, once the average radionuclide concentration in water is known, it is possible to estimate the average concentration of the radionuclide in organisms in the water. This, in turn, can be used to derive the internal dose to the organism.

A generic methodology for calculating radiation dose rates to aquatic organisms has been described by the International Atomic Energy Agency in two separate reports (IAEA 1976, 1979). This approach is referred to as the point source dose distribution method. The approach uses empirically derived dose rate formulas for selected organisms categorized by size. The dose rate at a specified point can be obtained by the integration of an appropriate point source dose function over the source geometry, which is assumed to be ellipsoid. The dimensions of the ellipsoid in turn are used to estimate the fraction of the energy emitted from the radionuclide that is absorbed by the organism. Depending on the type of radiation that is emitted (i.e., α, β, and/or γ) and whether the radionuclide is internal or external to the organism, the fraction of energy absorbed by the organism per disintegration will vary. Presented below are generic equations that correspond to the point source dose distribution method for calculating dose rates.

3.2.1 Generic Dose Rate Formulae

This section presents the generic methods described by IAEA (1976 and 1979) for assessing doses to aquatic organisms, along with the modeling assumptions adopted by the Department of Energy and the CRITR computer code (Soldat and Baker 1992) for deriving screening levels.

Internal Dose Rate. The dose rate (μGy h^{-1}) from radionuclides accumulated within the organism (i.e., internal dose rate) is given by:

$$D_{intorg} = 5.76 \ x \ 10^{-4} En\Phi C_o$$

where

5.76×10^{-4} = the conversion factor from MeV dis^{-1} to μGy h^{-1}
E = the average emitted energy for alpha, beta, or gamma radiations (MeV dis^{-1})
n = the proportion of transitions producing an emission of energy E
Φ = the fraction of the emitted energy absorbed by the organism
C_o = the concentration of the radionuclide in organism (Bq kg^{-1} wet weight)

External Dose Rate from Water. The dose rate (μGy h^{-1}) to the organism from radionuclides in the water is derived from the mean dose rate in an effectively infinite (i.e., dimensions much greater than the radiation attenuation length) uniformly contaminated source as:

$$D_{ext.w.} = 5.76 \; x \; 10^{-4} \; En \, C_w$$

where

$5.76 \text{ x } 10^{-4}$ = the conversion factor from MeV dis^{-1} to μGy h^{-1}
E = the average emitted energy for alpha, beta, or gamma radiations (MeV dis^{-1})
n = the proportion of transitions producing an emission of energy E
C_w = the concentration of the radionuclide in the water (Bq L^{-1})

External Dose Rate from Sediment. Many of the radionuclides released into aquatic ecosystems concentrate in sediment to such a degree that sediments are often referred to as sinks. The concentration of a given radionuclide in sediment is frequently obtained by multiplying the concentration of a radionuclide in water times the distribution coefficient (K_d) for sediment.

The external dose rate (μGy h^{-1}) to organisms at the sediment-water interphase from radionuclides in the sediment is given by:

$$D_{ext.s.} = (0.5)(5.76 \; x \; 10^{-4}) En C_s$$

where

0.5 = the geometry factor for the water sediment interphase
$5.76 \text{ x } 10^{-4}$ = the conversion factor from MeV dis^{-1} to μGy h^{-1}
E = the average emitted energy for alpha, beta, or gamma radiations (MeV dis^{-1})
n = the proportion of transitions producing an emission of energy E
C_s = the concentration of the radionuclide in sediment (Bq kg^{-1} wet weight) (or C_w K_d where C_w is concentration in water (Bq L^{-1}) and K_d is the sediment distribution coefficient (L kg^{-1}))

From the above equation, it is seen that, for organisms that are deeply immersed in sediment, the dose rate from sediment is defined by:

$$D_s = 5.76 \; x \; 10^{-4} En C_s$$

3.2.2 Generic Formulae in Common Units

Formulae presented by IAEA (1976, 1979) used Standard International units (i.e., becquerels and grays). These units may be converted to conventional units of curies and rads for convenience; these are the units typically used for reporting radionuclide activities and evaluating exposures. Specifically, the converted dose rates (rad d^{-1}) from an individual radioactive isotope in the organism ($D_{internal}$), in the water ($D_{external, w}$), and in the surface sediment ($D_{external, s}$) are given by:

$$D_{internal} = 5.11 \times 10^{-8}\ E\ n\ \Phi\ C_o$$

$$D_{external, w} = 5.11 \times 10^{-8}\ E\ n\ C_w$$

$$D_{external, s} = 2.88 \times 10^{-5}\ E\ n\ C_s$$

where

C_o = the concentration of the radionuclide in the organism (pCi kg^{-1} wet weight)
C_w = the concentration of the radionuclide in the water (pCi L^{-1})
C_s = the concentration of the radionuclide in the sediment (pCi kg^{-1} wet weight)

The formulae were derived using 0.01 Gy per rad and 2.703×10^{-11} Ci per Bq as the unit conversion factors.

It is important to note that these formulae are the same for each type of radiation (i.e., alpha, beta, and gamma), but the dose from each must be calculated separately. That is, the emission energy (E) is specific to the isotope and type of radiation. For any given isotope, the total dose rate from each pathway is the sum of the dose rates from each type of radiation. For example:

$$D_{internal, total} = D_{internal, alpha} + D_{internal, beta} + D_{internal, gamma}$$

Then, for each isotope, the total dose rate (D_{Total}) is the sum of the total internal dose ($D_{internal, total}$), the total external dose from water ($D_{external, w, total}$), and the total external dose from surface sediment ($D_{external, s, total}$).

3.2.3 Estimates of Dose Based on Contamination Levels of Water

If not impossible, it is highly impracticable to obtain estimates of radiation dose to organisms in a contaminated, but otherwise natural, environment by direct measurement. Besides cost considerations, difficulties with direct measurements include: (1) logistical complications imposed by the requirements for a capture - recapture program if a passive dosimeter (e.g., LiF) were to be implanted for *in situ* measurements; (2) limitations imposed by the dosimeter (e.g., the ability to assess internal exposure from α and β emitters); or (3) errors introduced by the variations in external exposure due to the mobility of aquatic organisms in a nonuniformly contaminated environment. Collectively, these and other factors limit estimates of dose or dose-rates to modeling methods that require key assumptions.

Radionuclide Uptake - The Bioaccumulation Factor Approach

Estimates of internal exposure require an understanding of the distribution and concentration of individual radionuclides within target tissues of a given species. For humans, extensive studies have been performed that have determined the uptake, distribution, and retention of individual radionuclides within discrete tissues of the body. For humans, therefore, definitive dosimetric models have been developed that allow reasonably accurate estimates of internal doses that would result from the internalization of radionuclides. However, such detailed data have not been developed for other species.

Radionuclides released into the aquatic environment are assimilated by living organisms. The intake of an element by an aquatic organism may be represented by:

$$\frac{dC}{dt} = \frac{I_w}{m} C_w - rC$$

where

C = the concentration in the organism
C_w = the concentration in water
I_w = the intake rate by the organism
m = the mass of the organism
r = the biological elimination rate of the element by the organism

This equation has the solution:

$$C(t) = \frac{I_w C_w}{mr}[1 - \exp(-rt)]$$

Thus, the concentration of the element in the organism will build up with time asymptotically approaching an equilibrium value of:

$$C_{equil} = \lim_{t \to \infty} C(t) = \frac{I_w C_w}{mr}$$

The ratio of the concentration in the organism to that in water is:

$$\frac{C_{equil}}{C_w} = \frac{I_w}{mr}$$

This ratio is termed the bioaccumulation factor, BF, and is defined as:

$$BF = \frac{\text{equilibrium concentrations in organism}}{\text{concentration in water}}$$

The preceding derivation also applies to radionuclides except that, in addition to biological elimination, losses by radioactive decay must be accounted for by replacing r by $r + \lambda$. The above equations then become:

$$BF = \frac{I_w C_w}{m(r+\lambda)}[1 - \exp - (r+\lambda)t]$$

where

λ = radioactive decay constant

$$BF = \frac{I_w}{m(r+\lambda)}$$

Under equilibrium conditions and for radionuclides with long half-lives (or when the physical half-life of a radionuclide is much longer than its biological half-life), the bioaccumulation factor for radionuclides is generally defined as:

$$BF = \frac{C_{biota}}{C_{water}} \quad (L/kg)$$

where

C_{biota} = radionuclide concentration (pCi/kg fresh weight) in biota or tissue
C_{water} = radionuclide concentration in water (pCi/L)

Bioaccumulation factors reported in the literature may vary by several orders of magnitude (NCRP 1991). The values of BF recommended by the Department of Energy, and adopted as default values in the CRITR code, for use with screening models for estimating dose to freshwater biota are listed in Table 3-1. Separate bioaccumulation factors have been identified for fish, crustacea, molluscs, and aquatic plants. (Table 3-1 also provides values for the biological half-lives of elements (T_b) and their fractional uptake from the gut (f_1). These values are representative of Reference Man but are assumed to apply to secondary aquatic organisms such as fish, crustacea, molluscs, and plants.)

Absorbed Dose

The above equations define absorbed dose as a function of the emission energy (E) and the absorbed fraction (Φ) of the radiation. Values for the absorbed fraction are very complex and reflect (1) the type of radiation (i.e., α, β, and γ), (2) whether the radiation is internal or external to the organism, and (3) the physical dimensions of the organism. Due to their short range, the CRITR code assumes that alpha particles produce no significant external exposure but must be assumed to be totally absorbed when internalized.

For beta and gamma radiation, however, the magnitude of internal and external radiation dose rates are strongly affected by the radiation energy and physical dimensions of the organism. Table 3-2 provides emission energies for radionuclides with the potential for environmental impacts. The calculated absorbed fractions for gamma and beta emission energies are depicted in Figures 3-1 through 3-3 and correspond to organisms with mass and physical dimensions cited in Table 3-3.

It should be noted that the absorbed dose, as calculated in the above equations, does not account for the relative biological effectiveness of the different types of radiation. A quality factor is normally used to account for the relative biological effectiveness of the different radiation types (NCRP 1987; Blaylock et al. 1993). The standard quality factors for exposure of humans are 1 for gamma and beta radiations and 20 for alpha radiations. However, those factors account for the potential to cause cancer, which is not an endpoint of concern for natural populations of aquatic biota. However, the soft tissue composition of non-human vertebrates is generally similar to humans in water content and basic cell structure (NCRP 1991). In the absence of standard quality factors for non-human biota, the default values for humans may be used as recommended by Blaylock et al. (1993). Thus, and depending upon the biological endpoint under consideration, the absorbed dose from alpha emissions may be multiplied by 20 so that the total dose rate is normalized for the biological effectiveness of the absorbed dose rate of each type of radiation.

Table 3-1. Default Bioaccumulation Factors and Human Biological Half-Lives (T_b) and Uptake Fractions (f_1) Used in CRITR

	Fish	Crustacean	Mollusc	Plant	T_b	f_1	Kd
	L kg^{-1}						
Ac	330	1000	1000	10000	24000	0.001	450
Ag	100	200	200	1000	5	0.05	90
Am	100	100	100	3000	20000	0.001	5000
Ar	1	1	1	1	0	0	—
As	200	200	200	200	280	0.5	—
Ba	200	200	200	500	65	0.1	60
Be	10	50	50	200	180	0.005	250
Bi	15	100000	100000	1500	5	0.05	100
Bk	50	500	20000	1	65000	0.001	—
Br	420	330	330	50	8	1	5
C	9000	9000	9000	4500	10	1	5
Ca	200	2000	2000	1000	16400	0.3	5
Cd	200	10000	10000	500	200	0.05	80
Ce	500	1000	1000	4000	563	3E-4	10000
Cf	25	1000	1000	5000	65000	0.001	—
Cl	50	50	50	50	29	1	—
Cm	30	1000	1000	10000	24000	0.001	4000
Co	330	2000	2000	1000	9.5	0.3	5000
Cr	20	2000	2000	4000	616	0.1	30
Cs	2000	100	100	500	115	1	1000
Cu	2500	400	400	2000	80	0.5	5000
Dy	25	1000	5000	1	700	3E-4	—
Er	500	1000	1000	4000	650	3E-4	—
Eu	300	3000	3000	5000	635	0.001	500
F	10	100	100	2	808	1	—
Fe	2000	100	100	1000	800	0.1	220
Ga	1000	10000	10000	1	6	0.001	—
Gd	500	2000	5000	1	550	3E-4	—
H	1	1	1	1	10	1	0
Hf	40	1000	3000	1	563	0.002	450
Hg	20000	20000	20000	34000	10	1	—
Ho	300	3000	3000	5000	750	3E-4	—
I	50	100	100	300	100	1	10
In	1000	10000	10000	1	48	0.02	—
Ir	50	200	200	200	20	0.01	—
Kr	1	1	1	1	0	0	—
La	25	1000	1000	5000	500	0.001	—
Mn	4000	100000	100000	10000	17	0.1	170
Mo	10	100	100	1000	5	0.8	—
N	1	1	1	1	90	1	—
Na	100	100	100	100	11	1	100
Nb	100	50	50	500	760	0.01	160
Nd	25	1000	1000	5000	656	3E-4	—
Mi	100	500	500	500	667	0.05	400

Table 3-1. Default Bioaccumulation Factors and Human Biological Half-Lives (T_b) and Uptake Fractions (f_1) Used in CRITR (continued)

	Fish	Crustacean	Mollusc	Plant	T_b	f_1	Kd
	L kg^{-1}						
Np	2500	30	30	300	39000	0.001	10
P	170	100000	1100000	500000	257	0.8	9
Pa	30	30	30	300	41000	0.001	540
Pb	2000	500	500	2000	1460	0.2	270
Pd	50	2000	2000	2000	5	0.005	180
Pm	300	3000	3000	5000	656	3E-4	1000
Po	50	20000	20000	2000	30	0.1	150
Pe	25	1000	1000	5000	750	3E-4	---
Pu	250	100	100	890	65000	0.001	100000
Ra	50	1000	1000	30000	8100	0.2	500
Rb	2000	1000	1000	1000	45	1.0	180
Rh	10	300	300	200	10.4	0.05	---
Rn	57	1	1	1	0	0	---
Ru	100	300	300	2000	7.3	0.05	55
S	750	100	100	1	90	0.8	---
Sb	200	100	100	1000	38	0.1	45
Sc	100	1000	1000	10000	30	1E-4	---
Se	1000	2000	2000	100	11	0.8	150
Si	1000	10000	10000	50000	60	0.01	55
Sm	300	3000	3000	5000	656	3E-4	245
Sn	1000	10000	10000	50000	35	0.02	130
Sr	50	100	100	3000	4000	0.3	1000
Ta	60	3000	3000	1	240	0.001	220
Tb	25	1000	1000	5000	670	3E-4	—
Tc	15	100	100	5000	1	0.8	1
Te	400	6100	6100	100	15	0.2	5
Th	100	100	100	3000	57000	2E-4	10000
Tl	5000	1000	5000	1	5	1	—
Tm	500	1000	5000	1	675	3E-4	—
U	50	100	100	900	100	0.05	50
W	1200	10	10	1200	1	0.3	—
Xe	1	1	1	1	0	0	—
Y	25	1000	1000	5000	14000	1E-4	—
Yb	200	1000	3000	1	685	3E-4	—
Zn	64	10000	10000	20000	933	0.5	500
Zr	200	50	50	5000	450	0.002	1000

Sources:

T_b: NUREG-0172 (NRC 1977), ICRP-2 (1959), ICRP-10 (1968)
f_1: ICRP-30 Parts 1 through 4 (1979-1988)
Biofactors: GENII BIOACH.DAT file dated 7 Mar 90 (Napier et al. 1988)

Table 3-2. Default Emission Energies (E) for Selected Radionuclides Used in CRITR

		Emission Energies (MeV)			
Radionuclide* (yield)	Half-life	Average Alpha	Maximum Beta[b]	Average Beta	Average Gamma
Antimony- 125	2.77y		6.12e-01	9.93e-02	4.30e-01
Barium-140	12.74d		1.01e+00	3.11e-01	1.82e-01
Lanthanum-140	40.27h		2.20e+00	5.33e-01	2.31e+00
Cerium-141	32.501d		5.80e-01	1.70e-01	7.61e-02
Cerium- 144	284.3d		3.18e-01	9.10e-02	2.07e-02
Praseodymium-144m (98.22% of Ce-144)	7.2m			4.72e-02	1.27e-02
Praseodymium- 144 (1.78% of Ce- 144)	17.28m		3.00e+00	1.21e+00	3.18e-02
Cesium-134	2.062y		6.58e-01	1.63e-01	1.55e+00
Cesium-137	30y		1.17e+00	1.87e-01	
Barium-137m (94.6% of ^{137}Cs)	2.55m			6.51e-02	5.96e-01
Chromium-51	27.704d			3.86e-03	3.26e-02
Cobalt-60	5.271y		3.18e-01	9.65e-02	2.50e+00
Europium-154	8.8y		1.85e+00	2.88e-01	1.22e+00
Europium-155	4.96y		2.47e-01	6.26e-02	6.05e-02
Hydrogen-3	12.35y		1.86e-02	5.68e-03	
Iodine-131	8.04d		8.07e-01	1.90e-01	3.80e-01
Xenon- 131 m (1.11 % of 1- 131)	11.9d			1.44e-01	2.00e-02
Niobium-95	35.15d		1.60e-01	4.44e-02	7.66e-01
Phosphorous-32	14.29d		1.71e+00	6.95e-01	
Potassium-40	1.28e+09y		1.32e+00	5.23e-01	1.56e-01
Ruthenium- 103	39.28d		7.10e-01	7.45e-02	4.68e-01
Rhodium-103m (99.7% of Ru-103)	56.12m			3.80e-02	1.75e-03
Ruthenium-106	368.2d		3.90e-02	1.00e-02	
Rhodium-106	29.9s		3.54e+00	1.41e+00	2.01e-01
Sodium-24	15h		1.39e+00	5.53e-01	4.12e+00
Strontium-90	29.12y		5.46e-01	1.96e-01	
Yttrium-90	64h		2.28e+00	9.35e-01	1.69e-06
Technetium-99	213000y		2.95e-01	1.01e-01	
Uranium-237	6.75d		2.48e-01	1.94e-01	1.42e-01
Zinc-65	243.9d		3.30e-01	6.87e-03	5.84e-01
Zirconium-95	63.98d		1.23e+00	1.16e-01	7.39e-01
Plutonium-239	24065y	5.23e+00		6.65e-03	7.96e-04
Plutonium-240	6537y		5.24e+00	1.06e-02	1.73e-03
Thorium-232	1.405e+10y	4.07e+00		1.25e-02	1.33e-03
Radium-228	5.75y		5.50e-02	1.69e-02	4.14e-09
Actinium-228	6.13h		2.08e+00	4.60e-01	9.30e-01
Thorium-228	1.9131y	5.49e+00		2.05e-02	3.30e-03
Radium-224	3.66d	5.78e+00		2.21e-03	9.89e-03
Radon-220	55.6s	6.40e+00		8.91e-06	3.85e-04
Polonium-216	0.15s	6.91e+00		1.61e-07	1.69e-05
Lead-212	10.64h		5.86e-01	1.75e-01	1.48e-01
Bismuth-212	60.55m	2.22e+00	2.26e+00	4.69e-01	1.85e-01
Polonium-212 (64.07% of Bi-212)	0.305us	8.95e+00			
Thallium-208 (35.93% of Bi-212)	3.07m		2.38e+00	5.91e-01	3.36e+00
Americium-241	432.2y	5.57e+00		5.19e-02	3.24e-02
Neptunium-237	2.14e+06y	4.84e+00		6.85e-02	3.43e-02
Protactinium-233	27d		5.68e-01	1.95e-01	2.03e-01
Uranium-233	158500y	4.89e+00		6.08e-03	1.31e-03

Table 3-2. Default Emission Energies (E) for Selected Radionuclides Used in CRITR (continued)

		Emission Energies (MeV)			
Radionuclide* (yield)	Half-life	Average Alpha	Maximum Beta[b]	Average Beta	Average Gamma
Thorium-229	7340y	4.95e+00		1. 14e-01	9.54e-02
Radium-225	14.8d		3.20e-01	1.07e-01	1.37e-02
Actinium-225	10d	5.86e+00		2.17e-02	1.79e-02
Francium-221	4.8m	6.41e+00		9.8le-03	3.10e-02
Astatine-217	0.0323s	7.19e+00		3.66e-05	3.08e-04
Bismuth-213	45.65m	1.29e-01	1.42e+00	4.40e-01	1.33e-01
Polonium-213 (97.84% of Bi-213)	4.2us	8.54e+00			
Lead-209 (2.16% of Bi-213)	3.253h		6.37e-01	1.98e-01	
Uranium-238	4.468e+09y	4.26e+00		1.00e-02	1.36e-03
Thorium-234	24.1d		1.93e-01	5.92e-02	9.34e-03
Protactinium-234m	1. 17m		1.50e+00	8.20e-01	1.13e-02
Protactinium-234	6.7h		1.40e+00	4.22e-01	1.75e+00
Uranium-234	2.445e+05y	4.84e+00		1.32e-02	1.73e-03
Thorium-230	7.7e+4y	4.74e+00		1.46e-02	1.55e-03
Radium-226	1600y	4.86e+00		3.59e-03	6.74e-03
Radon-222	3.8235d	5.59e+00		1.09e-05	3.98e-04
Polonium-218	3.05m	6.11e+00		1.42e-05	9.12e-06
Lead-214 (99.98% of Po-218)	26.8m		9.80e-0 1	2.91e-01	2.48e-01
Astatine-218 (0.02% of Po-218)	2s	6.82e+00		4.00e-02	6.72e-03
Bismuth-214 (100% of Pb-214 & At-218)	19.9m		3.27e+00	6.48e-01	1.46e+00
Polonium-214	164.3us	7.83e+00		8.19e-07	8.33e-05
Lead-210	22.3y		6.30e-02	3.80e-02	4.81e-03
Bismuth-210	5.012d		1.16e+00	3.89e-01	
Polonium-210	138.38d	5.40e+00		8.18e-08	8.50e-06
Uranium-235	7.038e+08y	4.47e+00		4.80e-02	1.54e-01
Thorium-231	25.52h		3.05e-01	1.63e-01	2.55e-02
Protactinium-231	3.276e+04y	5.04e+00		6.28e-02	4.76e-02
Actinium-227	21.773y	6.91e-02	4.30e-02	1.56e-02	2.31e-04
Thorium-227 (98.62% of At-227)	18.718d	5.95e+00		4.57e-02	1.06e-01
Francium-223 (1.38% of At-227)	21.8m		1.15e+00	3.9le-01	5.88e-02
Radium-223 (100% of Th-227 & Fr-223)	11.434d	5.75e+00		7.46e-02	1.33e-01
Radon-219	3.96s	6.88e+00		6.30e-03	5.58e-02
Polonium-215	0.178e-02s	7.52e+00		6.30e-06	1.76e-04
Lead-211	36.1m		1.39e+00	4.54e-01	5.03e-02
Bismuth-211	2.14m	6.68e+00	6.00e-01	9.78e-03	4.66e-02
Thallium-207 (99.72% of Bi-21 1)	4.77m		1.44e+00	4.93e-01	2.21e-03
Polonium-211 (0.28% of Bi-21 1)	0.516s	7.59e+00		1.69e-04	7.79e-03
Curium-244	18.11y	5.89e+00		8.59e-03	1.70e-03
Plutonium-238	87.74y	5.58e+00		1.06e-02	1.8le-03

[a] Selected isotopes are those presented in Blaylock et al. (1993) plus several minor daughter products and Cm-244 and Pu-238. Indented radionuclides are the daughter products of the preceding long-lived radionuclide, as presented in Blaylock et al. (1993). Yields, half-lives, and average energies are from ICRP (1983).

[b] Maximum beta energies presented are from *The Health Physics and Radiological Health Handbook* and its 1986 supplement (Shleien and Terpilak 1984, 1986). The exception is actinium-228, which is from Kocher (1981).

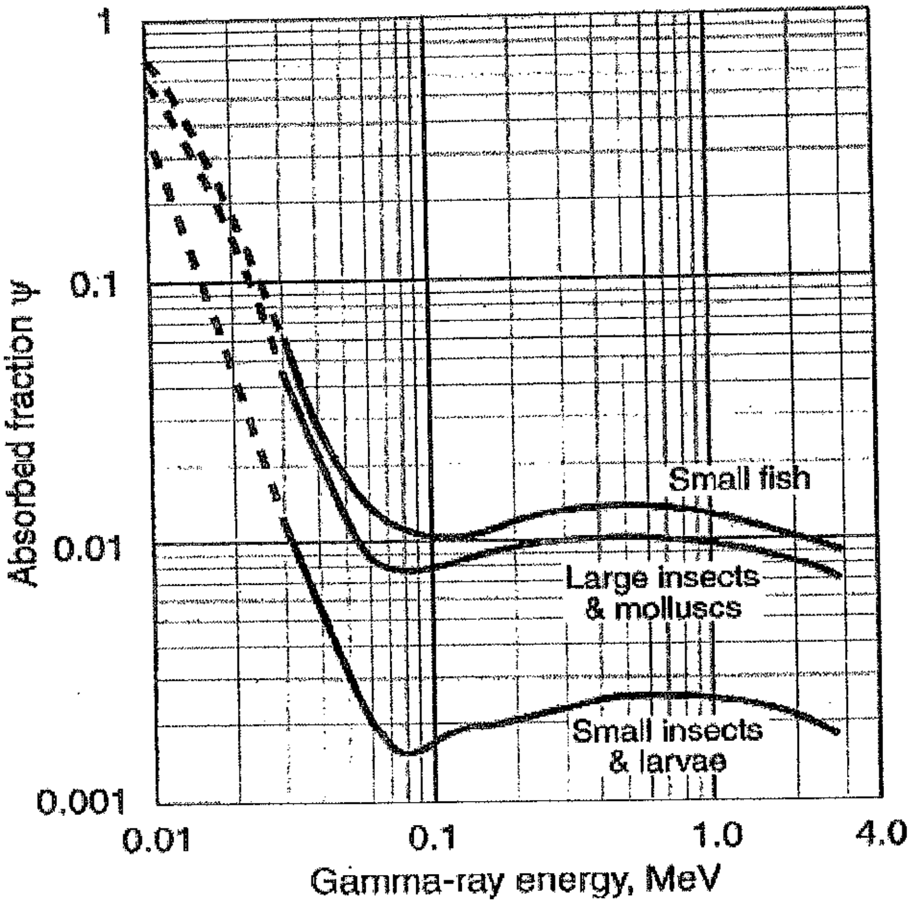

Figure 3-1. Derived Absorbed Fractions as a Function of Gamma Energy for Small Fish, Large Insects and Molluscs, and Small Insects and Larvae (Source: NCRP 1991)

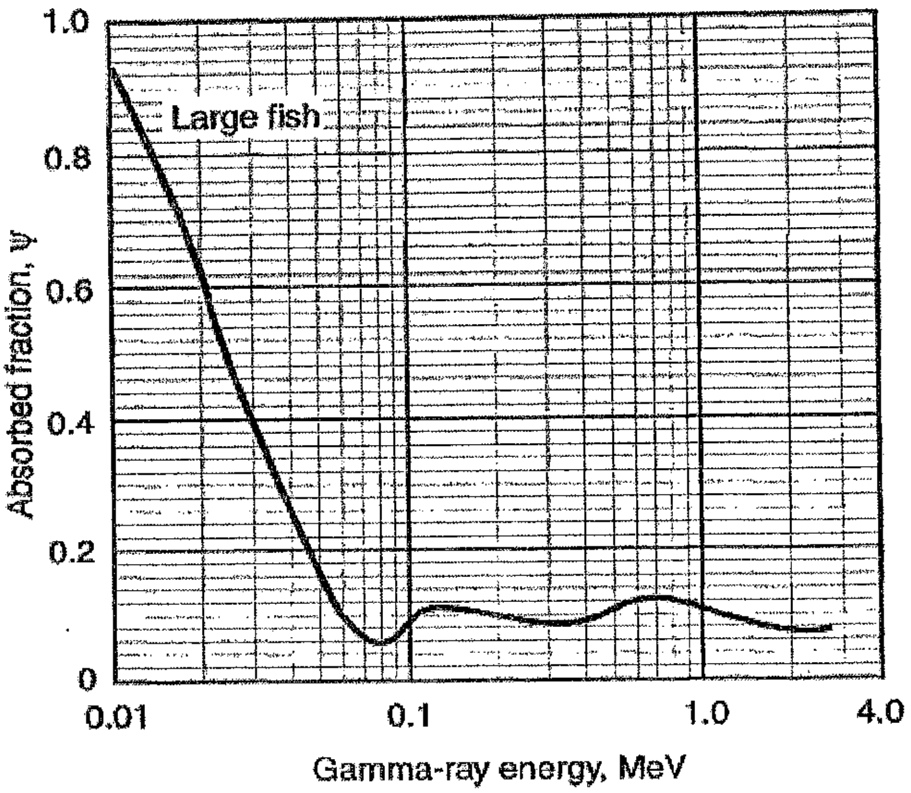

Figure 3-2. Derived Absorbed Fractions as a Function of Gamma Energy For Large Fish (Source: NCRP 1991)

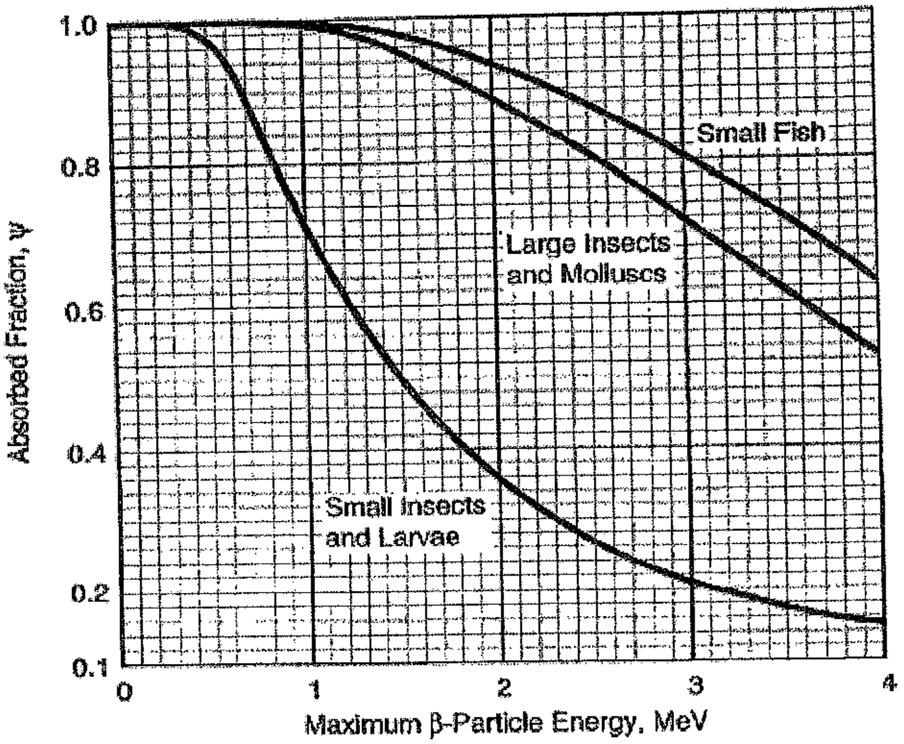

Figure 3-3. Derived Absorbed Fractions as a Function of Beta Energy for Small Fish, Large Insects and Molluscs, and Small Insects and Larvae (Source NCRP 1991)

Table 3-3. Dimensions of Organisms Representing Different Size Categories Used in the Point Source Dose Distribution Methodology for Estimating Radiation Doses

Organism	Mass (kg)	Length of the Major Axes of the Ellipsoid (cm)
Small insects and larvae	1.6×10^{-5}	0.62 x 0.31 x 0.16
Large insects and molluscs	1.0×10^{-3}	2.5 x 1.2 x 0.62
Small fish	2.0×10^{-3}	3.1 x 1.6 x 0.78
Large fish, turtles	1.0	45 x 8.7 x 4.9

Source: NCRP Report No. 109, 1991

3.3 A Simplified Method for Calculating Internal and External Dose Rates to Aquatic Species

In 1974, Soldat et al. introduced dose models and a computer code (CRITR) for calculating radiation doses to aquatic organisms and their predators (Soldat et al. 1974). These models, which were updated in 1992 (Soldat and Baker 1992), provide a simplified method for estimating doses to the two groups of aquatic organisms using a restricted number of parameters related to the concentration of radionuclides in water at a specific location. For the first group or fully aquatic species (i.e., water weeds, molluscs, crustacea, and fish), the equilibrium body burden (and internal dose) is simply determined from water concentration by application of the appropriate bioaccumulation factor. For the second or semi-aquatic group of organisms (e.g., ducks, muskrats, etc.), the main source of internal radionuclides is the consumption of organisms of the first group.

For both groups of organisms, the contaminant radionuclides are assumed to be uniformly distributed throughout the body and in the surrounding medium of water. The contamination level in sediment is assumed to be that of water multiplied by the corresponding K_d value.

This section presents a summary of the basic model equations and lookup tables of the required input parameters needed to calculate dose from both internal and external sources as adopted by the DOE and the CRITR code.

3.3.1 Estimates of Internal Dose for Primary and Secondary Aquatic Organisms

Radionuclide concentrations in primary organisms can be calculated directly from the water concentrations and bioaccumulation factors. The primary indicator organisms considered are fish, crustacea, molluscs, and plants. Radionuclide concentrations for secondary organisms can be calculated from their diet of primary organisms. Representative secondary birds and mammals were selected such that each primary organism would be in the diet of at least one secondary organism. Predatory birds and mammals commonly selected are herons (fish-eating), raccoons (crustacea-, mollusc-, or fish-eating), muskrats (plant-eating), and ducks (plant- or fish-eating).

Primary Organisms. The internal total-body dose rate to an organism for N radionuclides is given as

$$R_c = \sum_{i=1}^{n} b_{i,c}E_{i,c}$$

where

Rc = dose rate to total body of organism *c* (rad d^{-1})

$E_{i,c}$ = effective absorbed energy rate for nuclide *i* per unit activity in organism *c* (kg rad $Ci^{-1}d^{-1}$)

$E_{i,c} = \epsilon_{i,e}$MeV dis^{-1}3.70E10dis s^{-1} Ci^{-1} x 86,400s d-1 x 1.602E-11kgradMeV^{-1}

$= 5.12E4\ \epsilon_{i,c}$

where ϵ is the effective absorbed energy per disintegration for nuclide *I* in organism *c* from all radiation emissions, and

$b_{i,c}$ = specific body burden of nuclide *I* in organism *c* (Ci kg^{-1})

For a primary organism,

$$b_{i,c} = C_{i,c}BF_{i,dc}$$

where $C_{i,c}$ is the concentration of nuclide *i* in the water to which organism *c* is exposed (Ci m^{-3}), and $BF_{i,c}$ is bioaccumulation factor for nuclide *i* and organism *c* (m^3 kg^{-1}). (Note: the water concentration has already been corrected for dilution and radioactive decay during transit from the point of release into the receiving water body to the region of the organism's habitat.)

Combining equations yields the dose rate in rad d^{-1} to the primary organism:

$$R_c = \sum_{i=1}^{N} C_{i,c}BF_{i,c}E_{i,c}$$

<u>Secondary Organism</u>. For the secondary organism, it is possible to write an expression for a single radionuclide equating the change in body burden for the uptake and removal of the radionuclide

$$\frac{db^s}{dt} = \frac{P}{M} - \lambda b^s$$

where

b^s = specific body burden of the secondary organism (Ci kg^{-1})
P = rate of uptake of radionuclide by body of organism (Ci d^{-1})
$\lambda = (\lambda_b + \lambda_r)$ effective decay constant in secondary organism, (d^{-1}), where λ_b = $1n(2)/T_b$ is the biological removal rate constant for the nuclide in the secondary organism and $\lambda_r = 1n(2)/T_r$ is the radiological decay constant for the nuclide
M = mass of secondary organism (kg)

The secondary organism uptake rate is given by

$$P = b\,U f_l$$

where

b = body burden of primary organism (Ci kg^{-1})
U = intake rate of primary organism by predator (kg d^{-1})
f_1 = fraction of radionuclide initially retained in total body of secondary organism (unitless)

Solving the equation with $b^s = 0$ when $t = 0$:

$$b^s = \frac{P}{M}\,\frac{(1 - e^{-\lambda T_e})}{\lambda}$$

where T_e is the period of exposure (d).

Then, for a secondary organism *c*, the dose rate in terms of the body burden b_i of the primary organism for *N* radionuclides is

$$R_c = \sum_{i=1}^{N} \frac{b_1 U_c f_{1,i}}{m_c}\,\frac{(1 - e^{-\lambda_{i,c} T_e})}{\lambda_{i.c}}\,E_{i,c}$$

where

U_C = intake rate of primary organism by secondary organism *c* (kg d^{-1})
$\lambda_{i,c}$ = effective decay constant of nuclide *i* in secondary organism *c* (d^{-1})
m_c = mass of secondary organism *c* (kg)

In the absence of species-specific data, the removal constants, $\lambda_{i,c}$, and uptake fractions, $f_{1,i}$, are taken to be that of Standard Man as derived by the International Commission on Radiological Protection. See Table 3-4 for a list of representative values. The values of effective energy, $\epsilon_{i,c}$, depend on knowing the effective radius of the organism. Table 3-4 gives values for the energies in MeV dis^{-1} for selected nuclides and radii. Energies for radii falling between these values may be found by linear interpolation. However, for most estimates, selecting the energy associated with the radius closest to that of the organism suffices. The exposure time, T_e, is usually assumed to be one year for regulatory purposes, and the water concentration is averaged over one year. These doses to organisms may be obtained by hand calculation as illustrated below.

Sample Calculation for Internal Dose Estimates

As an example of how this methodology may be applied to some representative aquatic biota, an estimate of the internal dose rate is derived from ^{137}Cs to a fish residing in water having the concentration of 100 pCi per liter or 1.0E-7 Ci m^{-3} and to a heron whose total diet consists of such fish. The radiological decay constant for ^{137}Cs is 6.33E-5 d^{-1} (half-life of 30.0 y).

The solution is as follows. First, the body burden of the fish is calculated. The bioaccumulation factor for fresh-water fish is obtained from Table 3-1 for cesium: 2000 L kg^{-1} or 2 m^3 kg^{-1}. The body burden of the fish is then

$$b_{fish} = 1.0E\text{-}7\ Ci\ m^{-3} \times 2\ m^3\ kg^{-1} = 2.0E\text{-}7\ Ci\ kg^{-1}$$

Table 3-5 shows the effective radius of a reference fish to be 5 cm. According to Table 3-5, the energy absorbed in this radius for ^{137}Cs is 0.316 MeV dis^{-1}. Then the dose rate is

$$\begin{aligned} R_{fish} &= 2.0E\text{-}7\ Ci\ kg^{-1} \times (5.12E4 \times 0.316)\ kg\ rad\ Ci^{-1}\ d^{-1} \\ &= 3.2E\text{-}3\ rad\ d^{-1} \end{aligned}$$

The internal dose to the heron is estimated from Equation 23. As seen in Table 3-5, the typical heron has a mass of 5 kg and an effective radius of 10 cm and eats 0.6 kg of fish per day. From Table 3-4, the effective energy of the secondary organism (heron) with an effective radius of 10 cm is 0.388 MeV dis^{-1}.

$$E = 5.12E4 \times 0.388 = 1.99E4\ kg\ rad\ Ci^{-1}\ d^{-1}$$

The biological half-life is 115 d from Table 3-1, which can be converted to a loss rate: 0.693/115 d = 6.03E-3 d^{-1}.

Thus, the effective decay rate is

$$\lambda = 6.33E\text{-}5 + 6.03E\text{-}3 = 6.09E\text{-}3\ d^{-1}$$

Substituting the above values and the uptake fraction of 1.0 for cesium from Table 3-1 into the equations, the following dose rate for heron is calculated:

$$\begin{aligned} R_{heron} &= \frac{(2.0E{-}7\,Ci\,kg^{-1})(0.6\,kg\,d^{-1}x\,1.0)[(1 - \exp(-6.09E{-}3\,d^{-1}x\,365d)](1.99E4\,kg\,rad\,Ci^{-1}\,d^{-1})}{5\,kg\ x\ 6.09E{-}3\,d^{-1}} \\ &= 0.07\ rad\ d^{-1} \end{aligned}$$

3.3.2 External Dose Rates from Water and Sediment

The methods used for calculating external radiation dose rates to aquatic organisms from exposure to water and sediment are similar to those used in calculating doses to man. The external pathways for a crawling or fixed organism such as a crab or clam include immersion in water and contact with bottom sediment. From Soldat et al. (1974), the water immersion dose rate from *N* nuclides is

$$R_{immers} = \sum_{i=1}^{N} C_{i,c} DF_{immers,i} F_{\exp}$$

where $DF_{immers,i}$ is the water immersion dose factor for nuclide *i*, rad d^{-1} per Ci m^{-3}, and F_{exp} is the exposure fraction (unitless).

The model for the direct irradiation dose from <u>bottom sediment</u> or mud is similar to the shoreline dose equation of Soldat et al. (1974). For *N* nuclides, the dose rate in rad d^{-1} is

$$R_{sed} = F_{sed} F_{ruf} F_{\exp} \sum_{i=1}^{N} C_{i,c} DF_{gnd,i} (1 - \exp^{-\lambda_T T_s})/\lambda_r$$

where

F_{sed} = sediment deposition transfer factor, 0.07 Ci m^{-2} d^{-1} Ci^{-1} m^3 (Soldat et al. 1974)

F_{ruf} = geometry-roughness factor (unitless) of 0.2 is assumed

$DF_{gnd,i}$ = ground irradiation dose factor for nuclide *I*, rad d^{-1} Ci^{-1} m^2

T_s = time sediment is exposed to contaminated water, d

The remaining parameters in the above equations were defined for the internal dose equation. For annual exposures, the resulting dose rate would be multiplied by the number of days in a year (365). T_s would be 1 year or 365 days. The geometry-roughness factor modifies the "infinite plane" dose factor to account for the height of the organism above the surface, the relative size of the contaminated area, and the roughness of the surface, which causes scattering of the photons emitted from the sediment surface. The exposure fraction is the fraction of time the organism spends exposed to the medium.

For an organism such as a fish, which spends 100% of its time immersed in water, the exposure fraction would be 1; for a clam or crayfish living on the bottom, the water exposure geometry would be similar to that of the water surface. For ducks, geese, and other surface-swimming animals, half of the immersion dose may be used as an estimate of external dose. If the animal spends time on the shore, a fraction of the sediment dose may be included. This factor may vary between one-fourth and one-half, depending on the habits of the animal. Table 3-5 lists some typical exposure fractions. The roughness factor is assumed to be 0.2 – the normal shore-width factor for humans standing on the shore of a river.

Sample Calculation for External Dose Rate

As an example of estimating the external dose rate, consider the ^{137}Cs dose to a fish and to a muskrat residing in and near the surface water with the same concentration of ^{137}Cs as in the previous example. The fish is assumed to feed on the bottom 50% of the time. The muskrat, as shown in Table 3-5, spends a third of its time on the shore and a third totally immersed in the water. For these creatures, the external dose comes from both immersion in the surrounding water and from sediment.

For the immersion dose rate, Equation 24 is used, with the dose factor for water immersion (taken from Table 5-1) of 18.0 rad d^{-1} Ci^{-1} m^3.

$$\begin{aligned} R_{immers} &= 1.0E\text{-}7\ Ci\ m^{-3}\ x\ 18.0\ rad\ d^{-1}\ Ci^{-1}\ m^{3} \\ &= 1.80\ E\text{-}6\ rad\ d^{-1} \end{aligned}$$

The sediment dose rate is estimated as follows; the value for $\lambda = 6.33E\text{-}5\ d^{-1}$ as previously determined. Thus,

$$\begin{aligned} R_{sed} &= (1.0E-7\,Ci\,m^{-3})(0.07\,Ci\,m^{-2}d^{-1}Ci^{-1}m^{3})(0.2)(167\,rad\ d^{-1}Ci^{-1}m^{2})x\frac{[1-\exp^{-6.33E-5d^{-1}(365\,d)}]}{6.33E-5\,d^{-1}} \\ &= 8.45E-5\ rad\ d^{-1} \end{aligned}$$

For the fish, the total external dose consists of up to 100% immersion and 50% sediment:

$$\begin{aligned} R_{Fish\ total\ ext.} &= (1.80E\text{-}6)(1) + (8.45E\text{-}5)(0.5)\ rad\ d^{-1} \\ &= 4.40E\text{-}5\ rad\ d^{-1} \end{aligned}$$

For the muskrat, the total external dose rate is one-third water immersion and one-third sediment:

$$\begin{aligned} R_{Muskrat\ total\ ext} &= (1.80E\text{-}6)(0.33) + (8.45E\text{-}5)(0.33)\ rad\ d^{-1} \\ &= 2.85E\text{-}5\ rad\ d^{-1} \end{aligned}$$

Table 3-4. Half-Lives and Energies (MeV dis^{-1}) for Selected Effective Radii (cm) of Aquatic Organisms and External Dose Rate Factors

Radionuclide	Half-life	Energy by Radius (cm)								Dose Rate Factors	
		1.4	2	3	5	7	10	20	30	Immersion (rad d^{-1} per Ci/m^3)	Sediment (rad d^{-1} per Ci/m^2)
H-3	12.35 y	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.01	0	0
C-14	5730 y	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0	0
N-13	9.965 m	0.538	0.557	0.587	0.646	0.701	0.777	0.983	1.13	3.04E+01	2.88E+02
F-18	109.77m	0.285	0.304	0.334	0.391	0.444	0.518	0.717	0.861	2.96E+01	2.79E+02
Na-22	2.602 y	0.286	0.325	0.387	0.507	0.619	0.775	1.20	1.51	6.66E+01	5.75E+02
Na-24	15.00 h	0.712	0.771	0.868	1.05	1.23	1.48	2.19	2.74	1.41E+02	9.75E+02
P-32	14.29 d	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0	0
Ar-39	269 y	0.194	0.194	0.194	0.194	0.194	0.194	0.194	0.194	0	0
Ar-41	1.827 h	0.519	0.541	0.576	0.642	0.705	0.793	1.04	1.22	3.95E+01	3.15E+02
Sc-46	83.83 d	0.197	0.232	0.290	0.399	0.501	0.644	1.03	1.32	6.25E+01	5.32E+02
Cr-51	27.704 d	0.00222	0.00276	0.00363	0.00529	0.00685	0.00901	0.0149	0.0191	9.51E-01	9.34E+00
Mn-54	312.5 d	0.0364	0.0514	0.0758	0.122	0.166	0.227	0.392	0.512	2.58E+01	2.30E+02
Mn-56	2.5785 h	0.875	0.904	0.951	1.04	1.13	1.24	1.57	1.82	5.51E+01	4.38E+02
Fe-55	2.7 y	0.00726	0.00726	0.00726	0.00726	0.00726	0.00726	0.00726	0.00726	7.84E-04	6.05E-02
Fe-59	44.529 d	0.171	0.191	0.224	0.286	0.346	0.428	0.655	0.824	3.67E+01	3.01E+02
Co-57	270.9 d	0.0390	0.0409	0.0439	0.0496	0.0550	0.0626	0.0840	0.100	3.94E+00	3.92E+01
Co-58	70.80 d	0.0728	0.0905	0.119	0.174	0.226	0.297	0.492	0.633	2.99E+01	2.70E+02
Co-60	5.271 y	0.195	0.237	0.306	0.437	0.560	0.732	1.21	1.56	7.73E+01	6.22E+02
Ni-63	96 y	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0	0
Ni-65	2.520 h	0.641	0.651	0.666	0.695	0.723	0.762	0.869	0.949	1.70E+01	1.36E+02

Table 3-4. Half-Lives and Energies (MeV dis^{-1}) for Selected Effective Radii (cm) of Aquatic Organisms and External Dose Rate Factors (Continued)

Radionuclide	Half-life	Energy by Radius (cm)								Dose Rate Factors	
		1.4	2	3	5	7	10	20	30	Immersion (rad d^{-1} per Ci/m^3)	Sediment (rad d^{-1} per Ci/m^2)
Cu-64	12.701 h	0.133	0.137	0.143	0.154	0.165	0.180	0.220	0.249	5.64E+00	5.34E+01
Zn-65	243.9 d	0.0289	0.0289	0.0544	0.0846	0.113	0.153	0.261	0.342	1.80E+01	1.50E+02
Zn-69M+D	13.76 h	0.0400	0.0400	0.0603	0.0842	0.107	0.138	0.221	0.282	1.48E+01	1.19E+02
Zn-69	57 m	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	1.79E-04	1.73E-03
As-76	26.32 h	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.31E+01	1.17E+02
Br-82	35.30 h	0.248	0.294	0.368	0.510	0.643	0.828	1.33	1.70	8.11E+01	7.12E+02
Br-83+D	2.39 h	0.363	0.363	0.364	0.364	0.364	0.365	0.366	0.367	2.23E-01	2.10E+00
Br-84	31.80 m	1.31	1.34	1.39	1.47	1.56	1.67	2.00	2.25	6.05E+01	4.36E+02
Br-85	2.87 m	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	2.06E+00	1.79E+01
Kr-83M	1.83 h	0.0438	0.0438	0.0438	0.0438	0.0438	0.0438	0.0438	0.438	3.29E-03	3.12E-01
Kr-85M	4.48 h	0.245	0.248	0.252	0.260	0.268	0.279	0.309	0.331	4.99E+00	4.93E+01
Kr-85	10.72 y	0.224	0.224	0.224	0.244	0.224	0.225	0.225	0.225	6.66E-02	6.30E-01
Kr-87	76.3 m	1.21	1.24	1.27	1.34	1.41	1.50	1.77	1.97	2.64E+01	2.03E+02
Kr-88	2.84 h	0.449	0.475	0.517	0.599	0.677	0.786	1.09	1.33	6.71E+01	4.85E+02
Rb-86	18.66 d	0.666	0.668	0.671	0.676	0.680	0.687	0.705	0.719	2.93E+00	2.46E+01
Rb-88	17.8 m	2.15	2.16	2.18	2.21	2.24	2.28	2.40	2.49	2.12E+01	1.58E+02
Rb-89	15.2 m	0.694	0.733	0.797	0.919	1.03	1.20	1.64	1.95	6.74E+01	5.21E+02
Sr-89	50.5 d	0.564	0.564	0.564	0.564	0.564	0.564	0.564	0.564	4.25E-03	3.73E-02
Sr-90	29.12 y	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	0	0
Sr-91	9.5 h	0.702	0.721	0.752	0.812	0.867	0.944	1.15	1.31	2.12E+01	1.85E+02

Table 3-4. Half-Lives and Energies (MeV dis^{-1}) for Selected Effective Radii (cm) of Aquatic Organisms and External Dose Rate Factors (Continued)

Radionuclide	Half-life	Energy by Radius (cm)								Dose Rate Factors	
		1.4	2	3	5	7	10	20	30	Immersion (rad d^{-1} per Ci/m^3)	Sediment (rad d^{-1} per Ci/m^2)
Sr-92	2.71 h	0.249	0.272	0.310	0.381	0.449	0.543	0.805	1.00	4.11E+01	3.26E+02
Y-90	64.0 h	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0	0
Y-91M	49.71 m	0.518	0.0615	0.0773	0.107	0.135	0.174	0.280	0.355	1.59E+01	1.50E+02
Y-91	58 51 d	0.590	0.590	0.591	0.591	0.591	0.591	0.592	0.592	1.11E-01	9.07E-01
Y-92	3.54 h	1.47	1.47	1.48	1.49	1.51	1.52	1.57	1.61	7.81E+00	6.63E+01
Y-93	10.1 h	1.18	1.18	1.18	1.19	1.19	1.20	1.22	1.23	2.88E+00	2.34E+01
Xr-95	63.98 d	0.227	0.254	0.297	0.380	0.458	0.565	0.857	1.07	2.25E+01	2.05E+02
Xr-97	16.90 h	0.763	0.778	0.802	0.848	0.891	0.951	1.11	1.23	6.58E+00	4.77E+01
Nb-95	35.15 d	0.0767	0.0906	0.113	0.156	0.197	0.253	0.405	0.515	2.35E+00	2.13E+02
Nb-97	72.1 m	0.500	0.512	0.532	0.570	0.606	0.656	0.790	0.887	2.01E+01	1.86E+02
Mo-99+D	66.0 h	0.419	0.423	0.430	0.444	0.457	0.475	0.524	0.561	4.74E+00	4.38E+01
Tc-99M	6.02 h	0.132	0.134	0.138	0.144	0.150	0.158	0.181	0.199	4.08E+00	4.05E+01
Tc-99	2.13E5 y	0.084	0.084	0.084	0.084	0.084	0.084	0.084	0.084	1.69E-05	1.72E-04
Tc-101	14.2 m	0.485	0.492	0.503	0.524	0.543	0.570	0.643	0.697	1.04E+01	1.01E+02
Ru-103+D	39.28 d	0.116	0.125	0.140	0.168	0.194	0.230	0.328	0.399	1.44E+01	1.37E+02
Ru-105+D	4.44 h	0.496	0.508	0.527	0.563	0.597	0.644	0.772	0.865	2.38E+01	2.21E+02
Ru-106+D	368.2 d	1.44	1.44	1.45	1.46	1.47	1.49	1.53	1.56	0	0
Rh-105	35.36 h	0.158	0.159	0.162	0.167	0.172	0.179	0.198	0.212	2.34E+00	2.30E+01
Pd-109+D	13.427 h	0.389	0.389	0.389	0.389	0.389	0.390	0.390	0.391	2.05E-02	1.95E-01
Ag-110M+D	249.9 d	0.188	0.235	0.311	0.456	0.593	0.782	1.30	1.68	8.41E+01	7.34E+02

Table 3-4. Half-Lives and Energies (MeV dis^{-1}) for Selected Effective Radii (cm) of Aquatic Organisms and External Dose Rate Factors (Continued)

		Energy by Radius (cm)								Dose Rate Factors	
Radionuclide	**Half-life**	**1.4**	**2**	**3**	**5**	**7**	**10**	**20**	**30**	**Immersion (rad d^{-1} per Ci/m^3)**	**Sediment (rad d^{-1} per Ci/m^2)**
Ag-111	7.45 d	0.361	0.362	0.362	0.364	0.365	0.367	0.372	0.376	7.95E-01	7.78E+00
Sn-125	9.64 d	0.906	0.907	0.910	0.914	0.919	0.925	0.942	0.954	9.59E+00	7.97E+01
Sb-124	60.20 d	0.459	0.491	0.544	0.644	0.739	0.871	1.24	1.51	5.89E+01	4.82E+02
Sb-125	2.77 y	0.105	0.113	0.126	0.150	0.173	0.205	0.291	0.353	1.27E+01	1.21E+02
Sb-127	3.85 d	0.433	0.448	0.472	0.518	0.561	0.620	0.782	0.899	2.00E+01	1.86E+02
Te-125M	58 d	0.111	0.111	0.112	0.112	0.112	0.113	0.113	0.114	3.40E-01	5.75E+00
Te-127M	109 d	0.00197	0.00197	0.00197	0.00198	0.00199	0.00200	0.00203	0.00205	1.09E-01	1.83E+00
Te-127	9.35 h	0.223	0.223	0.223	0.223	0.223	0.224	0.224	0.224	1.45E-01	1.40E+00
Te-129M+D	33.6 d	0.599	0.601	0.605	0.612	0.619	0.627	0.651	0.667	1.03E+00	1.01E+01
Te-129	69.6 m	0.535	0.538	0.541	0.548	0.555	0.563	0.585	0.601	1.63E+00	1.56E+01
Te-131	25.0 m	0.786	0.791	0.800	0.817	0.833	0.855	0.916	0.961	1.29E+01	1.19E+02
Te-132	78.2 h	0.121	0.125	0.131	0.143	0.154	0.169	0.211	0.242	6.66E+00	6.79E+01
Te-133M+D	55.4 m	0.502	0.542	0.605	0.726	0.840	0.998	1.43	1.74	6.93E+01	6.00E+02
Te-134	41.8 m	0.114	0.117	0.122	0.130	0.138	0.148	0.175	0.194	2.64E+01	2.49E+02
I-129	1.57E7 y	0.0602	0.0628	0.0652	0.0694	0.0728	0.0769	0.0844	0.0872	2.93E-01	6.03E+00
Te-131M	30 h	0.269	0.291	0.327	0.369	0.460	0.550	0.796	0.978	4.41E+01	3.86E+02
I-130	12.36 h	0.388	0.427	0.490	0.611	0.724	0.881	1.31	1.61	6.47E+01	5.97E+02
I-131	8.04 d	0.206	0.213	0.224	0.245	0.266	0.293	0.368	0.422	1.14E+01	1.11E+02
I-132	2.30 h	0.581	0.624	0.693	0.826	0.950	1.12	1.59	1.94	7.01E+01	6.27E+02
I-133	20.8 h	0.467	0.478	0.497	0.533	0.566	0.613	0.738	0.829	1.82E+01	1.69E+02

Table 3-4. Half-Lives and Energies (MeV dis^{-1}) for Selected Effective Radii (cm) of Aquatic Organisms and External Dose Rate Factors (Continued)

Radionuclide	Half-life	Energy by Radius (cm)								Dose Rate Factors	
		1.4	2	3	5	7	10	20	30	Immersion (rad d^{-1} per Ci/m^3)	Sediment (rad d^{-1} per Ci/m^2)
I-134	52.6 m	0.779	0.838	0.934	1.12	1.29	1.53	2.19	2.67	8.16E+01	7.07E+02
I-135	6.61 h	0.481	0.514	0.566	0.667	0.761	0.893	1.26	1.53	4.96E+01	3.97E+02
Xe-131M	11.9 d	0.136	0.136	0.136	0.137	0.137	0.137	0.138	0.139	2.85E-01	5.01E+00
Xe-133M	2.188 d	0.176	0.177	0.178	0.180	0.182	0.184	0.191	0.196	9.23E-01	1.14E+01
Xe-133	5.245 d	0.137	0.137	0.138	0.140	0.141	0.143	0.148	0.152	1.15E+00	1.39E+01
Xe-135M	15.29 m	0.118	0.126	0.139	0.163	0.186	0.217	0.302	0.363	1.28E+01	1.21E+02
Xe-135	9.09 h	0.330	0.335	0.342	0.355	0.368	0.386	0.434	0.469	7.51E+00	7.42E+01
Xe-137	3.84 m	1.68	1.68	1.68	1.69	1.70	1.71	1.74	1.76	5.67E+00	5.18E+01
Xe-138	14.17 m	0.505	0.527	0.562	0.630	0.694	0.784	1.04	1.23	3.73E+01	2.88E+02
Cs-134M	2.90 h	0.0483	0.0496	0.0517	0.0558	0.0597	0.0652	0.0805	0.0922	6.58E-01	7.86E+00
Cs-134	2.062 y	0.230	0.259	0.306	0.396	0.480	0.596	0.913	1.14	4.74E+01	4.33E+02
Cs-135	2.3E6 y	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0	0
Cs-136	13.1 d	0.233	0.273	0.337	0.458	0.573	0.732	1.17	1.49	6.68E+01	5.86E+02
^{137}Cs+D	30.3 y	0.257	0.267	0.284	0.316	0.346	0.388	0.500	0.582	1.80E+01	1.67E+02
Cs-138	32.2 m	1.18	1.22	1.27	1.38	1.48	1.62	2.02	2.32	7.56E+01	5.89E+02
Cs-139	9.4 m	1.61	1.61	1.62	1.64	1.66	1.68	1.75	1.79	9.89E+00	7.48E+01
Ba-139	82.7 m	0.927	0.927	0.929	0.931	0.933	0.936	0.944	0.950	1.10E+00	1.06E+01
Ba-140	12.74 d	0.315	0.320	0.328	0.343	0.357	0.376	0.428	0.465	5.62E+00	5.42E+01
Ba-141	18.27 m	1.10	1.11	1.12	1.16	1.19	1.23	1.36	1.44	2.74E+01	2.45E+02
Ba-142	10.6 m	0.601	0.622	0.656	0.722	0.783	0.869	1.10	1.28	2.79E+01	2.42E+02

Table 3-4. Half-Lives and Energies (MeV dis^{-1}) for Selected Effective Radii (cm) of Aquatic Organisms and External Dose Rate Factors (Continued)

Radionuclide	Half-life	Energy by Radius (cm)								Dose Rate Factors	
		1.4	2	3	5	7	10	20	30	Immersion (rad d^{-1} per Ci/m^3)	Sediment (rad d^{-1} per Ci/m^2)
La-140	40.272 h	0.698	0.734	0.793	0.907	1.01	1.16	1.58	1.89	7.29E+01	5.84E+02
La-141	3.93 h	0.966	0.967	0.967	0.969	0.970	0.972	0.977	0.981	1.32E+00	1.04E+01
La-142	92.5 m	0.937	0.973	1.03	1.14	1.25	1.40	1.82	2.14	9.26E+01	6.68E+02
Ce-141	32.501 d	0.173	0.174	0.175	0.179	0.182	0.187	0.199	0.209	2.39E+00	2.41E+01
Ce-143	33.0 h	0.420	0.426	0.435	0.453	0.470	0.493	0.555	0.601	7.92E+00	7.81E+01
Ce-144+D	284.3 d	1.32	1.32	1.32	1.33	1.33	1.33	1.34	1.35	5.70E-01	5.92E+00
Pr-143	13.56 d	0.314	0.314	0.314	0.314	0.314	0.314	0.314	0.314	2.72E-07	2.48E-06
Pr-144	17.28 m	1.23	1.23	1.23	1.24	1.24	1.24	1.24	1.25	1.06E+00	8.16E+00
Nd-147	10.98 d	0.257	0.257	0.264	0.272	0.280	0.291	0.320	0.342	4.05E+00	4.05E+01
Pm-147	2.6234 y	0.0620	0.0620	0.0620	0.0620	0.0620	0.0620	0.0620	0.0620	1.14E-04	1.12E-03
Pm-148	5.37 d	0.727	0.727	0.755	0.788	0.819	0.862	0.982	1.07	1.77E+01	1.47E+02
Pm-149	53.08 h	0.366	0.367	0.367	0.367	0.368	0.368	0.370	0.371	3.51E-01	3.42E+00
Pm-151	28.40 h	0.327	0.332	0.340	0.356	0.370	0.390	0.445	0.484	1.00E+01	9.84E+01
Sm-153	46.7 h	0.270	0.271	0.272	0.273	0.275	0.277	0.283	0.288	1.67E+00	1.94E+01
Eu-154	8.8 y	0.311	0.311	0.38	0.428	0.487	0.570	0.798	0.965	3.86E+01	3.32E+02
Eu-156	15.19 d	0.471	0.490	0.521	0.580	0.636	.714	0.930	1.09	4.36E+01	3.45E+02
W-181	121.2 d	0.00316	0.00316	0.00317	0.00318	0.00320	0.0032	0.00327	0.00331	1.11E+00	1.28E+01
W-185	75.1 d	0.144	0.144	0.144	0.144	0.144	0.144	0.144	0.144	8.66E-04	8.52E-03
W-187	23.9 h	0.331	0.339	0.339	0.379	0.403	0.437	0.529	0.595	1.44E+01	1.35E+02
U-234	2.445E5 y	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	5.10E-03	2.21E-01

Table 3-4. Half-Lives and Energies (MeV dis^{-1}) for Selected Effective Radii (cm) of Aquatic Organisms and External Dose Rate Factors (Continued)

Radionuclide	Half-life	Energy by Radius (cm)								Dose Rate Factors	
		1.4	2	3	5	7	10	20	30	Immersion (rad d^{-1} per Ci/m^3)	Sediment (rad d^{-1} per Ci/m^2)
U-235+D	7.04E8 y	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.71E+00	4.68E+01
U-237	6.75 d	0.160	0.160	0.160	0.180	0.180	0.180	0.220	0.220	4.19E+00	4.41E+01
U-238+D	4.468E9 y	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	3.53E-03	1.77E-01
Np-238	2.117 d	0.263	0.270	0.270	0.306	0.327	0.357	0.440	0.513	1.72E+01	1.47E+02
Np-239	2.355 d	0.203	0.205	0.205	0.212	0.217	0.223	0.240	0.260	5.18E+00	5.26E+01
Pu-238	87.74 y	5.51	5.51	5.51	5.51	5.51	5.51	5.51	5.51	3.07E-03	2.35E-01
^{239}Pu	24065 y	5.15	5.15	5.15	5.15	5.15	5.15	5.15	5.15	2.67E-03	1.04E-01
Pu-240	6537 y	5.16	5.16	5.16	5.16	5.16	5.16	5.16	5.16	3.01E-03	2.25E-01
Pu-241+D	14.4 y	0.00535	0.00535	0.00535	0.00535	0.00535	0.00535	0.00535	0.00636	0	0
Pu-242	3.763E5 y	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.8	2.55E-03	1.87E-01
Am-241	432.2 y	5.51	5.51	5.51	5.52	5.52	5.52	5.52	5.4	6.38E-01	8.19E+00
Am-243+D	7380 y	5.28	5.28	5.28	5.29	5.29	5.29	5.30	5.3	1.67E+00	1.89E+01
Cm-242	162.8 d	6.11	6.11	6.11	6.11	6.11	6.11	6.11	6.1	3.42E-03	2.56E-01
Cm-244	18.11 y	5.80	5.80	5.80	5.80	5.80	5.80	5.80	5.8	2.93E-03	2.27E-01
Cf-252	2.638 y	12.2	12.2	12.2	12.2	12.2	12.2	12.2	16.5	2.61E-03	1.74E-01

Table 3-5. Recommended Parameters for Use in the CRITR2 Program

Organism	Body Mass (kg)	Effective Radius (cm)	Source of Nuclide	Intake Rate (kg d^{-1})	Exposure Fraction		
					Sediment	Immersion	Water Surface
Primary							
Fish	(a)	5	Water	(a)	0	1	0
Crustacea	(a)	2	Water	(a)	1	0	1
Mollusks	(a)	2	Water	(a)	1	0	1
Algae	(a)	2	Water	(a)	0	1	0
Secondary							
Muskrat	1	6	Plant	0.10	0.3	0.3	0
Raccoon	9	20	Crustacean, Mollusk, and Fish	0.80	0.2	0	0
Heron	5	10	Fish	0.60	0.3	0	0.3
Duck	1	5	Plant, Fish	0.10	0.2	0.3	0.5

(a) Not required for calculation of dose to primary organisms.

3.4 RESLs for Aquatic Organisms

The DOE benchmark radionuclide concentrations in water and soil that correspond to 1.0 rad/day were derived using the simplified mathematical models described above and the default parameters employed in the CRITR computer code. We have elected not to adopt the DOE benchmark values as our RESLs for aquatic organisms for the following three reasons:

- They are based on a NOREL of 1 rad/day, as opposed to 0.1 rad/day, which we have selected based on our review of the literature (see Appendix D)
- They do not include an RBE to account for the potentially greater radiobiological effects of exposure to alpha emitters, and
- They do not give sufficient consideration to external and internal exposure to fish eggs and embryos to alpha emitters.

The introduction to this guide discusses issues related to localized doses to alpha emitters and the distribution of internally deposited radionuclides. This section addresses these issues as applied to aquatic organisms and how these issues pertain to the derivation of screening levels. We then derive RESLs taking these issues into consideration.

3.4.1 Exposure to Alpha Emitters

Pentreath and Fowler (1979) describe the challenges associated with designing experiments to evaluate the dose-response relationship for exposure to fish eggs and developing embryos to alpha emitters. The distribution of the radionuclides in the eggs and embryos is often uncertain, which prevents a reliable assessment of the dose. In this guide, we address the issue of alpha emitters by assuming that the concentration of each radionuclide in the eggs and developing embryo is the same as in sediment. Given the high distribution coefficients for sediment, this approach will tend to bound the doses to eggs and embryos in intimate contact with the sediment.

The energy deposition of 1 pCi/g of a typical 5 MeV alpha emitter in sediment is derived as follows:

D (rad/day per pCi/g) = 1 pCi/g x .037 dis/sec per pCi x 5 Mev/dis x 1.6e-6 erg/Mev x .01 rad-g/erg x 3600 sec/hr x 24 hr/day = 2.6e-04 rad/day per pCi/g.

An organism immersed in the sediment will experience this absorbed dose if it is small relative to the range of alpha emitters in tissue/water (i.e. about 70 microns) and it does not have a protective outer layer which will shield the alpha particle. In addition, if the organism accumulates the alpha emitter internally to a concentration that is comparable to the concentration of the alpha emitter in the sediment, it will also experience this dose. The implication is that, if the concentration of the alpha emitter in sediment exceeds about 100 pCi/g, the effective dose (which includes an RBE of 5) could exceed 0.1 rem/day. Later in this section, we use 100 pCi/g as our upper limit on the screening level of alpha emitters in sediment.

3.4.2 Organ Doses

The distribution of internally deposited alpha emitters in aquatic organisms is non-uniform, resulting in relatively high doses to certain organs and tissues, such as bone, gills and liver. Because of this, the use of the concentration factor for the organism, followed by an assessment of the absorbed dose to the whole organism could be misleading. One way to address this issue is to determine the overall body burden of a given radionuclide in an organism using the concentration factor approach, then apply an empirically determined adjustment factor to determine the radionuclide concentrations in the various organs. We can then, in theory, determine the dose to the organs, multiply by a weighting factor specific for each organ, multiply by an RBE, and then sum the doses to the various organs. Due to the unavailability of this level detailed information for all organisms and radionuclides, we derived RESLs simply by applying an RBE of 5 to the internal dose derived using the concentration factor approach. This is considered a reasonable approach because of the offsetting effects of the localized concentrations in specific organs and the weighting factors for the organs. For example, though the bone or liver may experience a ten to fifty times higher absorbed dose than the average dose to the overall organism from an internally deposited alpha or beta emitter, the weighting factor for the organ will offset this effect. For example, as discussed in Section 1.3.1, the concentration of uranium in bone in mullet was observed to be 41 times higher than in muscle. However, this effect is offset by the fact that, when deriving the effective whole body dose to bone, a weighting factor of 0.03 (i.e., a 33-fold reduction) is applied. With regard to eggs and reproductive organs, the literature reveals that the radionuclide concentrations in these organs and tissues are not that different than in muscle tissue (i.e., perhaps a factor of two higher). Hence, the concentration factor approach, including an RBE of 5, will not significantly underestimate the absorbed doses to these tissues. We recognize that these simplifying assumption are not the best solution to these issues, but, given the complexity of the problem, they represent approximations that we believe will not result in a significant underestimate of the potential adverse effects associated with a given radionuclide concentration in the environment.

3.4.3 Derivation of RESLs for the Aquatic Environment

Tables 3-6 and 3-7 present the RESLs for water and sediment, respectively. The water RESLs were derived using CRITR, which is a computer code developed by Soldat and Baker (1992) at Pacific Northwest Laboratories for implementing the models described above. All values are based on the assumption that the fish spends all its time away from the sediment, or that the sediment is not contaminated. Issues related to contaminated sediment are addressed in Table 3-7.

As may be noted, Table 3-6 presents several columns of values , each representing increasing levels of conservatism. The first column presents the DOE benchmark values. They are based on the default bioaccumulation factors used by CRITR for freshwater fish, and a NOREL of 1 rad/day. The second column is the same as the first, except it is based on a NOREL of

0.1 rad/day. Note the 10-fold difference in the values. The third column is also based on a NOREL of 0.1 rad/day, but uses the high-end bioaccumulation factors presented in Table 3-8 instead of the default CRITR values. For example, note that CRITR uses a bioaccumulation factor of 60 for Sr-90 but the high-end bioaccumulation factor we used here is 1000, a 60-fold difference. The fourth column is the same as the first, except an RBE of 5 is used for alpha emitters.

These four sets of values are provided because they represent the range of RESLs that may be considered appropriate. Clearly, depending on your level of risk aversion, the RESLs can vary by several orders of magnitude. In this guide, we use the most conservative values, i.e., column four. The values in column four reflect adjustments to the input to CRITR to accommodate a NOREL of 0.1 rad/day, high end bioaccumulation factors, and an RBE of 5 for alpha emitters.

Table 3-7 presents the sediment RESLs. The values are expressed in units of pCi/g of sediment that result in 0.1 rem/day to sediment dwelling organisms. The values consider external and internal exposure to fish, fish eggs, and developing embryos, including the use of an RBE of 5 for both internally deposited alpha emitters and external exposure to alpha emitters that may penetrate to sensitive tissue. All calculational parameters are presented so that we may be able to describe fully how the RESLs were derived.

External doses are based on the assumption that the energy emitted per gram of sediment is also the energy absorbed per gram of organism in the sediment. This is considered appropriate for organisms that are small relative to the range of the emissions, such as fish eggs and developing embryos. Internal doses were derived by first estimating the radionuclide concentration in the interstitial water based on the distribution coefficient for sand listed in Table IX of IAEA 1994, and then using high-end bioaccumulation factors for freshwater organisms (see Table 3-8). The internal dose was then derived assuming that all of the beta and alpha energy and 20% of the gamma energy is absorbed. In addition, an RBE of 5 is applied to the alpha energy.

3.4.4 Benchmark Comparison

The RESLs presented in Tables 3-6 and 3-7 are based on a number of modeling assumptions which tend to result in highly restrictive RESLs. It is, therefore, not unreasonable to ask whether, in fact, adverse effects have been observed at radionuclide concentrations in water and sediment that exceed these levels. Whicker and Schultz (1982) present an overview of chronic irradiation investigations of aquatic organisms which can serve as a "reality check" for the RESLs. Table 3-9 summarizes those studies where no effects were observed, and compares these concentrations with the RESLs.

Table 3-9 reveals that the radionuclide concentrations in water where effects have and have not been observed cover several orders of magnitude and reveal no consistent pattern. The implication is that, depending on the species and biological endpoints, the NOREL for a given radionuclide can vary by several orders of magnitude. In addition, the results probably reflect some of the concerns raised by many of the authors in IAEA 1979 regarding the difficulty associated with designing and interpreting the results of investigations on the effects of chronic exposures of aquatic organisms to incorporated radionuclides. In addition, the ecological significance of the results of the studies is also difficult to interpret. For example, would the stability and diversity of an ecosystem be adversely affected by environmental agents that temporarily have the types of effects observed in the cited studies, which include depressed growth rate, increased chromosome breaks, and increased developmental abnormalities? This issue begs the question of the meaning of a NOREL for an individual species as applied to ecological impacts of environmental agents. This issue is explored in Chapter 3 of IAEA 1976.

Another approach to exploring the merits of the derived RESLs, is to compare the values to the radionuclide concentrations observed in water and sediment in the natural environment and at sites contaminated with radionuclides. Table 3-10 summarizes some of the literature on this topic. Chapter 3 of IAEA 1976 summarizes observations made on the "health" of the ecosystems that have experienced elevated levels of radionuclides in water and sediment, as follows:

- The fecundity of populations of fish, Gambusia affinis, subject to chronic irradiation in White Oak creek, USA, was higher than that of control populations
- Beneficial effects have been observed in populations of chinook salmon
- The catch of plaice in the North Irish Sea has been closely follows and no evidence of adverse effects on fish have been observed

An important observation is the difference in the RESLs developed here and DOE's benchmark values. For example, for alpha emitters, the RESLs are two orders of magnitude more restrictive. In light of these radioecological studies, both the benchmarks developed by DOE and also the screening levels developed here can be supported in spite of their large differences. This is basically due to large uncertainties in the doses associated with a given level of a radionuclide in water or sediment and the effects of those doses on the organisms and ecosystem. Both the benchmarks and RESLs should be used with a full appreciation of their limitations.

Table 3-6. RESLs for the Aquatic Environment (pCi/L)

	RESL (water)			
	1	**2**	**3**	**4**
Nuclide	**NOREL of 1.0 rad/day Default CRIT2 CF**	**NOREL of 0.1 rad/day Default CRIT2 CF**	**NOREL of 0.1 rad/day High-End CF**	**NOREL of 0.1 rem/day High-End CF with RBE=5**
H-3	3.33e+09	3.33e+08	3.33e+08	3.33e+08
C-14	7.69e+03	7.69e+02	7.69e+02	7.69e+02
N-13	2.00e+02	2.00e+01	1.52e+01	1.52e+01
F-18	4.35e+06	4.35e+05	4.35e+05	4.35e+05
NA-22	1.70e+06	1.70e+05	3.75e+04	3.75e+04
NA-24	8.06e+05	8.06e+04	1.81e+04	1.81e+04
P-32	5.56e+02	5.56e+01	2.78e+01	2.78e+01
AR-39	0.00e+00	0.00e+00	0.00e+00	0.00e+00
AR-41	2.56e+07	2.56e+06	2.56e+06	2.56e+06
SC-46	4.85e+05	4.85e+04	4.85e+04	4.85e+04
CR-51	1.82e+07	1.82e+06	1.85e+05	1.85e+05
MN-54	3.20e+05	3.20e+04	3.20e+04	3.20e+04
MN-56	3.70e+04	3.70e+03	3.70e+03	3.70e+03
FE-55	1.35e+07	1.35e+06	1.35e+05	1.35e+05
FE-59	3.40e+05	3.40e+04	3.44e+03	3.44e+03
CO-57	1.31e+06	1.31e+05	1.19e+05	1.19e+05
CO-58	3.66e+05	3.66e+04	3.41e+04	3.41e+04
CO-60	1.48e+05	1.48e+04	1.34e+04	1.34e+04
NI-63	1.11e+07	1.11e+06	1.11e+06	1.11e+06
NI-65	0.00e+00	0.00e+00	2.76e+04	2.76e+04
CU-64	6.23e+05	6.23e+04	5.00e+03	5.00e+03
ZN-65	2.32e+05	2.32e+04	7.68e+03	7.68e+03
ZN-69M+D	2.32e+05	2.32e+04	7.69e+03	7.69e+03
ZN-69	2.32e+05	2.32e+04	7.69e+03	7.69e+03
AS-76	4.35e+04	4.35e+03	4.35e+03	4.35e+03
BR-82	9.92e+04	9.92e+03	9.02e+03	9.02e+03
BR-83+D	1.33e+05	1.33e+04	1.28e+04	1.28e+04
BR-84	3.33e+04	3.33e+03	3.12e+03	3.12e+03

Table 3-6. RESLs for the Aquatic Environment (pCi/L) (continued)

Nuclide	RESL (water)			
	1	2	3	4
	NOREL of 1.0 rad/day Default CRIT2 CF	NOREL of 0.1 rad/day Default CRIT2 CF	NOREL of 0.1 rad/day High-End CF	NOREL of 0.1 rem/day High-End CF with RBE=5
BR-85	4.76e+04	4.76e+03	4.55e+03	4.55e+03
KR-83M	3.03e+11	3.03e+10	3.03e+10	3.03e+10
KR-85M	2.00e+08	2.00e+07	2.00e+07	2.00e+07
KR-85	2.00e+08	2.00e+07	2.00e+07	2.00e+07
KR-87	3.85e+07	3.85e+06	3.85e+06	3.85e+06
KR-88	1.49e+07	1.49e+06	1.49e+06	1.49e+06
RB-86	1.45e+04	1.45e+03	3.23e+02	3.23e+02
RB-88	4.35e+03	4.35e+02	1.00e+02	1.00e+02
RB-89	1.06e+04	1.06e+03	2.38e+02	2.38e+02
SR-89	5.88e+05	5.88e+04	3.45e+03	3.45e+03
SR-90	2.86e+05	2.86e+04	1.72e+03	1.72e+03
SR-91	3.97e+05	3.97e+04	2.38e+03	2.38e+03
SR-92	8.06e+05	8.06e+04	4.99e+03	4.99e+03
Y-90	7.14e+05	7.14e+04	7.14e+04	7.14e+04
Y-91M	5.68e+06	5.68e+05	5.68e+05	5.68e+05
Y-91	5.68e+06	5.68e+05	5.68e+05	5.68e+05
Y-92	4.33e+05	4.33e+04	4.33e+04	4.33e+04
Y-93	5.55e+05	5.55e+04	5.55e+04	5.55e+04
ZR-95	1.72e+05	1.72e+04	1.72e+04	1.72e+04
ZR-97	7.69e+04	7.69e+03	7.69e+03	7.69e+03
NB-95	4.13e+05	4.13e+04	4.17e+02	4.17e+02
NB-97	1.13e+05	1.13e+04	1.14e+02	1.14e+02
MO-99+D	4.26e+06	4.26e+05	4.26e+05	4.26e+05
TC-99M	6.49e+06	6.49e+05	1.68e+05	1.68e+05
TC-99	6.49e+06	6.49e+05	1.68e+05	1.68e+05
TC-101	1.82e+06	1.82e+05	4.74e+04	4.74e+04
RU-103+D	1.00e+07	1.00e+06	5.83e+04	5.83e+04
RU-105+D	3.18e+06	3.18e+05	1.72e+04	1.72e+04
RU-106+D	1.33e+06	1.33e+05	6.67e+03	6.67e+03
RN-105	0.00e+00	0.00e+00	0.00e+00	0.00e+00
PD-109+D	5.00e+06	5.00e+05	5.00e+05	5.00e+05
AG-110M+	3.18e+06	3.18e+05	4.19e+04	4.19e+04

Table 3-6. RESLs for the Aquatic Environment (pCi/L) (continued)

Nuclide	RESL (water)			
	1	2	3	4
	NOREL of 1.0 rad/day Default CRIT2 CF	**NOREL of 0.1 rad/day Default CRIT2 CF**	**NOREL of 0.1 rad/day High-End CF**	**NOREL of 0.1 rem/day High-End CF with RBE=5**
AG-111	5.24e+06	5.24e+05	5.26e+04	5.26e+04
SN-125	7.14e+03	7.14e+02	7.14e+02	7.14e+02
SB-124	2.98e+05	2.98e+04	1.50e+04	1.50e+04
SB-125	1.28e+06	1.28e+05	6.61e+04	6.61e+04
SB-127	3.68e+05	3.68e+04	1.88e+04	1.88e+04
TE-125M	4.35e+05	4.35e+04	1.75e+04	1.75e+04
TE-127M	2.43e+07	2.43e+06	9.99e+05	9.99e+05
TE-127	2.43e+07	2.43e+06	9.99e+05	9.99e+05
TE-129M+	7.69e+04	7.69e+03	3.23e+03	3.23e+03
TE-129	7.69e+04	7.69e+03	3.23e+03	3.23e+03
TE-131M	1.23e+05	1.23e+04	4.99e+03	4.99e+03
TE-131	1.23e+05	1.23e+04	4.99e+03	4.99e+03
TE-132	3.44e+05	3.44e+04	1.37e+04	1.37e+04
TE-133M+	6.64e+04	6.64e+03	2.70e+03	2.70e+03
TE-134	3.67e+05	3.67e+04	1.49e+04	1.49e+04
I-129	7.13e+06	7.13e+05	4.76e+04	4.76e+04
I-130	7.33e+05	7.33e+04	5.25e+03	5.25e+03
I-131	1.96e+06	1.96e+05	1.33e+04	1.33e+04
I-132	5.65e+05	5.65e+04	3.99e+03	3.99e+03
I-133	8.94e+05	8.94e+04	6.24e+03	6.24e+03
I-134	4.20e+05	4.20e+04	2.93e+03	2.93e+03
I-135	6.90e+05	6.90e+04	4.75e+03	4.75e+03
XE-131M	3.57e+09	3.57e+08	3.57e+08	3.57e+08
XE-133M	1.09e+09	1.09e+08	1.09e+08	1.09e+08
XE-133	1.09e+09	1.09e+08	1.09e+08	1.09e+08
XE-135M	7.69e+07	7.69e+06	7.69e+06	7.69e+06
XE-135M	7.69e+07	7.69e+06	7.69e+06	7.69e+06
XE-137	1.75e+08	1.75e+07	1.75e+07	1.75e+07
XE-138	2.70e+07	2.70e+06	2.70e+06	2.70e+06
CS-134M	1.75e+05	1.75e+04	1.16e+04	1.16e+04
CS-134	1.75e+05	1.75e+04	1.16e+04	1.16e+04
CS-135	1.69e+05	1.69e+04	1.12e+04	1.12e+04

Table 3-6. RESLs for the Aquatic Environment (pCi/L) (continued)

Nuclide	RESL (water)			
	1	2	3	4
	NOREL of 1.0 rad/day Default CRIT2 CF	**NOREL of 0.1 rad/day Default CRIT2 CF**	**NOREL of 0.1 rad/day High-End CF**	**NOREL of 0.1 rem/day High-End CF with RBE=5**
CS-136	2.12e+04	2.12e+03	1.43e+03	1.43e+03
CS-137+D	3.12e+04	3.12e+03	2.04e+03	2.04e+03
CS-138	7.14e+03	7.14e+02	4.76e+02	4.76e+02
CS-139	5.88e+03	5.88e+02	4.00e+02	4.00e+02
BA-139	5.23e+06	5.23e+05	1.05e+04	1.05e+04
BA-140	1.32e+07	1.32e+06	2.85e+04	2.85e+04
BA-141	3.75e+06	3.75e+05	8.31e+03	8.31e+03
BA-142	5.62e+06	5.62e+05	1.35e+04	1.35e+04
LA-140	6.79e+05	6.79e+04	6.79e+04	6.79e+04
LA-141	6.66e+05	6.66e+04	6.66e+04	6.66e+04
LA-142	5.28e+05	5.28e+04	5.28e+04	5.28e+04
CE-141	3.54e+06	3.54e+05	2.17e+04	2.17e+04
CE-142	0.00e+00	0.00e+00	0.00e+00	0.00e+00
CE-144+D	5.00e+05	5.00e+04	2.94e+03	2.94e+03
PR-143	6.25e+05	6.25e+04	6.25e+04	6.25e+04
PR-144	1.56e+05	1.56e+04	1.56e+04	1.56e+04
NB-147	0.00e+00	0.00e+00	0.00e+00	0.00e+00
PM-147	1.05e+07	1.05e+06	1.05e+06	1.05e+06
PM-148	8.21e+05	8.21e+04	8.21e+04	8.21e+04
PM-149	1.78e+06	1.78e+05	1.78e+05	1.78e+05
PM-151	1.79e+06	1.79e+05	1.79e+05	1.79e+05
SM-153	2.84e+06	2.84e+05	2.84e+05	2.84e+05
EU-154	8.78e+05	8.78e+04	8.78e+04	8.78e+04
EU-156	6.48e+05	6.48e+04	6.48e+04	6.48e+04
W-181	5.00e+05	5.00e+04	5.00e+04	5.00e+04
W-185	5.00e+05	1.12e+03	5.00e+04	5.00e+04
W-187	4.35e+03	4.35e+02	4.35e+02	4.35e+02
U-234	4.00e+05	4.00e+04	4.00e+04	8.00e+03
U-235+D	4.16e+05	4.16e+04	4.16e+04	8.32e+03
U-237	1.04e+07	1.04e+06	1.04e+06	2.08e+05
U-238+D	4.55e+05	4.55e+04	4.55e+04	9.10e+03
NP-238	2.05e+06	2.05e+05	2.05e+05	4.10e+04

Table 3-6. RESLs for the Aquatic Environment (pCi/L) (continued)

	RESL (water)			
	1	**2**	**3**	**4**
Nuclide	**NOREL of 1.0 rad/day Default CRIT2 CF**	**NOREL of 0.1 rad/day Default CRIT2 CF**	**NOREL of 0.1 rad/day High-End CF**	**NOREL of 0.1 rem/day High-End CF with RBE=5**
NP-239	2.98e+06	2.98e+05	2.98e+05	5.96e+04
PU-238	1.18e+05	1.18e+04	1.18e+04	2.36e+03
PU-239	1.27e+05	1.27e+04	1.27e+04	2.54e+03
PU-240	1.27e+05	1.27e+04	1.27e+04	2.54e+03
PU-241+D	1.22e+08	1.22e+07	1.22e+07	2.44e+06
PU-242	1.33e+05	1.33e+04	1.33e+04	2.66e+03
AM-241	1.18e+05	1.18e+04	1.18e+04	2.36e+03
AM-243+D	1.23e+05	1.23e+04	1.23e+04	2.46e+03
CM-242	1.06e+05	1.06e+04	1.06e+04	2.12e+03
CM-244	1.12e+05	1.12e+04	1.12e+04	2.24e+03
CF-252	6.25e+04	6.25e+03	6.25e+03	1.25e+03

Table 3-7. RESLs for Freshwater Sediment

Nuclide	MeV/disintegration*						CFs**	Kds***		Int Dose	Ext Dose	RESL
	Total	α	β^-	β^+	e^-	γ		Sand	Clay	rem/day per pCi/g	rem/day per pCi/g	pCi/g yielding 0.1 rem/day
Ac-227	33.8	32.3	0.96	0	0.129	0.403		450	2400	0.00e+00	8.34e-03	1.20e+01
Ag-108m	1.69	0.000	5.668E-2	8.184E-5	1.419E-2	1.62	100	90	180	9.24e-03	8.65e-05	1.07e+01
Ag-110m	2.82	0.000	8.121E-2	0.000	2.892E-3	2.73	100	90	180	2.24e-05	1.44e-04	6.01e+02
Am-241	5.54	5.48	0.000	0.000	2.940E-2	2.810E-2	300	2000	8100	4.83e-06	1.40e-03	7.10e+01
Am-243	5.76	5.26	0.115	0.000	0.153	0.230	300	2000	8100	2.10e-04	1.37e-03	6.32e+01
Bi-207	1.65	0.000	0.000	0.000	0.110	1.54		120	670	0.00e+00	8.44e-05	1.18e+03
C-14	4.947E-2	0.000	4.947E-2	0.000	0.000	0.000	50000			NC	2.53e-06	3.95e+04
Cd-109	0.107	0.000	0.000	0.000	8.044E-2	2.616E-2	5e4	74	540	1.71e-03	5.45e-06	5.83e+01
Ce-144	1.35	0.000	1.29	0.000	9.906E-3	5.136E-2	500	490	20000	4.47e-06	6.91e-05	1.36e+03
Cl-36	0.249	0.000	0.249	0.000	1.763E-5	1.586E-6				??	1.27e-05	NC
Cm-243	6.09	5.83	0.000	0.000	0.123	0.133	300	4000	5400	9.55e-07	1.50e-03	6.64e+01
Cm-244	5.80	5.80	0.000	0.000	6.439E-3	1.490E-3	300	4000	5400	1.12e-04	1.48e-03	6.27e+01
Cm-248	4.66	4.65	0.000	0.000	4.772E-3	1.054E-3	300	4000	5400	1.11e-04	1.19e-03	7.69e+01
Co-57	0.143	0.000	0.000	0.000	1.827E-2	0.125	330	60	540	6.54e-03	7.33e-06	1.53e+01
Co-60	2.60	0.000	9.579E-2	0.000	0.000	2.51	330	60	540	1.22e-05	1.33e-04	6.87e+02
Cs-134	1.72	0.000	0.157	0.000	5.169E-3	1.56	3000	270	1800	3.40e-04	8.81e-05	2.34e+02
Cs-135	5.630E-2	0.000	5.630E-2	0.000	0.000	0.000	3000	270	1800	2.69e-04	2.88e-06	3.67e+02
Cs-137	0.796	0.000	0.171	0.000	6.023E-2	0.566	3000	270	1800	3.20e-05	4.08e-05	1.37e+03
Eu-152	1.28	0.000	8.369E-2	0.000	4.028E-2	1.15	300			??	6.52e-05	ERR
Eu-154	1.53	0.000	0.225	0.000	4.847E-2	1.25	300			??	7.79e-05	ERR
Eu-155	0.122	0.000	4.544E-2	0.000	1.635E-2	6.058E-2	300			??	6.26e-06	ERR
Fe-55	5.664E-3	0.000	0.000	0.000	4.003E-3	1.661E-3	300	220	160	5.15e-06	2.90e-07	1.84e+04
Gd-153	0.152	0.000	0.000	0.000	4.186E-2	0.110				??	7.77e-06	ERR
H-3	5.685E-3	0.000	5.685E-3	0.000	0.000	0.000	1	1	1	3.27e-06	2.91e-07	2.81e+04
I-129	7.894E-2	0.000	4.090E-2	0.000	1.340E-2	2.464E-2	600	1	180	1.74e-04	4.04e-06	5.60e+02
Mn-54	0.840	0.000	0.000	0.000	3.820E-3	0.836	500	49	180	3.09e-05	4.30e-05	1.35e+03

Table 3-7. RESLs for Freshwater Sediment (continued)

Nuclide	MeV/disintegration*						CFs**	Kds***		Int Dose	Ext Dose	RESL
	Total	α	β^-	β^+	e^-	γ		Sand	Clay	rem/day per pCi/g	rem/day per pCi/g	pCi/g yielding 0.1 rem/day
Na-22	2.39	0.000	0.000	0.194	7.544E-5	2.19	100			??	1.22e-04	ERR
Nb-94	1.72	0.000	0.146	0.000	1.108E-3	1.57	30000	160	900	6.06e-03	8.78e-05	1.63e+01
Pa-231	5.45	5.38	0	0	0.0355	0.0372	10	540	2700	4.37e-07	1.38e-03	7.25e+01
Pb-210	5.73	5.3	0.396	0	0.0279	0.005	2000	270	540	1.02e-02	1.38e-03	8.63e+00
Pm-147	6.196E-2	0.000	6.196E-2	0.000	0.000	3.456E-6	200			??	0	ERR
Pu-238	5.50	5.49	0.000	0.000	8.260E-3	1.600E-3	300	540	4900	0	0.0014	71.1086
Pu-239	5.15	5.15	0.000	0.000	4.880E-3	6.540E-4	300	540	4900	0.0008	0.0013	47.6729
Pu-240	5.16	5.15	0.000	0.000	8.332E-3	1.526E-3	300	540	4900	0.0007	0.0013	48.79381
Pu-241	5.230E-3	0.000	5.230E-3	0.000	0.000	0.000	300	540	4900	0.0007	0	136.5701
Pu-242	4.92	4.91	0.000	0.000	6.839E-3	1.267E-3	300	540	4900	0	0.0013	79.60096
Pu-244	7.30	4.59	0.956	0.000	0.250	1.50	300	540	4900	0.0007	0.0013	49.74907
Ra-226	26.7	24	0.851	0	0.0851	1.77	200	490	9000	0.0005	0.0063	14.7344
Ra-226-ser**	32.4	29.3	1.247	0	0.113	1.775	200	490	9000	0.00253	0.0077	9.817559
Ra-228	1.37	0	0.375	0	0.0659	0.927	200	490	9000	0.00309	0	31.60296
Ru-106	1.63	0	1.42	0	0	0.207	200	55	400	0.0001	0	500.7307
Sb-125	0.690	0.000	8.644E-2	0.000	0.136	0.468	200	45	240	0.0003	0	272.0849
Sm-147	2.25	2.25	0.000	0.000	0.000	0.000		240	1300	0	0.001	173.7849
Sm-151	1.979E-2	0.000	1.963E-2	0.000	1.428E-4	1.260E-5		240	1300	0	0	98814.28
Sr-90	1.13	0.000	1.13	0.000	0.000	0.000	1000	13	110	0	0	737.4381
Tc-99	8.460E-2	0.000	8.460E-2	0.000	0.000	5.183E-7	80	0.14	1.2	0.033028	0	3.027382
Th-228	34.4	31.9	0.759	0	0.116	1.56	10000	3000	5400	0	0.0083	12.05225
Th-229	33.6	32.4	0.725	0.000	0.162	0.341	10000	3000	5400	0.027396	0.0083	2.797562
Th-230	4.69	4.68	0	0	0.0129	0.001	10000	3000	5400	0.027783	0.0012	3.45056
Th-232	4.02	4.00	0	0	0.0109	0.001	10000	3000	5400	0.00399	0.001	19.93849
Th-232-ser**	39.8	35.9	1.134	0	0.193	2.49	10000.0 0	3000.00	5400.00	0.00	0.01	7.82

Table 3-7. RESLs for Freshwater Sediment (continued)

Nuclide	MeV/disintegration*						CFs**	Kds***		Int Dose	Ext Dose	RESL
	Total	α	β^-	β^+	e^-	γ		Sand	Clay	rem/day per pCi/g	rem/day per pCi/g	pCi/g yielding 0.1 rem/day
Tl-204	0.239	0.000	0.238	0.000	1.221E-4	1.136E-3				??	0	ERR
U-232	5.32	5.31	0.000	0.000	1.438E-2	1.782E-3	50	33	1500	0	0.0014	72.60588
U-233	4.82	4.81	0.000	0.000	3.004E-3	7.181E-4	50	33	1500	0.00206	0.0012	30.40403
U-234	4.78	4.76	0	0	0.0113	0.001	50	33	1500	0.00186	0.0012	32.44598
U-235	4.75	4.38	0.08	0	0.117	0.176	50	33	1500	0.00185	0.0011	33.50549
U-236	4.50	4.49	0.000	0.000	9.564E-3	1.373E-3	50	33	1500	0.00172	0.0011	34.91553
U-238	5.11	4.19	0.864	0	0.0265	0.0248	50	33	1500	0.00174	0.0011	34.9775
U-sep**	10.1	9.16	0.868	0	0.0433	0.0341	50	33	1500	0.00169	0.0024	24.4925
U-series**	49.1	44.9	2.16	0	0.177	1.83	50.00	33.00	1500.00	0.00	0.01	6.53
Zn-65	0.590	0.000	0.000	2.023E-3	4.561E-3	0.584	3000	600	3300	0.058115	0	1.719847

* See Table 2-1
** See Table 7-3
*** See Table IX of IAEA 1994.
NC not calculated

Table 3-8. Comparison of Freshwater Concentration Factors for Fish

	IAEA (1994) (Edible Portion)			CRITR (Soldat & Baker 1992)	NCRP (1996)	Values Used for RESLs
Element	Expected	Lower	Upper			
H-3	1	0.6	1	1	1	1
He	1			0	0	1
Be	100			100	100	100
C	50000	5000	50000	50000	50000	50000
N	200000			150000	150000	200000
O	1			1	1	1
NA	20	20	100	20	20	100
P	50000	3000	100000	50000	50000	100000
S	800			1000	1000	1000
SC	100	2	100	100	100	100
CR	200	40	2000	200	200	2000
MN	400	50	500	500	500	500
FE	200	50	2000	200	200	2000
CO	300	10	300	300	300	330*
NI	100			100	100	100
CU	200	50	200	200	200	2500*
ZN	1000	100	3000	1000	1000	3000
BR	400			400	400	420*
RB	2000	200	9000	2000	2000	9000
SR	60	1	1000	60	60	1000
Y	30			30	30	30
ZR	300	3	300	300	300	300
NB	300	100	30000	300	300	30000
MO	10			10	10	10
TC	20	2	80	20	20	80
RU	10	10	200	10	10	200
RH	10			300	300	300
AG	5	.2	10	10	10	100*
SN	3000			3000	3000	3000
SB	100	1	200	100	100	200
TE	400	400	1000	400	400	1000
I	40	20	600	40	40	600
CS	2000	30	3000	2000	2000	3000
BA	4	4	200	4	4	200
LA	30			30	30	30
CE	30	30	500	30	30	500

Table 3-8. Comparison of Freshwater Concentration Factors for Fish (continued)

Element	IAEA (1994) (Edible Portion)			CRITR (Soldat & Baker 1992)	NCRP (1996)	Values Used for RESLs
	Expected	Lower	Upper			
PR	100	30	100	100	100	100
ND	100	30	100	100	100	100
PM	30	10	200	30	30	300*
EU	50	10	200	50	50	300*
TA	100	100	30000	100	100	30000
W	10	10	1000	12000	12000	12000
HG	1000			1000	1000	20000*
PB	300	100	300	300	300	2000*
BI	50	10	500	15	15	500
PO	50	10	500	100	100	500
RA	50	10	200	50	50	200
TH	100	30	10000	100	100	10000
PA	10			10	10	30*
U	10	2	50	10	10	50
NP	30	10	3000	30	30	3000
PU	30	4	300	30	30	300
AM	30	30	300	30	30	300
CM	30	30	300	30	30	300

* The asterisked values are values reported for the Columbia River at Hanford that are higher than the values tabulated here.

Table 3-9. Reality Check on NORELs for Fish Eggs and Larvae

Selected Radioecological Studies				RESL for water at 0.1 rem/day (pCi/L)
Radionuclide/Author	**Experiment**	**Results**	**NOREL**	
H-3 Walden	Raised stickleback embryo in 0.5, 1.0, and 2.0 mCi/ml of H-3	No effects at 5e12 pCi/L	146 rad/day	3.33e8
H-3 Strand	Rainbow trout eggs exposed to H-3 from 0.01 to 10 uCi/L	No effect at 1e4 pCi/L	3 rad/day	
H-3 Erickson	Guppies raised in .035 mCi/ml	Effect on sexual development at 3.5e10 pCi/L	7.3 rad/day	
Pu-238 (IV) Till	Minnow eggs exposed to 1 mCi/ml	No effects above 1e9 pCi/L	1e9 pCi/L	2360
Pu and U Blaylock review	Effects on developing fish eggs	Effects at 2.6e5 pCi/L		2540
Sr-90/Y-90 Blaylock review	Effects on developing fish eggs	Effect at 20 pCi/L		1720
		Effect at 0.2 pCi/L		
		No effect at 20 pCi/L	20 pCi/L	
		Effect a 20 pCi/L		
		No effect at 1e5 pCi/L	1e5 pCi/L	
		Effect at 1 pCi/L		
Cs-137 Blaylock review	Effects on developing fish eggs	Effect at 1 pCi/L		2040
	Effects on developing eggs	No effects at 1e4 pCi/L	1e4 pCi/L	

Table 3-10. Radionuclide Concentrations in Water and Sediment

Levels in the Environment				**DOE Benchmarks**		**MCLs***	**RESLs (0.1 rem/day)**	
Site/Reference	**Radionuclide**	**Water (pCi/L)**	**Sediment (pCi/g)**	**Water (pCi/L)**	**Sediment (pCi/g)**	**pCi/L**	**Water Dwellers Only (pCi/L)**	**Sediment and Water Dwellers (pCi/g of sediment)**
Natural Background (IAEA 1976) Fresh Water	H-3	5.4 to 16.5		3.45e9		20,000 (85,616)	3.33e8	3.33e8
	K-40	0.1 to 6.6	2.7 (beach sand)	727	3.16e5			
	Rb-87	.024				300		
	U-238	5e-3 to 1.7	1 (beach sand)	4550	1.75e6	20	9100	35
	U-234	.01 to 3.4		4040	1e8	19	8000	32
	Ra-226	.01 to 3		160	2.8e4	4		15
	Rn-222	.01 to 3						
	Pb-210	.025 to 0.36		3.02e4	9.77e6	0.75		8.6
	Po-210	.007 to 0.23		725				
	Th-232	.001 to .011	0.69 (beach sand)	477	5.47e4	2		20
	U-235	2e-4 to .07	.05 (beach sand)	4370	2.96e5	21	8320	34
Gable Mountain Pond, Hanford (NCRP 1991)	Cs-137		88 to 7.96e4	6190	9.32e4	110	2040	1370
	Pu-238		5e-4 to 8.8e-2	1170	9.59e7	1.7	2360	71
	Pu-239		1.1e-2 to 8	1250		1.6	2540	47
	Am-241		9e-3 to 1.4	1170	1.67e6	1.5	2360	71

Table 3-10. Radionuclide Concentrations in Water and Sediment (continued)

Levels in the Environment				DOE Benchmarks		MCLs*	RESLs (0.1 rem/day)	
Site/Reference	Radionuclide	Water (pCi/L)	Sediment (pCi/g)	Water (pCi/L)	Sediment (pCi/g)	pCi/L	Water Dwellers Only (pCi/L)	Sediment and Water Dwellers (pCi/g of sediment)
White Oak Lake, Oak Ridge (NCRP 1991)	H-3	3e5		3.45e9		20,000	3.33e8	3.33e8
	Co-60	63	150	4.78e4	2.1e4	204	1.34e4	687
	Sr-90	300		5.77e4	5.57e5	36	1720	737
	Cs-137	42	1550	6190	9.32e5	110	2040	1370
Par Pond Savannah River (NCRP 1991)	Sr-90	4		5.77e4	5.57e5	36	1720	737
	Cs-137	21	810	6190	9.32e5	110	2040	1370
	Pu-238	6e-4		1170	9.59e7	1.7	2360	71
	Pu-239/240	2e-4		1250		1.6	2540	48
	Am-241	2e-4		1170	1.67e6	1.5	2360	71
	Cm-244	2e-2		1110	1.02e8	2.7	2240	63
	Sr-90		7	5.77e4	5.57e5	36	1720	737
Beaver Log lake, Saskatchewan (NCRP 1991)	Pb-210	0.8	43	3.02e4	9.77e6	0.75		8.6
	Ra-226	1.6	22	160	2.82e4	4		14.7
	U-238	113	4	4550	1.75e6	20	9100	35
	U-235	5.3	0.1	4370	2.96e5	21	8320	34

Table 3-10. Radionuclide Concentrations in Water and Sediment (continued)

Levels in the Environment				DOE Benchmarks		MCLs*	RESLs (0.1 rem/day)	
Site/Reference	Radionuclide	Water (pCi/L)	Sediment (pCi/g)	Water (pCi/L)	Sediment (pCi/g)	pCi/L	Water Dwellers Only (pCi/L)	Sediment and Water Dwellers (pCi/g of sediment)
Columbia River (IAEA 1976) McNary Reservoir	P-32	8.1 to 190		117	1.87e6		27.8	
	Cr-51	250 to 6900	1900	1.34e6	1.66e6		1.85e5	
	Co-60	96 to 310	62	4.78e4	2.1e4	204	1.34e4	687
	Zn-65	16 to 190	2100	5.08e4	9.03e4	381	7680	1.7
	I-131	3 to 20		4.3e5	1.39e5		1.33e4	
	Sc-46		130				4.85e4	
	Mn-54		59				3.20e4	1350

* Maximum Containment Levels (MCLs) are the concentrations that correspond to a dose of 4 mrem/yr using Federal Guidance Report No. 11 (EPA 1988) DCFs and 2 L/day.

For H-3, the actual MCL of 20,000 pCi/L is presented along with the derived value.

4.0 HOW TO USE THE RADIOECOLOGICAL SCREENING GUIDANCE

This section presents guidance on how to use the radioecological screening levels developed in this report.

4.1 Overview

Radioecological Screening Guidance (RESG) is a tool that the New Mexico Environmental Division (NMED) developed to help standardize and accelerate the evaluation and cleanup of soil, water and sediment contaminated with radioactive materials. This guidance provides a methodology for environmental science/engineering professionals with a background in radiological risk assessment to calculate radioecologically-based, site-specific, screening levels for radionuclides in soil, water, and sediment. The guide does not address scenarios where organisms are contaminated directly, such as the contamination of grass and trees from radioactive fallout. The guide is limited to screening sites where the soil, water, and/or sediment have been contaminated and cleanup decisions are required, such as at sites on the National Priorities List, sites undergoing decontamination and decommissioning, and sites with elevated levels of naturally occurring radioactivity.

The guidance employs a three-tiered approach for site evaluation. The first tier consists of look-up tables that provide the radionuclide concentrations in soil, sediment, and water that correspond to the No Observed Radiological Effect Level (NOREL) for virtually any organism (other than man) or any ecosystem. These levels are referred to as default Radioecological Screening Levels (RESLs). If radionuclide concentrations in soil, sediment, and water are below the tabulated default RESLs, there is little or no possibility that the contamination can have an adverse effect on the ecosystem or its most sensitive members. The guide also presents DOE benchmark levels for aquatic organisms that are less conservative than the aquatic RESLs.

The default RESLs are based on a set of mathematical models and modeling assumptions and input parameters (representative of the most sensitive species) that are relatively conservative; i.e., the default RESLs provide a large margin of safety and provide a high level of assurance that contamination levels below the default RESLs have a very low likelihood of having adverse radioecological effects. Because of the conservatism provided in the default RESLs, the guide provides simple equations (i.e., Tier 2) that can be used to derive site-specific radionuclide contamination levels in soil, sediment, and water that correspond to the default NOREL of

0.1 rem/day for terrestrial and aquatic organisms and ecosystems. Alternatively, species-specific or ecosystem-specific NORELs may be developed using Appendix A for terrestrial organisms and Appendix D for aquatic organisms. In order to use Tier 2, however, the analysts must have a considerable amount of site-specific information so that site-specific NORELs and site-specific RESLs can be determined. This involves identifying the specific species at risk and obtaining site-specific information on the environmental transport and reconcentration factors required by the equations.

Finally, Tier 3 analyses involve modification of the equations provided in the guide in order to simulate site-specific conditions. The equations used to derive the default RESLs are simple, but bounding, simulations of the environment. Specifically, the Tier 1 default models do not take into consideration the following environmental features or processes:

- Radioactive decay and progeny (i.e., radioactive daughters) ingrowth (the default RESLs conservatively assume that short lived progeny are in secular equilibrium with each parent)
- Correction factors for the non-uniformity of the contaminated soil (the default RESLs conservatively assume uniform contamination)
- Depletion of the contaminated soil horizon by environmental processes, such as leaching, erosion, or plant uptake (the default RESLs conservatively assume no depletion)
- Limitations in the depth and aerial extent of the contamination (the default RESLs conservatively assume an effective infinite extent of contamination)

A Tier 3 analysis would take into account all of these processes and considerations, including site-specific NORELs and environmental transport and reconcentration factors. Taking such factors into consideration will result in less restrictive RESLs. This guide does not explicitly provide Tier 3 models since each Tier 3 analysis would be unique for each site and event and would need to be developed by individuals with specialized training and experience in radioecological modeling.

4.2 Example Tier 1 Analysis for a Terrestrial Contamination Event

A Tier 1 screening analysis would involve going directly to Table 2-8. Let us assume that the soil at a site is contaminated with ^{239}Pu. As indicated in Table 2-8, the default RESL for ^{239}Pu is

15 pCi/g. This means that if the ^{239}Pu contamination in soil is less than 15 pCi/g, no further consideration need be given to the radioecological effects of the contamination. If the contamination is above 15 pCi/g, the analyst may recommend cleaning up the contamination to below the default RESL or move on to a Tier 2 or Tier 3 analysis.

If multiple radionuclides are present, the site will pass the radioecological screening process if the following equation is satisfied, referred to as the sum of fractions rule:

$$SF = \Sigma\, C_i / RESL_i < 1.0$$

where:

SF = sum of fractions
C_i = the concentration of radionuclide i in soil (pCi/g)
$RESL_i$ = the limiting RESL for radionuclide i in soil as presented in Table 2-8

For example, if soil is contaminated with 10 pCi/g of ^{239}Pu, 300 pCi/g of Co-60, and 100 pCi/g of ^{137}Cs, the sum of fractions would be derived as follows:

$$SF = 10/15 + 300/440 + 100/250 = 0.66 + 0.68 + 0.4 = 1.74$$

In this example, since the contamination levels fail the sum of fractions rule, i.e., the SF is greater than 1.0, some cleanup may be required or the analyst may elect to perform a higher tier analysis using more site-specific data.

4.3 Example Tier 2 Analysis for Terrestrial Contamination

The following presents examples of how to use the RESG equations to derive site-specific RESLs for specific exposure pathways, species, sites, and events.

External RESL for plants exposed to ^{137}Cs in soil

Assuming the ^{137}Cs concentration in the soil is 1 pCi/g, it can be assumed that all of the energy of disintegration ($E_T = 0.796$ MeV/dis) emitted by ^{137}Cs in a gram of soil is absorbed by the gram of soil. Therefore:

Ds (Rad/day) = 1 pCi/g x 0.796 MeV/dis x 0.037 dis/sec-pCi x 1.6E-6 erg/MeV x 0.01 rad-g/erg x 3600 sec/hr x 24 hr/day

Ds = 4.1E-05 Rad/day per pCi/g of ^{137}Cs in soil

Assuming that the NOREL is 0.1 Rad/day, the RESL is derived as follows:

$RESL_{ext}$= 0.1 Rad/day ÷ 4.1E-05 Rad/day per pCi/g

$RESL_{ext}$= 2430 pCi/g

If site-specific investigations reveal that a different NOREL applies (see Appendix A), replace the default NOREL with the site-specific NOREL.

Internal RESL for plants exposed to ^{239}Pu in soil

Let us assume the ^{239}Pu concentration in soil is 1 pCi/g. Using a soil-to-plant transfer factor (RF) of 0.0738, the ^{239}Pu concentration in the plant is .0738 pCi/g. Because of the small dimensions of the plant, it is assumed that only alpha and beta energy will be absorbed within the plant ($E\alpha$ and $E\beta$). Therefore the internal dose to the plant per pCi/g of ^{239}Pu in soil is derived as follows:

D_{int} (rem/d) = 1 pCi/g x .0738 x 5.15 MeV x 5 RBE x 0.037 dis/sec-pCi x 1.6E-06 erg/MeV x .01 rad-g/erg x 3600 sec/hr x 24 hr

D_{int} (rem/d) = 9.7E-05

$RESL_{int}$ = 1028 pCi/g

In this calculation, a site-specific RESL would be derived by using site-specific values of the soil-to-plant transfer factors, along with site-specific NORELs.

Internal RESL for deer exposed to ^{239}Pu in soil

Assuming the soil contains 1 pCi/g of ^{239}Pu, the grasses growing in the soil will contain .0738 pCi/g. This is based on a high-end empirically determined soil-to-plant transfer factor of .0738 pCi/g of vegetation (fresh wt) per pCi/g of soil (dry wt). Assuming a large deer ingests 20 kg per day of fresh grass, and 400 g/day of soil, internal dose is derived using the ingestion dose conversion factor recommended in Federal Guidance Report No 11 (EPA 1988) of 3.54e-3 mrem/pCi ingested, as follows:

D (rem/day) = [(1 pCi/g x .0738 x 20,000 g/d) + (1 pCi/g x 400 g/d)] x 3.54e-3 mrem/pCi x .001 rem/mrem

D = 6.6e-03 rem/day
RESL = .1 rem/day/6.6e-03 = 15 pCi/g

In this example, site-specific values can be used for the NOREL, soil-to-plant transfer coefficient, and the quantity of grass and soil ingested.

4.4 Example Tier 1 Analysis for an Aquatic Contamination Event

For the purpose of illustration, let us assume the following: (1) an event occurs that results in the contamination of a river, lake, pond, or other waterway, and (2) information is available on the radionuclide contamination level in the water and sediment. Under these conditions, Tables 3-6 and 3-7 may be used to determine whether there is a potential for radioecological damage. For example, let us assume that a contaminating event results in a ^{137}Cs contamination level of 1000 pCi/l in a water resource and the sediment contains 1000 pCi/g of Cs-137. Tables 3-6 and 3-7 indicate that, as long as the radionuclide concentration in the water is less than 2040 pCi/l, and the sediment contains less than 1370 pCi/g, there is very little risk of an adverse effect on the aquatic ecosystem. As a result, it can be concluded that, for this particular example, there is little potential for an adverse radioecological effect.

If multiple radionuclides are present in water or sediment, the sum of fractions rule is used, as described above.

4.5 Example of Higher Tier Analysis for Aquatic Contamination

The derivation of the screening levels depend on two critical parameters: bioaccumulation factors and distribution coefficients. Bioaccumulation factors are empirically determined relationships between the radionuclide concentrations in water and the radionuclide concentrations in aquatic organisms residing in the water. In deriving the screening levels presented in Table 3-6, default bioaccumulation factors were used. If site-specific and event-specific bioaccumulation factors are available, they may be used to replace the default values used in the equations presented in Section 3 of the report in order to derive site-specific and event-specific screening levels.

Distribution coefficients are empirically determined relationships between the radionuclide concentration in sediment and that in water. In deriving the screening levels presented in Table 3-7, default distribution coefficients were used. If site-specific and event-specific distribution coefficients are available, they may be used to replace the default values used in the equations presented in Section 3 of the report in order to derive site-specific and event-specific screening levels.

Before leaving this topic, we should mention the Law of Bergonie and Tribondeau which states that cells are radiosensitive if (1) they have a high mitotic rate, (2) they have a long mitotic future, and (3) they are of a primitive type. (Casarette, 1968). These factors were further expanded upon by Sparrow (1962), which lists the following parameters as indicative of high radiosensitivity:

- Large nucleus (high DNA)
- Large nuclear/nucleolar volume ratio
- Much heterochromatin
- Large chromosomes
- Acrocentric chromosomes
- Normal centromere
- Uninucleate cells
- Low chromosome number
- Diploid or haploid
- Sexual reproduction
- Slow rate of cell division
- Long dormant period
- Meiotic stages present at dormancy
- Slow meiosis and premeiosis

- Low concentration of protective chemical (e.g., ascorbic acid)

These are mentioned here because they can be useful in identifying organisms at a site that may be particularly sensitive to radiation for the purpose of a site-specific analysis.

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GLOSSARY

Alpha (α) decay: one of the three principal modes of radioactive decay. Occurs when the neutron to proton ratio is too low and the unstable nucleus ejects an alpha particle.

Alpha (α) particle: doubly charged cations composed of two protons and two neutrons which are ejected monoenergetically from an unstable nucleus as a result of radioactive decay. Alpha particles are relatively massive and slow, and will usually not penetrate an ordinary sheet of paper or the outer layer of skin. Consequently, alpha particles normally represent a significant hazard only when taken into the body where the energy they emit will be completely absorbed by small volumes of tissue.

Beta (β) decay: one of the three principal modes of radioactive decay. Occurs when an electrically-neutral neutron splits into two parts (a proton and an electron) and the electron is emitted from the nucleus. The atomic number of the decay product is increased by one and the chemical properties differ from those of the parent.

Beta (β) particle: an electron emitted at high speed from the nucleus of an unstable atom when a neutron spontaneously converts to a proton and an electron. Beta particles are not emitted with discrete energies but are ejected from the nucleus over a continuous energy spectrum. Unshielded beta sources can constitute external hazards if the beta radiation is within a few centimeters of exposed skin surfaces and if the beta energy is greater than 70 keV. Internally, beta particles have a much greater range than alpha particles in tissue. However, because of their low specific ionization potential, beta particles will deposit much less energy to small volumes of tissue and consequently will inflict less damage than alpha particles.

Bioaccumulation Factors: are empirically determined relationships between radionuclide concentrations in water and the aquatic organisms residing in the water.

Curie: 3.7×10^{10} nuclear disintegrations per second, the name for the conventional unit of activity. $1\ \text{Ci} = 3.7 \times 10^{10}\ \text{Bq}$.

Diploid: a cell characterized by having double the basic chromosome number.

Distribution Coefficients: are empirically determined relationships between the radionuclide concentration in sediment and that in water.

Effective whole body dose equivalent: the sum over specified tissues of the products of the dose equivalent in a tissue or organ and the weighting factor for that tissue.

External emitter: substance that emits energy from outside an organism.

Gamma (γ) radiation: photons of energy originating from the nucleus that may accompany alpha, beta, or neutron decay. Gamma radiation is not a mode of radioactive decay.

Gray (Gy): the special name for the SI unit of absorbed dose. 1 Gy = 1 Joule kg^{-1} = 100 rad.
Haploid: a cell characterized by having half of the basic chromosome number.

Internal emitter: substance that emits energy from inside an organism.

Ionizing radiation: any radiation capable of displacing electrons from atoms thereby producing ions.

Ionization: the removal of an orbital electron from an atom.

LD (Lethal Dose) 50: the dose of a toxicant that will kill 50 percent of the test organisms within a designated period. The lower the LD 50, the more toxic the compound.

Positron: a positively charged beta particle.

Procaryotic: a cellular organism (such as bacterium) that does not have a distinct nucleus.

Rad: the name for the conventional unit for absorbed dose of ionizing radiation; the corresponding SI unit is the gray (Gy); 1 rad = 0.01 Gy = 0.01 Joule/kg.

Radioactive: characterized by atoms with unstable nuclei due to an imbalance in the ratio of neutrons to protons.

Radioactive decay: the process by which the unstable nucleus of a radioactive atom ejects one or more particles to achieve a more stable state.

Radioactive half-life ($t_{1/2}$): the time required for any given radioisotope to decrease to one-half its original quantity.

Radioactivity: spontaneous nuclear transformations that result in the formation of new elements.

Radionuclide: a radioactive species of atom characterized by the number of protons and neutrons in its nucleus.

Rem: an acronym of radiation equivalent man, the name for the conventional unit of dose equivalent; the corresponding SI unit is the Sievert; 1 Sv = 100 rem.

Roentgen (R): the unit of exposure expressed as coulombs of charge per kilogram of air ($1\ R = 2.5 \times 10^{-4}\ C/kg$).

Relative Biological Effectiveness (RBE): a unitless measure of the effectiveness of one type of radiation relative to another type of radiation to have a given biological effect

Radioecological Screening Levels (RESLs): Radionuclide concentrations that correspond to NORELs.

Trophic Levels: One of the hierarchical strata of a food web characterized by organisms which are the same number of steps removed from the primary producers.

APPENDIX A

SUMMARY OF RADIOECOLOGICAL LITERATURE ON THE EFFECTS OF RADIATION ON TERRESTRIAL ORGANISMS

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A1.0 SUMMARY OF RADIOECOLOGICAL LITERATURE ON THE EFFECTS OF RADIATION ON TERRESTRIAL ORGANISMS

A1-1. Plants

Most studies on the effects of radiation on plants were conducted in the 1960s and early 1970s. The most comprehensive review pertaining to the effects of ionizing radiation on terrestrial plants and the plant communities was published by Whicker and Fraley in 1974. The authors emphasized that when one considers the radiosensitivity of individual plant species, one must remember that effects on one plant species in an ecosystem will have an indirect effect on the entire ecosystem. The total ecological impact of a contaminating radiation event will be governed in large part by the effects of radiation on the higher plant community, since some plants are quite radiosensitive and since the plant community is the major structural framework, including food base, for the entire ecosystem. Moving from considerations at the organismal level to effects at the population or community levels, a much greater degree of complexity is realized. The changes observed in the plant community following irradiation are caused not only by radiation *per se*, but also by interactions and secondary effects that result from the inherent nature of that community and its supporting elements.

A fundamental feature of plant communities, which explains many of the changes observed following irradiation, is the widely varying radiosensitivities of different plant species. The effects of radiation are seen to a much greater degree on certain plant tissues than others. The meristem, a region of active cell division at the growing tips of shoots and roots, is a critical tissue, especially from the standpoint of growth and possibly survival of the plant. Another critical tissue is the flower bud, where meiosis takes place to produce pollen and egg cells. One must consider the actual doses to these critical tissues to properly evaluate the effective radiation dose to the plant.

As in the case of mammals, radiation effects can be classified as (a) somatic or physiological, or (b) genetic in nature. Both effects are largely caused by chromosome damage and gene mutations. While recognizing that genetic effects can occur, Whicker and Fraley (1974) considered that altered gene frequencies within the standing gene pool would revert to pre-irradiation frequencies following a radiation event. Therefore, they did not further consider genetic changes of plants due to radiation exposure.

The major studies of radiation effects on plants were conducted in plant ecosystems at the Brookhaven National Laboratory (BNL) (Oak-Pine Forest), North-Central Colorado (shortgrass plains), Savannah River Plant (pine forest), Northern Georgia (abandoned farmland), and Puerto Rico (tropical rain forest). Additional studies were conducted around unshielded reactors (Georgia and Oak Ridge National Laboratory) and at nuclear detonation test sites.

The types of effects observed following radiation exposures relate to the community physiognomy (form and structure), community composition, and species diversity or individual radiosensitivities. The make-up of a plant community consists of several levels of organization, including: trees of several types, shrubs (woody plants like trees but of smaller stature), epiphytes (which grow on other plants), herbs (which include ferns, grasses, sedges, and forbs), and thallophytes (which include lichens, mosses, and liverworts). The actual physiognomy of a plant community is primarily determined by the climate, e.g., desert or moist climatic conditions. For example, the dominant plant form in one community might be large trees, whereas in another, it might be grasses or shrubs.

Studies at the Brookhaven National Laboratory on Long Island were some of the most extensive dealing with the effects of radiation on plants. An oak-pine forest dominated by white oak, scarlet oak, and pitch pine with a high concentration of vacciniaceous shrubs and a sparse herb stratum was chronically exposed for five years to gamma radiation from a ^{137}Cs source (Woodwell and Whittaker, 1968). In addition to the tree populations, shrub and lichen subcommunities of the forest were also studied. Another study consisted of the irradiation of an abandoned field of herbaceous plants (known as the "Old Field"), exposed to gamma radiation from a ^{60}Co source for 2 years. The exposures in both studies were 20 hours/day.

In the oak-pine forest study, effects on plant life around the irradiation source took the form of several zones related to the lethal effects of radiation on various plant species. Within the inner zone, which received the greatest exposure (>200 R/day), all woody and most herbaceous plants were killed during the first year. This zone was called the Devastated Zone. The next zone, which received exposures of 150-200 R/day, was known as the Carex Zone. In this zone, woody plants were also killed, but the sedge, *Carex pensylvania*, expanded its population in 2 years from about 1% in the undisturbed forest to cover as much as 70% of the ground surface in some irradiated areas. In the third zone, which received 40-150 R/day, the tree canopy was reduced by 50% or more with the vacciniaceous shrubs becoming the dominant plant life. The fourth zone, with doses of 16-40 R/day, was simply known as the Oak Forest. The pitch pine had been killed in this zone leaving an oak canopy and undisturbed undergrowth. While the oak trees were not killed, sublethal damage (such as perturbed bud/twig development) had occurred.

In the very outermost zone (the Oak-Pine Forest), the exposures were less than 12 R/day and no plant deaths were observed. However, an appreciable reduction of shoot growth was seen with exposures as low as 1 R/day. Radial increments (ring widths) of pine tree trunks were reduced at exposure rates of 1-5 R/day. Leaf production was altered at exposure rates as low as 2 R/day.

The most dramatic response was a change in diversity of the vascular plants. The BNL Oak-Pine Forest consisted originally of ~18 vascular plant species per plot, which is in the range of many mountain forests, although on the lower-middle species diversity range for most other forests. Clear differences in radiosensitivity were evident within the pine-oak forest. Diversity was clearly reduced within 6 months after the irradiation began, beginning at 20 R/day with a linear decline above 50 R/day, reaching 50% of controls by 150 R/day, and complete loss of all vascular plants at 350 R/day.

The diversity of species in the Old Field required higher doses than in the Oak-Pine Forest. After 1 year of exposure, no decrease was seen below 100 R/day. Diversity was reduced by 50% at about 1000 R/day with complete loss of plants at 3200 R/day. The reduction of the lichen community required even greater radiation doses with a threshold ~200-300 R/day and 50% reduction at 2700 R/day. Some lichens were highly resistant with 11 species surviving on trees at exposures of 2250 R/day after 32 months.

The threshold for reduction of diversity, for 50% reduction, and reduction to zero for the three communities were all in the same sequence. The forest vascular plants disappeared first, followed by the Old Field herbs, and finally the forest lichens. Of the tree species, the pitch pine (*P. rigida*) was the most radiosensitive. Ninety percent inhibition of growth occurred at 20 R/day with *P. rigida*, at 30 R/day with white oaks (*Q. alba*), and at 40 R/day with the scarlet oak (*Q. coccinea*).

The effects of ionizing radiation on another forest, primarily containing slash pine (*P. ellottii*) and longleaf pine (*P. palustries*), were extensively studied by McCormick (1969) using a ^{137}Cs source. These studies at the Savannah River Plant site confirmed the high radiosensitivity of pine trees and included additional pine species from those in the Brookhaven studies. Slash pines were particularly sensitive; all slash pine trees had died within 4 months after receiving

300 R or more. All longleaf pines that were 5 years of age or younger died following exposures of 800 R or more. The older trees did not die until exposures of 2800 R were reached. There was also a clear correlation of radiosensitivity with plant size. Growth of longleaf pines decreased sharply in the smallest trees following exposures of 400 R but not in the larger trees until doses of 600 R were reached. As described for the Brookhaven studies, a great diversity in plant species occurred in this irradiated forest as well. Following the death of the canopy trees, the forest microenvironment changed drastically. Above 2000 R, the microenvironment was more characteristic of open fields than of a forest. By one year, the seedlings and rosettes of old field species were completely covered by dense populations of trumpet vine which apparently had sprouted from underground root systems. In these studies, the pine forest was the most radiosensitive and the deciduous-evergreen forests ranked as the second most radiosensitive plant community.

In one of the more recent studies of radiation effects on plants, Amiro and Dugle (1985) exposed a North American boreal forest in Southwestern Manitoba to gamma radiation from a ^{60}Co source for 19 hrs/day at dose rates of 0.005 to 65 mGy x h^{-1} (0.0005-6.5 rads/hour). The tree community of the boreal forest consisted of about two-thirds Black Spruce with the remainder Jack Pine, Balsam Fir, Paper Birch, Trembling Aspen, White Spruce, Balsam Poplar, Black Ash, and Tamarack. The most common large shrubs were Bebb's Willow and Speckled Alder. Most of the trees were younger than 70 years. The coniferous species were more radiosensitive than the deciduous species as shown in Table A-1, with Jack Pine being defoliated most quickly. All species were killed within the first 1.5 years at the highest dose-rate (30-55 mGy x h^{-1}). Total loss of the tree canopy occurred after 10 years at mean dose rates >25 mGy x h^{-1}, with a reduction in canopy at mean dose rates of >4.5 mGy x hr^{-1} (~10.8 rads/day). The results in this Canadian study are consistent with those obtained at Brookhaven National Laboratory and the Savannah River Plant site, i.e., the coniferous species (especially pine trees) are the most radiosensitive tree species.

Table A-1. Sensitivity of Canopy of Seven Species to Radiation (Years to Total Defoliation at 90% of Stations)

	Mean Dose Rate (mGy x h^{-1})		
	55-30	30-13	13-4
Species	(n = 84)	(n = 121)	(n = 128)
Bebb's Willow	<1.5	>10	>10
Trembling Aspen	<1.5	5.5	>10
Speckled Alder	<1.5	2.5	>10
Paper Birch	<1.5	2.5	>10
Black Spruce	<1.5	2.5	4.5
Balsam Fir	<1.5	2.5	4.5
Jack Pine	<1.5	>1.5	3.5

Reference: Amiro and Dugle (1985)

Franz and Woodwell (1973) studied the effect of irradiation on soil algae by sampling along the radiation gradient during the sixth year of irradiation of the Brookhaven Irradiated Pine-Oak Forest. They identified seventeen taxa of algae. They correlated a gradient in composition of the algal community with distance from the radiation and thus the radiation dose received. They also correlated the gradient with changes in the higher plant community and the radiation-induced changes in the soil.

There was an obvious threshold for a reduction in number of taxa per sample which was attributable to the presence of radioresistant procaryotic forms at the higher exposures. Such procaryotic forms were absent or scarce in the unirradiated forest. It appeared that a substitute of procaryotic forms for the eucaryotes took place at exposures in excess of 1000-2000 R/day. No effect on community composition occurred at dose rates of 50 and 730 R/day, with a 50% reduction evident for both coefficient of community and percentage similarity at 2250 R/day. At 6000-7000 R/day, both indices had dropped to zero.

Franz and Woodwell (1973) concluded that the soil algal community was more resistant than communities of higher plants with a radiosensitivity similar to the lichen community in the oak-pine forest. This high radioresistance in a field ecoenvironment confirmed the laboratory studies which had demonstrated very high radioresistance for algae.

Flaccus et al. (1974) studied the secondary succession of herbs following the demise of large trees at the Brookhaven site for 10 years. Interestingly, a great increase in *Carex pensylvania* occurred (as previously mentioned) within the first 5 years to ~70% cover, but decreased somewhat thereafter. Flaccus saw a sharp increase in diversity of species with an increase in Rubus spp. contributing most to the replacement of *Carex pensylvania*. He considered the change in dominance by *Carex pensylvania* over the 10-year period to be a reflection of the decay of the radiation source. The radioresistance of the *Carex* became less of an advantage, so that the excluded herb species could then survive in the sledge zone at the decreasing dose rates.

Fraley and Whicker (1973a, 1973b) studied the response of shortgrass plains to chronic or short-term (30-day) seasonal irradiation. Exposures were to a ^{137}Cs gamma source in a shortgrass plains in North Central Colorado. *Bouteloua gracilis* (blue gamma) dominated the grass community, typical of the shortgrass plains upland soils. In the chronic study, exposures ranged from 0.01 R/hour to 650 R/hour over a three-year period. While there were some slight changes in the diversity of species and plant dominance, it was obvious that the shortgrasses are highly radioresistant (Fraley and Whicker, 1973a). Within the inner lethal zone, all plants died within six months at dose rates of 115 R/hour and above. However, the threshold for the coefficient of community (CC) was approximately 5 R/hour (120 R/day) after 15 months of irradiation (total dose - ~55,000 R). This was considerably higher than the 50 R/(20-hr day) for the Brookhaven Old Field Community and the 20 R/(20-hr/day) for the Brookhaven Oak-Pine Forest. While the density of several species of grasses gradually decreased, effects on the CC were only minor since species were not eliminated. One plant did become dominant due to the radiation stress; *Lepidium densiflorum* emerged as the dominant species (a reflection of its high radioresistance). It is obvious from this study that shortgrass vegetation is very resistant to ionizing radiation.

Fraley and Whicker (1973b) also studied the effects of short-term (30-day) seasonal irradiation of the shortgrass plains vegetation. They found the greatest sensitivity in late fall. As in the chronic study, the shortgrass plains vegetation was very radioresistant with 50% coefficient of community effects resulting from exposures of 164, 207, and 95.5 kR for spring, summer, and late fall, respectively.

The University of Tennessee (UT-AEC) Agricultural Research Laboratory conducted a series of studies to determine the radiosensitivity of food crops (Killion and Constantine, 1969). Using ^{60}Co as the radiation source, food plants were irradiated at various times after emergence and allowed to mature in the field. The general order of radiosensitivity of the food crops studies was: winter barley = winter wheat > corn > soybean > rice. Seedlings of barley and wheat could tolerate only about 1000 R, with corn ~2000 R, soybean ~4000 R, and rice ~25,000 R. The stage of growth, however, greatly influenced the tolerance of plants to gamma radiation. The most sensitive periods in general were during reproductive primordial development, e.g., seedling stages and early bloom.

Whicker and Fraley (1974) conducted an excellent and rather comprehensive review of the effects of ionizing radiation on terrestrial plant communities. With the exception of the more recent studies of a North American boreal forest in Southwestern Manitoba (Amiro and Dugle, 1985) and the food crops, Whicker and Fraley extensively reviewed the primary literature discussed in this report as well as numerous other smaller studies. They arrived at the following conclusions about plant radiosensitivity:

- Large-stature, more advanced growth forms tend to be more radiosensitive than smaller-statured, more primitive forms. Within the plant community, the order of radiosensitivity appears to be trees (most sensitive) > shrubs > herbs > thallophytes > microflora (least sensitive). Coniferous trees are notably more sensitive than deciduous trees, and within each of the other growth-form groups above, examples exist where size, stature, or complexity contributes to radiosensitivity.

- Herbaceous, often "nuisance-type" weeds characteristic of disturbed or cultivated areas are frequently favored at the expense of trees, shrubs, or other specialized plants in irradiated communities. Thallophytes and microbial populations tend to persist in areas that have received sufficient irradiation to kill all vascular plants, unless secondary environmental changes become unfavorable to the lower plant forms. If coniferous trees form an important component of a plant community, drastic physiognomic changes can result from relatively low radiation exposures.

- The data indicate that in the oak-pine forest, exposure rates of the order of 50 R/day will produce detectable reductions in community structure and biomass within 6-30 months. Exposure rates in excess of 300 R/day will cause nearly complete devastation within 6-30 months. Exposure rates as low as 2 R/day will alter leaf production after several years of exposure. In the herbaceous communities, detectable effects on community structure can be expected at exposure rates of the order of 100 R/day (sometimes less) within a year of chronic irradiation treatment. Complete devastation of herbaceous communities appears to require exposure rates of the order of a few kiloroentgens per day for about one year. It is particularly evident from the shortgrass plains study that, until equilibrium is reached, the longer the exposure period, the smaller is the daily exposure required to produce a given effect. The lichen synusiae of the oak-pine forest showed structural change at 100-300 R/day, but exposure rates of 6-9 kR/day were necessary to eliminate the community after 26 months of chronic irradiation.

- As with the chronic studies, pine forest is clearly the most radiosensitive community type considered, while the lichen community of a tropical rain forest is the most resistant. Old field and shortgrass plains communities are in the low-intermediate sensitivity range. The *Artemisia* (shrub) and tropical rain forest communities probably lie somewhere between temperate forest and temperate herbaceous communities in terms of sensitivity to short-term radiation, but the available data are not sufficient to confirm this. Total exposures of less than 100 R delivered in 8 days caused detectable effects on community structure in the pine forest, while exposures of 5 kR caused a complete change in species composition. In the herbaceous communities studied, month-long exposures totaling on the order of 10-50 kR were required to elicit detectable reductions in community structure. Exposures in the range of 100 to 500 kR were required for complete response. Up to a million roentgens are required to kill all lichens in a rain forest when delivered over a 92-day period.

Based on their analyses, Whicker and Fraley (1974) presented estimates for short-term radiation exposures required to damage various plant communities as listed in Table A-2.

The IAEA (1992) also reviewed the major studies on the effects of radiation on plants. Like others, they concluded that pine trees (*Pinus*) are among the most sensitive to irradiation with all species of *P. elliotti* that received 300 R in a 200-hr period dead within a few months of exposure. All young (<5 years) *P. palustris* that received doses of at least 900 R also died, whereas exposures of > 2800 R killed the older *P. palustris* trees. The estimated dose rates ranged from ~0.01 Gy x hr^{-1} to ~0.7 Gy x hr^{-1} (1-70 R/hour). Based on its review, the IAEA presented Table A-3, which indicates the minimal gamma ray exposures and exposure rates needed to produce detectable effects in terrestrial plant communities. The IAEA concluded: *"it appears that in the natural environment, the most sensitive plants display acute radiation sensitivities which are similar in magnitude to those found for mammals, but that the majority of data relate to radiation exposures which are not acute for the plant species investigated but are more correctly described as short term or chronic."*

Table A-2. Estimated Short-Term Radiation[a] Exposures Required to Damage Various Plant Communities (Whicker and Fraley, 1974).

	Exposures (kR) to produce		
Community type	Minor effects[b]	Intermediate effects[c]	Severe effects[d]
Coniferous forest	0.1-1	1-2	> 2
Deciduous forest	1-5	5-10	> 10
Shrub	1-5	5-20	> 20
Tropical rain forest	4-10	10-40	> 40
Rock outcrop (herbaceous)	8-10	10-40	> 40
Old fields (herbaceous)	3-10	10-100	> 100
Grassland	8-10	10-100	> 100
Moss-lichen	10-50	50-500	> 500

[a] Short-term exposures range from about 8 to 30 days according to the literature from which this table was derived. Exposures might be reduced by factors of 2-4 for acute or fallout-decay irradiation.

[b] Minor effects = short-term changes in productivity, reproduction, and phenology. Recovery from such effects would occur rapidly following radiation stress.

[c] Intermediate effects = changes in species composition and diversity through selection mortality of the more radiosensitive components of the community. Recovery from such effects may take place through the processes of plant succession and may require from one to several generations.

[d] Severe effects = those which drastically change species composition, or which may cause mortality of all or nearly all higher plants. Recovery may be very slow following severe effects, or it may be delayed indefinitely if the soil becomes subject to leaching of nutrients or erosion.

Table A-3. Minimum γ-Ray Exposures and Exposure Rates Observed to Produce Detectable Effects in Terrestrial Plant Communities (IAEA, 1992)

Community type	Exposure period (d)	Attribute measured	Minimum exposure rate ($R \cdot d^{-1}$)	Minimum total exposure (kR)
Pine forest	8	CC	375	0.3
Oak-pine forest	540	CC	50	27
	900	H	50	45
	1440	L	2	2.9
Deciduous forest	165	B	24	4
Tropical forest	34	B	118	4
Old fields (abandoned cropland)	17	S, H	59	1
	29	CC	1200	35
	29	B, S, H	586	17
	365	CC	50	18
	365	H	100	36
Meadow vegetation	11	CC	227	2.5
Shortgrass plains	30	CC	467	14
	30	H, B	300	9
	420	CC	120	50
	420	H	40	95
	510	B	170	87
Lichen	92	S, B	2200	200
	780	CC,H	300	234

CC = Coefficient of Community
H = Diversity Index
L = Leaf Fall Index
B = Biomass Index
S = Similarity Index

A1.2 Mammals

As discussed earlier, ionizing radiation can cause a multitude of effects in humans and other mammals after acute and protracted exposures, including death, reproductive failure, birth defects, heritable mutations, life-shortening, and cancer. Whereas all these effects are of great concern in determining acceptable exposures to humans, the induction of heritable mutations, birth defects, and cancer is not viewed with the same level of concern for non-human organisms.

Indeed, there is a dearth of data for such effects, especially for chronic radiation exposures at low dose rates. In contrast, numerous laboratory studies have been conducted on the acute and chronic effects of radiation on mammals with death and life-shortening as the endpoints of concern. Several important studies have also been conducted on the effects of irradiation in natural environmental conditions using static irradiation sources in a few major ecosystems, which will be discussed later. The preceding section on plants briefly discusses the designs of those ecosystem studies.

Most studies have been conducted with common small laboratory animals, although several important studies have used large domesticated mammals. Virtually no data exist on which to base an assessment of the radiosensitivity of large wild mammals, such as deer, moose, bear, big cats, etc., and one can only assume that their radiosensitivity is similar to that of animals of comparable size and metabolic rate.

Bell (1971), Bond and Robertson (1957), Page (1968), Rice and Baptist (1974), and Still and Page (1971) conducted the most comprehensive reviews pertaining to the effects of acute or chronic radiation on mammals. The review by Bond and Robertson (1957) primarily covered the acute lethality studies conducted up to 1957, and since their results have been included by others, that review will not be considered further in this report.

Rice and Baptist's review pertains to the potential effects of radiation released by nuclear power plants. The main focus is on the effects on aquatic life forms due to radiation discharges into water at the nuclear power plants. In the shorter review on terrestrial organisms, Rice and Baptist presented a useful summary (see Table A-4) of the lethal doses for various terrestrial animals and man when exposed to gamma or X-radiation. As can be observed, several species have LD50s slightly lower than man, indicating that man is not the most radiosensitive of the mammalian species. It is also evident that the small laboratory mammals are more radioresistant than man: guinea pigs have LD50s in the range of 326 rads, and mice, rats, hamsters, and rabbits have LD50s between 600 and 750 rads.

In addition to the rodent studies reported by Rice and Baptist, several other studies of comparative radiosensitivity of rodent species have been reported. Dunaway et al. (1969) compared the lethality response for ten species of rodents (six species of *Cricetidae*, two of *Muridae,* and two of *Soricidae*) captured from the wild near Oak Ridge, Tennessee. The rodents

Table A-4. Lethal Doses (LD50/30) for Various Terrestrial Animals and Man Exposed to Gamma or X-Radiation (Modified from Rice and Baptist, 1974).

ANIMALS	LETHAL DOSES (RADS)
MAMMALS	
Dogs	250
Goat	240
Swine	250
Burro	255
Man	300
Guinea Pig	326
Pika	560 R
Raccoon	580
Red Squirrel	<600
Monkey	600
Hamster	610
Mouse	640
Gray Fox	710
Rat	714
Rabbit	750
Mongolian Gerbil	1,060
Ground Squirrel (active)	1,100 R
Ground Squirrel (hibernating)	1,500 - 1,750 R
Bat	15,000
AMPHIBIANS	
Newt	1,486
Toad	2,200
ANNELIDS	
Earthworm	67,800

were exposed to ^{60}Co gamma radiation at a dose rate of ~600 rads/minute. The range of LD50s was 525 to 1069 rads. Similarly, O'Farrell (1967) determined the LD50s for five species of rodents, three captured from the wild near Hanford, Washington, one from Alaska, and one standard laboratory strain, which were irradiated with ^{60}Co gamma radiation at a dose rate of 9.6 rads/sec. Very little variation in LD50s was found with a range of 651 to 919 rads, with no differences seen between *Cricetid* rodents and *Murid* mice.

In field studies of acute lethality response, Pelton and Provost (1969) irradiated wild adult female field-captured cotton rats to ^{137}Cs at 20 R/minute and released them back into environmental enclosures. The LD50 of this relatively radioresistant species was estimated as 1130 R.

U.S. Naval Radiological Defense Laboratory (NRDL) in San Francisco or the University of Tennessee-AEC Agricultural Research Laboratory (UT-AEC) in Oak Ridge, Tennessee conducted much of the radiation research on large mammals. At the NRDL, reseachers compared the effects of acute and protracted radiation in large mammals (dogs, sheep, goats, swine, and burros) using primarily 1000 Kvp X-rays and ^{60}Co gamma radiation. The results obtained at the NRDL were reviewed along with those of the UT-AEC studies and other literature reports by Page (1968) and Still and Page (1971). Table A-5 presents a summary of the median lethal doses (LD50s) for large animals exposed to gamma or X-irradiation.

Several large domestic animals, especially cattle, dogs, burros, and goats, are at least as radiosensitive (and perhaps more so) as humans to the effects of acute radiation exposure. One can speculate that the larger wild animals, such as bear and moose, are comparable to the large domestic animals in radiosensitivity. The range of lethality estimates for mammals (except perhaps bats) following acute or protracted radiation exposures is not particularly large (no more than a factor of 10 for the mammals studied). This is far less than the ranges found for plants and other terrestrial organisms.

The results in Table A-5 were obtained with exposures at a rather intense dose rate. While studies have not been conducted with large animals at dose rates around 1 R/day, studies have been conducted to ascertain the change in radiosensitivity with lower dose rates as indicated in Table A-6. With the exception of the burro and primates, a great change in radiosensitivity occurs at dose rates of 0.1 R/minute or less or when the radiation is protracted from a few minutes to 100 or more hours.

There is extensive literature on the effects of radiation on terrestrial mammals. The most comprehensive review is that of Turner (1975). Turner's main emphasis was on the effects of continuous irradiation on reproduction and survival and the size and age-composition of animal populations in irradiated ecosystems. He did not attempt to evaluate the genetic consequences of continuous irradiation on animal populations. While he recognized that genetic effects will occur in the irradiated animal populations, he agreed with other ecologists that natural selection and other compensating mechanisms will counteract genetic disturbances imposed by irradiation, and thus these effects will not be a determinant for survival or adverse effects in the irradiated animal populations.

Table A-5. Median Lethal Doses (LD50) Values for Large Animals Exposed to Gamma or X-Irradiation*

SPECIES	RADIATION SOURCE	DOSE RATE (R/M)	LD50 (RADS)
BURRO	1000 Kvp X-	7.0	175
	Cobalt-60	.85	280
	Cobalt-60	.35	290
	Cobalt-60	.30	350
CATTLE	Cobalt-60	6.6	125
	Cobalt-60	.9	150
	Cobalt-60	.9	160
DOG	Cobalt-60	50-65	250
	1000 Kvp X-	55	239
	1000 Kvp X-	15	239
	2000 Kvp X-	15	266
	2000 Kvp X-	15	248
	1000 Kvp X-	8-10	280
	Cobalt-60	6	335
GOAT	2500 Kev gamma	32.5	240
	1000 Kvp X-	7.5	200
	Cobalt-60	1.3	350
PRIMATES	Cobalt-60	800	380
	Cobalt-60	55	644
	250 Kvp X-	22	475
	250 Kvp X-	22	503
	250 Kvp X-	13.7	550
	2000 Kvp X-	10.7	670
	250 Kvp X-	3	510

Table A-5. Median Lethal Doses (LD50) Values for Large Animals Exposed to Gamma or X-Irradiation (Continued).*

SPECIES	RADIATION SOURCE	DOSE RATE (R/M)	LD50 (RADS)
SHEEP	Cobalt-60	11	145
	1000 Kvp X-	7.5	146
	250 Kvp X-	7.5	245
	Cobalt-60	4.35	194
	Cobalt-60	.5	206
	Cobalt-60	.3	205
	Cobalt-60	.06	302
	Cobalt-60	.033	389
SWINE	Cobalt-60	50	240
	1000 Kvp X-	30	250
	Cobalt-60	18-29	228
	Cobalt-60	18-29	218
	1000 Kvp X-	27	255
	2000 Kvp X-	15	230
	1000 Kvp X-	15	250
	Cobalt-60	11.5	260
	Cobalt-60	10	270
	1000 Kvp X-	9-10	270
	Cobalt-60	1	425
	Cobalt-60	.85	370
	Cobalt-60	.067	1350-1700

Table A-6. Median Lethal Doses (LD50) Values for Large Animals Exposed to Cobalt-60 Gamma Radiation at Protracted Dose Rates*

SPECIES	DOSE RATE (R/MINUTE)	MEDIAN LETHAL DOSE (RADS)
BURRO	.5-.85	280
	.28	325
	.14	350
	.07	350
	.035	300
	.017	400
CATTLE	.5-.85	160
	.07	425
	.035	400
SWINE	.5-.85	370
	.07	1600
	.035	5800
DOGS	13 R/M	258
	.055	700
	.035	900
	.027	1050
GOATS	1.3 R/M	350
	.033	650
	.017	1100

As Turner discussed, studies of irradiated animal populations at the site of nuclear tests are difficult to assess due to the confounding influences of heat and blast and the uncertain dosimetry and doses received by the animal populations. Due to these problems, he conducted a number of field studies. They were of three main types: (1) investigations of animal populations occupying areas of high natural radioactivity; (2) studies in areas with increased radiation levels due to reactor operations, radioactive wastes, and fallout; and (3) field experiments designed using artificial sources of radiation. Most of the well-controlled and reliable data come from the specially designed field studies using discrete sources of radiation. These are the same irradiated ecosystems previously described for the plant studies. The effects of irradiation were also studied on the existing animal populations.

Turner concluded that reproduction is the ecological process most sensitive to radiation impairment. The responses of animal populations are not predictable from conventional LD50 studies. Reactions of animal populations may entail complex interactions between impairment, recovery, and other compensatory responses. A limitation of most laboratory and field studies was that populations were exposed to only gamma radiation. Radiation from sources of probable radiation pollution (e.g., nuclear electric plants and nuclear waste sites) will be a mixture of gamma, beta, and perhaps some alpha emitters.

French and Kaaz (1968), as reported by Turner, exposed three strains of *Peromyscus maniculatus* to chronic irradiation at ~1.23 rads/day. They studied two groups: one consisted of the offspring of irradiated parents that had been irradiated during gestation (from the time of conception until birth), and the other consisted of mice irradiated for the remainder of their lives beginning at weaning (3-4 weeks of age). For mice that had been irradiated *in utero*, the birth rate was slightly lower than that of the controls, the death rate was higher, and age-specific fertility was reduced. There were no differences for those mice irradiated since weaning (and in fact there was an indication of an increase in survival time) indicating that the developing fetus is quite radiosensitive and that irradiation of the pregnant mother is of considerable importance in determining potential effects of radiation exposures. Turner emphasized that reproductive processes are much more important to the maintenance of stressed populations than survivorship and life span. Since reproduction is more radiosensitive than those of general maintenance, populations may succumb to chronic radiation levels far lower than lethal doses.

In contrast to these studies, Turner reviewed a series of Russian studies of high natural radioactivity in which voles had been exposed to 34.5 or 69 rads/year of gamma radiation. These studies reported that 60% of the male voles exposed to ~69 rads/year (~0.2 rad/day) were sterile with decreased testes weight. The testicular effects were observed within 6 months (accumulated dose <70 rads).

As regards to life-shortening of irradiated adult rodents, Sacher and Staffeldt (1973) found that hystricomorphs (*Chinchilla laniger* and *Cavia porcellus*) were extremely sensitive, whereas murids (*Mus musculus* and *Rattus spp.*) were relatively resistant to chronic radiation at dose rates of 5-125 R/day. In another study, French et al. (1969) exposed the pocket mouse (*Perognathus formosus*) in the Mojave Desert of southern Nevada to ^{137}Cs gamma radiation at a dose rate of 1 R/day. While there was a suggestion of shorter life span, it was not conclusive. Carlson and Jackson (1959) irradiated rats at dose rates ranging from 0.3 to 4.2 R/day. While observing some effects, they concluded that the effects of radiation interacted with the environmental effects in influencing longevity.

Lorenz et al. (1954) found an apparent increase in survival time of mice and guinea pigs exposed to 1.1 R/day as did French and Kaaz (1968) at 1.23 R/day. As pointed out by Turner, a similar increase in survival has also been found with insects exposed to low dose rates. There may be a scientific basis for this phenomenon. French et al. (1974), as reported by Turner, reported that *P. formosus* (pocket rodent) maintained generally higher densities and greater increases in numbers in areas where the radiation levels were ~1 R/day for 5 years.

Mole (1957) analyzed the results from different investigators and concluded that there was a threshold between 1 and 2 R/day below which no life-shortening occurs. It is not clear from the literature whether dose rates below 1 R/day would have a detrimental effect on survival and life span.

A1.3 Birds

Only a few laboratory studies or well-controlled field studies have compared the radiosensitivity of birds. The review by Mellinger and Schultz (1975) is the most comprehensive, but it covers the effects of radiation on wild birds only and does not provide information on domestic birds. Most studies cited in that review pertained to the uptake and accumulation of radionuclides around weapons test sites, from worldwide fallout, around nuclear power plant sites, and waste disposal sites. As expected, the concentrations of radionuclides in wild birds reflected their feeding habits. The highest concentrations observed in wild birds around the Hanford facilities were in shorebirds feeding mainly on larvae and insects, and the lowest levels were in piscivorous birds (fish eaters). The mallard and baldpate were intermediate to the shorebirds and piscivorous birds. Beta emitters concentrated in shorebirds about 45 times greater than in river ducks. ^{32}P concentrations in birds were measured by the following concentration factors: 75,000 for adult swallows, 5000 for gulls, 50,000 for diving ducks, 7500 for river ducks and geese, and 2500 for piscivorous ducks.

Phosphorous uptake would be anticipated as it is an important element in wild birds, and a principal constituent of bone, DNA, and ATP. ATP is present in high concentrations in the flight muscles of birds. The other radionuclides usually accumulated in wild birds were ^{65}Zn, ^{137}Cs,

^{90}Sr, ^{210}Po, ^{210}Pb, ^{131}I, ^{239}Pu, and ^{60}Co, depending on the geographical sites where they nested or fed.

Some laboratory studies of the radiosensitivity of birds have been conducted. These, as well as the limited studies of bird populations exposed to radiation in field experiments or environmental studies, provide data on a small percentage of the species of birds. Nevertheless, the data appear to be adequate to arrive at some general conclusions as to the relative radiosensitivity of birds.

From early papers, it appeared that wild birds had a lower radiosensitivity than domestic fowl. Maloney and Mraz (1939) observed that the Japanese quail (*Coturniz japonicum*) and bobwhite quail (*Colinus virginianus*) were less sensitive to whole body gamma radiation (^{60}Co @ 25 R/minute) than domestic white leghorn hens. This was based on only ~10% of Japanese quail dying after 1000 R and ~40% of bobwhite quail dying after 1200 R, as compared to an LD50 of 900 R for white leghorns. Similarly, Norris (1958) concluded that week-old songbirds might be less radiosensitive than week-old laboratory chicks and ducklings. This was based on studies with eastern bluebirds in which he estimated an LD50 of >1000 R. Willard (1963) also concluded that nesting eastern bluebirds were less radiosensitive than young chickens, reporting an LD50 of 2500 R for 16-day old nestlings. This current evaluation does not seem to support the conclusion that wild birds are less radiosensitive than domestic fowl.

In addition to determination of LD50s of individual species of songbirds, limited studies of other effects and population studies have been performed (Mellinger and Schultz, 1975). At doses of 50-210 R with weaver finches, Lopts and Rothblat (1962) did not observe testicular damage whereas at 420-1060 R, abnormal histological changes were seen. Willard (1963) observed stunting of growth and feather elongation in nestling eastern bluebirds when irradiated at 43 R/min (^{60}Co) at 2 and 16 days of age. A 10% reduction in feather growth occurred in 2-day old nestlings with exposures of 300-500 R. Growth was reduced by 50% at 1500-2000 R.

In a study of late summer bird populations in the vicinity of an air-shielded nuclear reactor in Georgia, Schnell (1964) reported that various species disappeared earlier than those disappearing from a control non-irradiated area. The disappearance varied with bobwhites declining first at a total dose of 310 rads and white-eyed vireos disappearing last at a dose of 27,700 rads. No differences, however, were observed in the decline of non-singing birds.

Wagner and Marples (1966) studied populations of five species of songbirds (tree swallows, rufous-sided towhee, brown thrasher, Baltimore oriole, and eastern songbird) in a pine-oak forest at Brookhaven National Laboratory. Negligible effects were observed over a 30-day nesting period with a total dose of 330 R. They found an LD50 of 500-1000 R for eggs of wild passerines (perching songbirds) exposed to ^{60}Co radiation for 20 hours per day at a dose rate of up to 50 R/day, whereas the LD50 for adults may have been as high as 2000 R at a dose rate of up to 150 R/day.

Zach and Mayoh (1984, 1986) conducted two field studies on the effects of radiation on birds, tree swallows, and house wrens. Both studies determined the effects of radiation on nestling birds and assessed mortality and growth depression. The source was ^{60}Co with a dose rate of 60 R/second. No radiation-induced mortality occurred with doses up to 600 R for house wrens and 450 R for tree swallows. However, pronounced growth effects were evident at 270 R and above, in the form of reduced body mass and depressed feather growth. Chronic exposure at ~100 R/day appeared to be even more effective than acute exposure at the same total dose and may have caused permanent stunting.

The UT-AEC Agricultural Research Laboratory determined that the LD50 for domestic poultry (white leghorn chickens) was ~900 R at a dose rate of 5 R/minute (^{60}Co). No deaths occurred at 400 R. In addition, they found that egg production temporarily dropped for 10 days starting at the 10th day following exposure to total doses of 400-800 R (Bell, 1971). They observed a dose rate effect in that the drop in egg production remained reduced for 40 days when the dose rate was increased to 45 R/minute with the same total doses. Additional studies at that laboratory revealed that exposure of incubated, fertilized eggs to doses of >80 R retarded development whereas an LD50 of 750 R was obtained with 12-day old eggs. The radiosensitivity was slightly greater for 3-day and 18-day old incubated eggs. Weatherbee (1966) did not observe reductions in egg production until doses were 600 R or greater, with the reductions occurring between 11-20 days. The radiation source was ^{60}Co and the dose rate was 0.9 R/minute, less than in the UT-AEC studies, which may explain the differences in radiosensitivity for egg production.

In a study of 2-day old broiler chickens to ^{60}Co γ-radiation at 8 R/minute, Brisbin (1969) found that growth rate over a 30-day period was significantly decreased only if doses were above 700 R.

In summary, the radiosensitivity among the wild birds appears to range from ~400 to >1000 R for acute LD50s. Table A-7 summarizes the LD50s for game and non-game wild birds. Minimal data are available to assess the effects of protraction of radiation exposures and effects of low intensities. However, protracting an 800 R exposure of white leghorn chickens from ~18 minutes (45 R/minute) to ~3 hours (5 R/minute) resulted in a 20% reduction in mortality.

Table A-7. Radiosensitivity of Wild Birds*

SPECIES/GENUS	TYPE	DOSE RATE	LD50
GAME BIRDS			
Blue-Winged Teal Duck	^{137}Cs γ	NA	715 R
Green-Winged Teal Duck	^{137}Cs γ	NA	485 R
Shoveler Duck	^{137}Cs γ	NA	894 R
Mallard Ducks, 4 mo. old	^{137}Cs γ	NA	704 R
Mallard Ducks, 12 mo. old	60Coγ	NA	630 R
Mallard Ducks, 12 mo. old	X-rays	NA	650 R
Ringed-Necked Pheasants	X-rays	NA	1500-2025 R
NON-GAME BIRDS			
Blue Birds	NA	23.5 R/m	>1000 R
Blue Birds, 16-day old nestlings	X-rays	NA	2500 R
Blue Birds, nestlings-fledglings	X-rays	NA	2500 R
Greenfinch	X-rays	NA	600 R
European Goldfinch	X-rays	NA	600 R
Linnet	X-rays	NA	400 R
House Sparrow	X-rays	NA	625 R
Serin	X-rays	NA	500 R
Weaver Finches	NA	NA	1060 R
Pigeon	NA	NA	~1060 R
Parakeet	NA	NA	>1060 R
California Starling	NA	^{60}Co-Γ	~800 R
Slate-Colored Junco	NA	NA	900 R
Song Sparrow	NA	NA	800 R

* Compiled from Mellinger and Schultz (1975).
NA - not available in report.

A1.4 Reptiles and Amphibians

Information on the effects of radiation on reptiles and amphibians is quite sparse. Only a few studies have been reported in the public literature. According to the IAEA (1992), reptiles and amphibians are somewhat less sensitive to the lethal effects of acute radiation than birds and mammals, although an overlap in sensitivity may exist. The studies of Tinkle (1965) indicate that radiation affects the reproduction system of a natural population of lizards, *Uta stansburiana*, in ways roughly similar to how it affects mammals. Turner et al. (1973, as reported in IAEA, 1992) studied the effects of chronic radiation on lizards in a desert ecosystem in which the lizards were maintained in enclosures and irradiated at dose rates of ~2 R/day. After 1 or 2 years of exposure, females of two long-lived species of lizards became sterile, and reproduction was blocked with the populations drifting towards extinction. Effects on iguanid lizards (*Crotaphytus wislizenii* and *Cnemidophorus tigris*) were not as dramatic at that time. After 5 years of exposure at that dose rate, there were no significant differences in the life spans, age distributions, and sex ratios between the irradiated and control iguanid lizards. A possible explanation for this difference in species response is that the ovaries of the two sensitive species would have accumulated a greater total dose before sexual maturation.

One of the most extensive studies of animal populations in an irradiated ecosystem was the study of lizards and tree frogs in the Puerto Rican rain forest (Turner, 1975). Beginning one year prior to the irradiation, two species of lizards (*Anolis gundlachi* and *A. evermanni*) and a tree frog (*Eleutherodactylus portoricensis*) were studied for individual and population attributes. Several effects were attributed to the radiation exposure including lethality within 15-20 meters of the source and indirect effects associated with the radiation-induced opening of the forest canopy. While the actual doses received were not presented, they would likely have been at least several thousand roentgens within 20 meters based on data presented in the Turner report.

In another study of an irradiated ecosystem, researchers studied whiptail lizards (*Cnemidophorus tigris*), horned lizards (*Phrynosoma platyrhinos*) and zebra-tailed lizards (*Callisaurus draconoides*), leopard lizards (*Crotaphytus wislizenii*), and Utas (*Uta stansburiana*) in an irradiated desert in Nevada. The dose rates to the lizards ranged from 1 rad/day to ~ 5 rads/day. Five years after irradiation began, no effects on body weights, mortality, or major organ systems were apparent. However, there was a suggestion of impaired reproduction in several species of lizards, including leopard lizards and horned lizards. Many of the survivors lacked ovaries and many of the males were sterile. Female sterility was also observed in several of the other species of lizards. Such conditions have never been observed in females of these species in other parts of the Rock Valley where there was no radiation exposure. It was judged that an accumulated dose of ~1500 rads was sufficient to destroy the ovary. Reproduction was unimpaired in the Utas, apparently because they have a more rapid turnover of cells and shorter lifespan than the other species of lizards.

A1-5 Invertebrates

Most information regarding the effects of radiation on invertebrates pertains to effects on insects. An extensive review of the nongenetic effects of radiation on insects provides clear evidence that adult insects are, in general, far less sensitive than vertebrates, (O'Brien and Wolfe, 1964). Indeed, producing lethality in adult insects usually requires doses about 100 times that needed to produce lethality in vertebrates.

While insects are less sensitive than vertebrates to either acute effects or reproductive effects of radiation exposure, many factors can modify their response to radiation. As regards to the effects of chronic environmental radiation exposure on insects, Turner (1975) has documented that invertebrates appear to be affected more by indirect effects than the direct radiation damage to the organisms. The exposure rates that significantly alter vegetation structure or character may not have a direct impact on the invertebrates, but the invertebrates exhibit clear responses to the vegetation changes. The indirect responses of invertebrates may be either a decrease in their prevalence or an increase in their population. An example of an indirect response was the reduction in insect population directly related to the reduction of litter production when trees were killed by radiation. The reduced litter led to a reduction of litter decomposition and depletion of carbon and nitrogen, essential nutrients for the invertebrates.

Lethality is not the most important effect leading to decreased insect populations following radiation exposure. Effects on fertility and reproduction are more sensitive, as was demonstrated by Styron and Dodson (1971) and Terasi and Newcombe (1966). This includes radiation by ß-radiation as well as γ-radiation. Investigators concluded that the genetic effects on insect populations following chronic irradiation were likely of less concern than effects on fertility. Severe genetic damage to *Drosophila* populations, exposed to radiation from nuclear detonations in the Marshall Islands, was repaired in succeeding generations (Stone et al. 1962).

As discussed in O'Brien and Wolfe's review, the radiation dose required to produce adverse effects in insects varies greatly. The variation appears especially related to the age of the insects at the time of irradiation and less so to the species of insect. O'Brien and Wolfe illustrate that the lethal doses for insects, in general, are in excess of 10,000 R, putting them in the range of lethal doses for unicellular organisms, which are much greater than the radiation doses required for lethality in vertebrates including man and other mammals.

O'Brien and Wolfe also documented the remarkable differences in radiation doses required to kill adults versus those producing severe effects (including lethality) in eggs and embryos. For example, whereas the lethal dose for adult *Bracon hebetro* (wasp) was 300,000 R, the sterilizing dose was only 5000 R. Indeed, effects on the embryo occurred at even lower doses, with the lethal dose for embryos in the cleavage stage only 100 R.

This extremely wide range in radiation doses required to produce effects occurs because very little cell division takes place after the insects hatch from the eggs and enter the larval life form. O'Brien and Wolfe conclude that the dividing insect cells are as sensitive as dividing vertebrate cells, but the peculiar static quality of the adult insect's cell life makes it insensitive to radiation. Maximum sensitivity occurs at cleavage and blastulation with a peak of insensitivity at gastrulation and just afterwards. As regards the precise stage of the cell cycle, the investigators concluded that damage was not evident until mitosis began and was prominent at the end of the metaphase.

The biological basis for the reduced radiosensitivity apparently is that, in adult insects, very little cell division and differentiation take place and thus the cells are in a stage of reduced sensitivity. An exception to this, however, is that the gonadal cells of the adults do divide and as might be expected, reproduction can be impaired at much lower doses than for somatic cells. Since juvenile insects have a high cell turnover rate, they are also more radiosensitive than adults.

There are several other interesting aspects to radiation effects on insects. As with vertebrates, a given dose is usually less effective when received in fractional increments than when received all at once. This effectiveness decreases with increasing intervals. This is interpreted as evidence that some recovery occurs soon after the radiation injury. Male insects are generally more sensitive (but not always) to effects of radiation than females. This phenomenon was observed in most studies and for most effects including lethality. One explanation advanced was that, at least in *Bracon*, most males are haploid whereas females are diploid. They concluded that differences in genome number were more important than gene kind at least for adults. This may not hold true for effects on all immature stages, however, because haploids are more resistant than diploids during cleavage in the egg stage.

Most crustacea are aquatic organisms and are not reviewed in this report. However, studies of a terrestrial isopod crustacea (*Armadillium vulgare*), also known as the "pillbug," warrant reporting. Nakatsuchi and Egami (1981) irradiated *A. Vulgare* with ^{137}Cs Γ-radiation at dose levels ranging from 5000-160,000 R at various times during their molt cycle. The LD50 was ~30,000 R, which falls within the range of other crustaceans (LD50s of 1500-51,000 rads).

Snails are another common organism in terrestrial ecosystems, although little research has been performed into this class of invertebrates. In one study (Cooley and Miller, 1971), the pond snail, *Physa heterstropha*, showed reduced survival for dose rates in excess of 240 rads-d^{-1}.

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APPENDIX B

DECAY ENERGIES AND DOSE CONVERSION FACTORS

LIST OF TABLES

DECAY ENERGIES AND DOSE CONVERSION FACTORS

A data file containing the energies and intensities of about 500 radionuclides had been obtained from the Health and Safety Research Division of Oak Ridge National Laboratory. This file, which includes the energy and intensity of each radiation that accompanies nuclear decay, had been produced by the computer program MEDLIST[1]. Most of these data were published by D.C. Kocher in the *Radioactive Decay Data Tables,* DOE-TIC-11026, Technical Information Center, U.S. Department of Energy, 1981. Although some of the data have since been revised, the changes are not large enough to significantly affect the present analysis.

The total energies of each type of radiation—alpha, beta (β^-), positron (β^+), Auger electrons (e^-) and photons (x- and gamma-radiation)—were calculated by multiplying the energy of each radiation of a given type by its intensity and summing these products. Radionuclides which have radioactive progenies with half-lives of six months or less were assumed to be in secular equilibrium with their progenies—the disintegration energies of the progenies are included in those of the parents. The branching ratios of the decay chains were obtained from Kocher, 1981 (cited above).

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[1] Described in NCRP Report No. 58: *A Handbook of Radioactivity Measurement Procedures,* 2nd Ed., 1985.

Table B-1. Progenies Included in Calculated Decay Energies

	Associated Nuclides		
Parent	**No. nuclides**	**Name**	**Ratio**
Ac-227	10	Th-227	.9862
		Fr-223	.0138
		Ra-223	1
		Rn-219	1
		Po-215	1
		Pb-211	1
		Bi-211	1
		Po-211	.00273
		Tl-207	.99727
Ag-108m	2	Ag-108	.093
Ag-110m	2	Ag-110	.0133
Am-243	2	Np-239	1
Cd-109	2	Ag-109m	1
Ce-144	3	Pr-144m	.0143
		Pr-144	1
Cs-137	2	Ba-137m	.946
Pb-210	3	Bi-210	1
		Po-210	1
Pu-244	4	U-240	1
		Np-240m	1
		Np-240	1
Ra-226	7	Rn-222	1
		Po-218	1
		Pb-214	.9998
		Bi-214	1
		Tl-210	.00021
		Po-214	.99979
Ra-226-ser	10	Rn-222	1
		Po-218	1
		Pb-214	.9998
		Bi-214	1
		Tl-210	.00021
		Po-214	.99979
		Pb-210	1
		Bi-210	1
		Po-210	1
Ra-228	2	Ac-228	1
Ru-106	2	Rh-106	1
Sb-125	2	Te-125m	1
Sr-90	2	Y-90	1

Table B-1. Progenies Included in Calculated Decay Energies (continued)

Parent	Associated Nuclides		
	No. nuclides	Name	Ratio
Th-228	8	Ra-224 Rn-220 Po-216 Pb-212 Bi-212 Po-212 Tl-208	1 1 1 1 1 .6407 .3593
Th-229	9	Ra-225 Ac-225 Fr-221 At-217 Bi-213 Po-213 Tl-209 Pb-209	1 1 1 1 1 .9784 .0216 1
Th-232-ser	11	Ra-228 Ac-228 Th-228 Ra-224 Rn-220 Po-216 Pb-212 Bi-212 Po-212 Tl-208	1 1 1 1 1 1 1 1 .6407 .3593
U-235	2	Th-231	1
U-238	4	Th-234 Pa-234m Pa-234	1 1 .0016
U-sep	7		
		U-234	1
		U-235	0.047
		Th-231	0.047
		U-238	1
		Th-234	1
		Pa-234m	1
		Pa-234	.0016

Table B-1. Progenies Included in Calculated Decay Energies (continued)

	Associated Nuclides		
Parent	**No. nuclides**	**Name**	**Ratio**
U-series	29	U-238	1
		Th-234	1
		Pa-234m	1
		Pa-234	.0016
		U-234	1
		Th-230	1.000
		Ra-226	1
		Rn-222	1
		Po-218	1
		Pb-214	.9998
		Bi-214	1
		Tl-210	.00021
		Po-214	.99979
		Pb-210	1
		Bi-210	1
		Po-210	1
		U-235	0.047
		Th-231	0.047
		Pa-231	0.047
		Ac-227	0.047
		Th-227	0.046
		Fr-223	6.49e-04
		Ra-223	0.047
		Rn-219	0.047
		Po-215	0.047
		Pb-211	0.047
		Bi-211	0.047
		Po-211	1.28e-04
		Tl-207	0.047

The last column of the table below shows the total energy in units of gram-rad per microcurie-hour, the units listed in Kocher, 1981. The values in this column were spot-checked against the values in Kocher, 1981 as part of the QA of the present calculation.

Table B-2. Decay Energy

Nuclide	MeV/disintegration						Δ(g-rad/ μCi-hr)
	Total	α	β	β^+	e^-	γ	
Ac-227	33.8	32.3	0.96	0	0.129	0.403	72.134
Ag-108m	1.69	0.000	5.668E-2	8.184E-5	1.419E-2	1.62	3.6067
Ag-110m	2.82	0.000	8.121E-2	0.000	2.892E-3	2.73	6.0182
Am-241	5.54	5.48	0.000	0.000	2.940E-2	2.810E-2	11.823
Am-243	5.76	5.26	0.115	0.000	0.153	0.230	12.293
Bi-207	1.65	0.000	0.000	0.000	0.110	1.54	3.5213
C-14	4.947E-2	0.000	4.947E-2	0.000	0.000	0.000	0.1056
Cd-109	0.107	0.000	0.000	0.000	8.044E-2	2.616E-2	0.2284
Ce-144	1.35	0.000	1.29	0.000	9.906E-3	5.136E-2	2.8811
Cl-36	0.249	0.000	0.249	0.000	1.763E-5	1.586E-6	0.5314
Cm-243	6.09	5.83	0.000	0.000	0.123	0.133	12.997
Cm-244	5.80	5.80	0.000	0.000	6.439E-3	1.490E-3	12.378
Cm-248	4.66	4.65	0.000	0.000	4.772E-3	1.054E-3	9.945
Co-57	0.143	0.000	0.000	0.000	1.827E-2	0.125	0.3052
Co-60	2.60	0.000	9.579E-2	0.000	0.000	2.51	5.5487
Cs-134	1.72	0.000	0.157	0.000	5.169E-3	1.56	3.6707
Cs-135	5.630E-2	0.000	5.630E-2	0.000	0.000	0.000	0.1202
Cs-137	0.796	0.000	0.171	0.000	6.023E-2	0.566	1.6988
Eu-152	1.28	0.000	8.369E-2	0.000	4.028E-2	1.15	2.7317
Eu-154	1.53	0.000	0.225	0.000	4.847E-2	1.25	3.2652
Eu-155	0.122	0.000	4.544E-2	0.000	1.635E-2	6.058E-2	0.2604
Fe-55	5.664E-3	0.000	0.000	0.000	4.003E-3	1.661E-3	0.012
Gd-153	0.152	0.000	0.000	0.000	4.186E-2	0.110	0.3244
H-3	5.685E-3	0.000	5.685E-3	0.000	0.000	0.000	0.012
I-129	7.894E-2	0.000	4.090E-2	0.000	1.340E-2	2.464E-2	0.1685
Mn-54	0.840	0.000	0.000	0.000	3.820E-3	0.836	1.7927
Na-22	2.39	0.000	0.000	0.194	7.544E-5	2.19	5.1006
Nb-94	1.72	0.000	0.146	0.000	1.108E-3	1.57	3.6707
Pa-231	5.45	5.38	0	0	0.0355	0.0372	11.631
Pb-210	5.73	5.3	0.396	0	0.0279	0.005	12.229
Pm-147	6.196E-2	0.000	6.196E-2	0.000	0.000	3.456E-6	0.1322
Pu-238	5.50	5.49	0.000	0.000	8.260E-3	1.600E-3	11.738
Pu-239	5.15	5.15	0.000	0.000	4.880E-3	6.540E-4	10.991
Pu-240	5.16	5.15	0.000	0.000	8.332E-3	1.526E-3	11.012
Pu-241	5.230E-3	0.000	5.230E-3	0.000	0.000	0.000	0.011
Pu-242	4.92	4.91	0.000	0.000	6.839E-3	1.267E-3	10.5
Pu-244	7.30	4.59	0.956	0.000	0.250	1.50	15.579
Ra-226	26.7	24	0.851	0	0.0851	1.77	56.981

Table B-2. Decay Energy (continued)

Nuclide	MeV/disintegration						Δ(g-rad/ μCi-hr)
	Total	α	β^-	β^+	e^-	γ	
Ra-226-ser	32.4	29.3	1.247	0	0.113	1.775	69.21
Ra-228	1.37	0	0.375	0	0.0659	0.927	2.9238
Ru-106	1.63	0	1.42	0	0	0.207	3.4786
Sb-125	0.690	0.000	8.644E-2	0.000	0.136	0.468	1.4726
Sm-147	2.25	2.25	0.000	0.000	0.000	0.000	4.8018
Sm-151	1.979E-2	0.000	1.963E-2	0.000	1.428E-4	1.260E-5	0.042
Sr-90	1.13	0.000	1.13	0.000	0.000	0.000	2.4116
Tc-99	8.460E-2	0.000	8.460E-2	0.000	0.000	5.183E-7	0.1805
Th-228	34.4	31.9	0.759	0	0.116	1.56	73.414
Th-229	33.6	32.4	0.725	0.000	0.162	0.341	71.707
Th-230	4.69	4.68	0	0	0.0129	0.001	10.009
Th-232	4.02	4.00	0	0	0.0109	0.001	8.5792
Th-232-ser	39.8	35.9	1.134	0	0.193	2.49	84.917
Tl-204	0.239	0.000	0.238	0.000	1.221E-4	1.136E-3	0.5101
U-232	5.32	5.31	0.000	0.000	1.438E-2	1.782E-3	11.354
U-233	4.82	4.81	0.000	0.000	3.004E-3	7.181E-4	10.287
U-234	4.78	4.76	0	0	0.0113	0.001	10.201
U-235	4.75	4.38	0.08	0	0.117	0.176	10.137
U-236	4.50	4.49	0.000	0.000	9.564E-3	1.373E-3	9.6036
U-238	5.11	4.19	0.864	0	0.0265	0.0248	10.905
U-sep	10.1	9.16	0.868	0	0.0433	0.0341	21.583
U-series	49.1	44.9	2.16	0	0.177	1.83	104.74
Zn-65	0.590	0.000	0.000	2.023E-3	4.561E-3	0.584	1.2591

DOSE CONVERSION FACTORS

Dose conversion factors were compiled from data files furnished by ORNL, which are the basis of FGR 11 and 12. The DCFs for each nuclide include the contributions of progeny with half-lives of six months or less, normalized to the specific activity of the parent—such nuclides bear the suffix "+D". Nuclides with the suffix "-ser" include include the contributions of the entire radioactive decay chain in full secular equilibrium, also normalized to the specific activity of the parent. "U-sep" refers to the three uranium isotopes in the ratios of their natural abundance, separated from the long-lived progeny, normalized to the specific activity of U-238. "U-ser" refers to the three uranium isotopes in the ratios of their natural abundance, in secular equilibrium with their entire decay chains, normalized to the specific activity of U-238.

These factors were compiled by use of a program written by Keith Eckerman and modified by SFM and RA. The decay scheme is listed in FGR 12, Table A.1, but has been corrected for Cd-109 and Th-234.

Table B-3. Dose Conversion Factors

Nuclide	External (mrem/hr per pCi/g or pCi/cm^2)					Internal (mrem per pCi)							
						Inhalation				Ingestion			
	surface	1 cm	5 cm	15 cm	infinite	highest	lowest	fastest	slowest	highest	lowest	high f_1	low f_1
Ac-227+D	5.15e-05	5.23e-05	1.47e-04	2.15e-04	2.30e-04	6.72e+00	1.31e+00	6.72e+00	1.32e+00	1.48e-02	1.48e-02	1.48e-02	1.48e-02
Ag-108m+D	2.13e-04	2.18e-04	6.29e-04	9.83e-04	1.10e-03	2.83e-04	2.53e-05	3.01e-05	2.83e-04	7.62e-06	7.62e-06	7.62e-06	7.62e-06
Ag-110m+D	3.53e-04	3.64e-04	1.06e-03	1.69e-03	1.96e-03	8.03e-05	3.09e-05	3.96e-05	8.03e-05	1.08e-05	1.08e-05	1.08e-05	1.08e-05
Am-241	3.66e-06	2.45e-06	4.65e-06	4.99e-06	4.99e-06	4.44e-01	4.44e-01	4.44e-01	4.44e-01	3.64e-03	3.64e-03	3.64e-03	3.64e-03
Am-243+D	2.88e-05	2.80e-05	7.35e-05	9.93e-05	1.02e-04	4.40e-01	4.40e-01	4.40e-01	4.40e-01	3.63e-03	3.63e-03	3.63e-03	3.63e-03
Bi-207	1.97e-04	2.02e-04	5.84e-04	9.25e-04	1.07e-03	2.00e-05	3.23e-06	3.23e-06	2.00e-05	5.48e-06	5.48e-06	5.48e-06	5.48e-06
C-14	2.14e-09	9.16e-10	1.44e-09	1.53e-09	1.53e-09	2.09e-06	2.90e-09	2.09e-06	2.35e-08	2.09e-06	2.09e-06	2.09e-06	2.09e-06
Cd-109+D	4.29e-06	1.45e-06	2.60e-06	3.03e-06	3.03e-06	1.14e-04	3.96e-05	1.14e-04	4.51e-05	1.31e-05	1.31e-05	1.31e-05	1.31e-05
Ce-144+D	7.77e-06	7.62e-06	2.11e-05	3.22e-05	3.70e-05	3.74e-04	2.16e-04	2.16e-04	3.74e-04	2.11e-05	2.11e-05	2.11e-05	2.11e-05
Cl-36	8.96e-08	7.52e-08	1.89e-07	2.60e-07	2.73e-07	2.19e-05	2.24e-06	2.24e-06	2.19e-05	3.03e-06	3.03e-06	3.03e-06	3.03e-06
Cm-243	1.67e-05	1.66e-05	4.56e-05	6.44e-05	6.65e-05	3.07e-01	3.07e-01	3.07e-01	3.07e-01	2.51e-03	2.51e-03	2.51e-03	2.51e-03
Cm-244	1.17e-07	1.39e-08	1.44e-08	1.44e-08	1.44e-08	2.48e-01	2.48e-01	2.48e-01	2.48e-01	2.02e-03	2.02e-03	2.02e-03	2.02e-03
Cm-248	7.99e-08	9.63e-09	1.00e-08	1.00e-08	1.00e-08	1.65e+00	1.65e+00	1.65e+00	1.65e+00	1.36e-02	1.36e-02	1.36e-02	1.36e-02
Co-57	1.53e-05	1.58e-05	4.24e-05	5.67e-05	5.71e-05	9.07e-06	2.63e-06	2.63e-06	9.07e-06	1.18e-06	7.44e-07	7.44e-07	1.18e-06
Co-60	3.13e-04	3.24e-04	9.48e-04	1.54e-03	1.85e-03	2.19e-04	3.31e-05	3.31e-05	2.19e-04	2.69e-05	1.02e-05	1.02e-05	2.69e-05
Cs-134	2.02e-04	2.08e-04	6.03e-04	9.53e-04	1.08e-03	4.62e-05	4.62e-05	4.62e-05	4.62e-05	7.33e-05	7.33e-05	7.33e-05	7.33e-05
Cs-135	4.44e-09	2.24e-09	3.94e-09	4.37e-09	4.37e-09	4.55e-06	4.55e-06	4.55e-06	4.55e-06	7.07e-06	7.07e-06	7.07e-06	7.07e-06
Cs-137+D	7.39e-05	7.58e-05	2.20e-04	3.45e-04	3.89e-04	3.19e-05	3.19e-05	3.19e-05	3.19e-05	5.00e-05	5.00e-05	5.00e-05	5.00e-05
Eu-152	1.47e-04	1.50e-04	4.33e-04	6.86e-04	7.99e-04	2.21e-04	2.21e-04	2.21e-04	2.21e-04	6.48e-06	6.48e-06	6.48e-06	6.48e-06
Eu-154	1.59e-04	1.62e-04	4.71e-04	7.50e-04	8.76e-04	2.86e-04	2.86e-04	2.86e-04	2.86e-04	9.55e-06	9.55e-06	9.55e-06	9.55e-06
Eu-155	7.86e-06	7.18e-06	1.69e-05	2.08e-05	2.08e-05	4.14e-05	4.14e-05	4.14e-05	4.14e-05	1.53e-06	1.53e-06	1.53e-06	1.53e-06
Fe-55	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	2.69e-06	1.34e-06	2.69e-06	1.34e-06	6.07e-07	6.07e-07	6.07e-07	6.07e-07
Gd-153	1.41e-05	1.10e-05	2.32e-05	2.79e-05	2.79e-05	2.38e-05	9.47e-06	2.38e-05	9.47e-06	1.17e-06	1.17e-06	1.17e-06	1.17e-06

Table B-3. Dose Conversion Factors (continued)

Nuclide	External (mrem/hr per pCi/g or pCi/cm^2)					Internal (mrem per pCi)							
						Inhalation				Ingestion			
	surface	1 cm	5 cm	15 cm	infinite	highest	lowest	fastest	slowest	highest	lowest	high f_1	low f_1
H-3	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	6.40e-08	6.40e-08	6.40e-08	6.40e-08	6.40e-08	6.40e-08	6.40e-08	6.40e-08
I-129	3.44e-06	1.27e-06	1.47e-06	1.48e-06	1.48e-06	1.74e-04	1.74e-04	1.74e-04	1.74e-04	2.76e-04	2.76e-04	2.76e-04	2.76e-04
Mn-54	1.08e-04	1.11e-04	3.22e-04	5.11e-04	5.88e-04	6.70e-06	5.25e-06	5.25e-06	6.70e-06	2.77e-06	2.77e-06	2.77e-06	2.77e-06
Na-22	2.80e-04	2.90e-04	8.42e-04	1.34e-03	1.56e-03	7.66e-06	7.66e-06	7.66e-06	7.66e-06	1.15e-05	1.15e-05	1.15e-05	1.15e-05
Nb-94	2.04e-04	2.10e-04	6.09e-04	9.65e-04	1.10e-03	4.14e-04	3.61e-05	3.61e-05	4.14e-04	7.14e-06	7.14e-06	7.14e-06	7.14e-06
Pa-231	5.42e-06	4.90e-06	1.38e-05	2.05e-05	2.17e-05	1.28e+00	8.58e-01	1.28e+00	8.58e-01	1.06e-02	1.06e-02	1.06e-02	1.06e-02
Pb-210+D	4.71e-07	2.95e-07	5.72e-07	6.81e-07	6.96e-07	2.32e-02	2.22e-02	2.30e-02	2.24e-02	7.27e-03	7.27e-03	7.27e-03	7.27e-03
Pm-147	4.54e-09	2.54e-09	4.88e-09	5.69e-09	5.71e-09	3.92e-05	2.58e-05	2.58e-05	3.92e-05	1.05e-06	1.05e-06	1.05e-06	1.05e-06
Pu-238	1.12e-07	1.35e-08	1.62e-08	1.72e-08	1.73e-08	3.92e-01	2.88e-01	3.92e-01	2.88e-01	3.20e-03	4.96e-05	3.20e-03	4.96e-05
Pu-239	4.89e-08	1.20e-08	2.45e-08	3.24e-08	3.37e-08	4.29e-01	3.08e-01	4.29e-01	3.08e-01	3.54e-03	5.18e-05	3.54e-03	5.18e-05
Pu-240	1.07e-07	1.32e-08	1.59e-08	1.67e-08	1.67e-08	4.29e-01	3.08e-01	4.29e-01	3.08e-01	3.54e-03	5.18e-05	3.54e-03	5.18e-05
Pu-241	2.57e-10	2.05e-10	5.20e-10	6.71e-10	6.73e-10	8.25e-03	4.96e-03	8.25e-03	4.96e-03	6.84e-05	7.66e-07	6.84e-05	7.66e-07
Pu-242	8.88e-08	1.11e-08	1.37e-08	1.46e-08	1.46e-08	4.11e-01	2.93e-01	4.11e-01	2.93e-01	3.36e-03	4.92e-05	3.36e-03	4.92e-05
Pu-244+D	4.42e-05	4.45e-05	1.29e-04	2.03e-04	2.30e-04	4.03e-01	2.89e-01	4.03e-01	2.89e-01	3.32e-03	6.28e-05	3.32e-03	6.29e-05
Ra-226+D	2.21e-04	2.29e-04	6.69e-04	1.08e-03	1.28e-03	8.60e-03	8.60e-03	8.60e-03	8.60e-03	1.33e-03	1.33e-03	1.33e-03	1.33e-03
Ra-226-ser	2.21e-04	2.29e-04	6.70e-04	1.08e-03	1.28e-03	3.18e-02	3.08e-02	3.16e-02	3.10e-02	8.60e-03	8.60e-03	8.60e-03	8.60e-03
Ra-228+D	1.24e-04	1.27e-04	3.69e-04	5.88e-04	6.82e-04	5.08e-03	4.86e-03	5.08e-03	4.90e-03	1.44e-03	1.44e-03	1.44e-03	1.44e-03
Ru-106+D	2.82e-05	2.90e-05	8.37e-05	1.31e-04	1.47e-04	4.77e-04	5.62e-05	5.62e-05	4.77e-04	2.74e-05	2.74e-05	2.74e-05	2.74e-05
Sb-125+D	5.77e-05	5.72e-05	1.64e-04	2.52e-04	2.80e-04	1.39e-05	3.41e-06	3.41e-06	1.39e-05	3.65e-06	3.64e-06	3.65e-06	3.64e-06
Sm-147	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	7.47e-02	7.47e-02	7.47e-02	7.47e-02	1.85e-04	1.85e-04	1.85e-04	1.85e-04
Sm-151	6.70e-10	1.11e-10	1.12e-10	1.12e-10	1.12e-10	3.00e-05	3.00e-05	3.00e-05	3.00e-05	3.89e-07	3.89e-07	3.89e-07	3.89e-07
Sr-90+D	7.46e-07	6.89e-07	1.83e-06	2.64e-06	2.81e-06	1.31e-03	2.47e-04	2.47e-04	1.31e-03	1.53e-04	2.27e-05	1.53e-04	2.27e-05
Tc-99	1.04e-08	6.22e-09	1.22e-08	1.43e-08	1.43e-08	8.32e-06	1.02e-06	1.02e-06	8.32e-06	1.46e-06	1.46e-06	1.46e-06	1.46e-06
Th-228+D	1.87e-04	1.96e-04	5.73e-04	9.39e-04	1.16e-03	3.45e-01	2.53e-01	2.53e-01	3.45e-01	8.08e-04	8.08e-04	8.08e-04	8.08e-04

Table B-3. Dose Conversion Factors (continued)

Nuclide	External (mrem/hr per pCi/g or pCi/cm²)					Internal (mrem per pCi)							
						Inhalation				Ingestion			
	surface	1 cm	5 cm	15 cm	infinite	highest	lowest	fastest	slowest	highest	lowest	high f_1	low f_1
Th-229+D	4.24e-05	4.18e-05	1.15e-04	1.68e-04	1.82e-04	2.16e+00	1.74e+00	2.16e+00	1.74e+00	4.03e-03	4.03e-03	4.03e-03	4.03e-03
Th-230	9.99e-08	4.97e-08	1.11e-07	1.36e-07	1.38e-07	3.26e-01	2.62e-01	3.26e-01	2.62e-01	5.48e-04	5.48e-04	5.48e-04	5.48e-04
Th-232	7.34e-08	2.47e-08	5.03e-08	5.92e-08	5.95e-08	1.64e+00	1.15e+00	1.64e+00	1.15e+00	2.73e-03	2.73e-03	2.73e-03	2.73e-03
Th-232-ser	2.83e-05	2.90e-05	8.38e-05	1.31e-04	1.47e-04	1.64e+00	1.15e+00	1.64e+00	1.15e+00	2.76e-03	2.76e-03	2.76e-03	2.76e-03
Tl-204	1.97e-07	1.71e-07	3.86e-07	4.58e-07	4.62e-07	2.41e-06	2.41e-06	2.41e-06	2.41e-06	3.36e-06	3.36e-06	3.36e-06	3.36e-06
U-232	1.35e-07	4.01e-08	8.25e-08	1.02e-07	1.03e-07	6.59e-01	1.27e-02	1.27e-02	6.59e-01	1.31e-03	6.92e-05	1.31e-03	6.92e-05
U-233	9.54e-08	4.60e-08	1.13e-07	1.54e-07	1.59e-07	1.35e-01	2.79e-03	2.79e-03	1.35e-01	2.89e-04	2.65e-05	2.89e-04	2.65e-05
U-234	9.96e-08	2.15e-08	3.88e-08	4.56e-08	4.58e-08	1.32e-01	2.73e-03	2.73e-03	1.32e-01	2.83e-04	2.61e-05	2.83e-04	2.61e-05
U-235+D	2.22e-05	2.17e-05	5.99e-05	8.40e-05	8.64e-05	1.23e-01	2.54e-03	2.54e-03	1.23e-01	2.67e-04	2.81e-05	2.67e-04	2.81e-05
U-236	8.66e-08	1.39e-08	2.15e-08	2.43e-08	2.45e-08	1.25e-01	2.59e-03	2.59e-03	1.25e-01	2.69e-04	2.47e-05	2.69e-04	2.47e-05
U-238+D	3.61e-06	3.41e-06	9.21e-06	1.35e-05	1.51e-05	1.18e-01	2.48e-03	2.48e-03	1.18e-01	2.68e-04	3.74e-05	2.68e-04	3.74e-05
U-sep	4.75e-06	4.45e-06	1.21e-05	1.75e-05	1.92e-05	2.56e-01	5.33e-03	5.33e-03	2.56e-01	5.64e-04	6.48e-05	5.64e-04	6.48e-05
U-series	2.29e-04	2.36e-04	6.89e-04	1.11e-03	1.31e-03	9.66e-01	3.78e-01	7.16e-01	6.29e-01	3.64e-03	3.14e-03	3.64e-03	3.14e-03
Zn-65	7.37e-05	7.61e-05	2.22e-04	3.58e-04	4.22e-04	2.04e-05	2.04e-05	2.04e-05	2.04e-05	1.44e-05	1.44e-05	1.44e-05	1.44e-05

APPENDIX C

OVERVIEW OF SOIL-TO-PLANT TRANSFER FACTORS

LIST OF TABLES

OVERVIEW OF SOIL-TO-PLANT TRANSFER FACTORS

Table C-1 lists the soil-to-plant transfer factors used by, recommended or reported by the U.S. Nuclear Regulatory Commission (NRC) in suport of various rulemakings, by the EPA in support of the Radionuclide NESHAPs (EPA 1989) and in their PRESTO code, which is used by EPA in support of their low-level radioactive waste rulemaking (EPA 1988), and recommended by the NCRP (1996). Table C-2 presents the soil-to-plant transfer factors reported in IAEA 1994 and converted to fresh weight using the wet weight-to-dry weight ratios also reported in IAEA 1994. Table C-2 also includes some data reduction, since these are the values selected for use in deriving the RESLs. Table C-3 presents selected, widely used soil-to-plant transfer factors taken from Tables C-1 and C-2. We elected to use the higest of these values for screening.

Table C-1. Comparison of Selected Biv Values for the Radionuclide NESHAPS, RESRAD, NUREG/CR-5512, PRESTO, NCRP and the NRC Yucca Mountan Report

	Selected NUREG/CR-5512 values (pCi/g dry per pCi/g dry)**		NRC CNWRA 95-018 (pCi/g dry per pCi/g dry)**				NESHAPS (EPA 1989)		RESRAD (Yu 1993) (pCi/g fresh per pCi/g dry)	PRESTO ((pCi/g dry per pCi/g dry)		NCRP (1996) for fresh vegetables
ELEMENT	Leafy Vegetables	Root Vegetables	Leafy Vegetables	Other Vegetables	Fruit	Grain	Pasture (pCi/g dry plant per pCi/g dry soil)	Vegetables (pCi/g fresh vegetables per pCi/g dry soil)	Applies to both pasture and crops	Leafy Vegetables and Pasture**	Grain	
Ac	3.5E-3 (3.5E-4)	3.5E-4 (4.9E-5)					3.5E-3	1.5E-4	2.5E-3	-		.001
Ag							4.0E-1	4.3E-2	1.5E-1	-		.004
Am	5.8E-4 (5.8E-5)	4.1E-4 (5.7E-5)	1.2E-3 (1.2E-4)	4.7E-4 (6.5E-5)	4.7E-4 (4.8E-5)	2.2E-5 (2.0E-5)	5.5E-3	1.1E-4	1.0E-3	5.5E-3 (5.5E-4)		.001
Ar							0.0	0.0	0	-		0
As							4.0E-2	2.6E-3	8.0E-2	-		.08
At							1.0	6.4E-2	-	-		.2
Ba							1.5E-1	6.4E-3	5.0E-3	-		.01
Be							1.0E-2	6.4E-4	4.0E-3	-		.004
Bi							3.5E-2	2.1E-3	1.0E-1	-		.1
Br							1.5	6.4E-1	7.6E-1	-		.4
C	7.0E-1 (7.0E)-2	7.0E-1 (9.7E-2)					0.0	0.0	5.5	5.5 (5.5E-1)	5.5	-
Ca							3.5	1.5E-1	5.0E-1	-		.5
Cd							5.5E-1	6.4E-2	3.0E-1	-		.5
Ce	1.0E-2 (1.0E-3)	4.0E-3 (5.6E-4)					1.0E-2	1.7E-3	2.0E-3	1.0E-2 (1.0E-3)	4.0E-3	.002
Cf							0.0	0.0	1.0E-3	-		.001
Cm							8.5E-4	6.4E-6	1.0E-3	8.5E-4 (8.5E-5)	1.5E-5	.001

Table C-1. Comparison of Selected Biv Values for the Radionuclide NESHAPS, RESRAD, NUREG/CR-5512, PRESTO, NCRP and the NRC Yucca Mountan Report (continued)

ELEMENT	Selected NUREG/CR-5512 values (pCi/g dry per pCi/g dry)**		NRC CNWRA 95-018 (pCi/g dry per pCi/g dry)**				NESHAPS (EPA 1989)		RESRAD (Yu 1993) (pCi/g fresh per pCi/g dry)	PRESTO ((pCi/g dry per pCi/g dry)		NCRP (1996) for fresh vegetables
	Leafy Vegetables	Root Vegetables	Leafy Vegetables	Other Vegetables	Fruit	Grain	Pasture (pCi/g dry plant per pCi/g dry soil)	Vegetables (pCi/g fresh vegetables per pCi/g dry soil)	Applies to both pasture and crops	Leafy Vegetables and Pasture**	Grain	
Co	8.1E-2 (8.1E-3)	4.0E-2 (5.6E-3)					2.0E-2	3.0E-3	8.0E-2	2.0E-2 (2.0E-3)	7.0E-3	.08
Cr							7.5E-3	1.9E-3	2.5E-4	-		.01
Cs	1.3E-1 (1.3E-2)	4.9E-2 (6.8E-3)	1.1E-1 (1.1E-2)	7.2E-2 (1E-2)	7.2E-2 (7.8E-3)	1.0E-2 (9.1E-3)	8.0E-2	1.3E-2	4.0E-2	8.0E-2 (8.0E-3)	3.0E-2	.2
Cu							4.0E-1	1.1E-1	1.3E-1	-		.05
Eu							1.0E-2	1.7E-3	2.5E-3	2.5E-3 (2.5E-4)	2.5E-3	.002
F							6.0E-2	2.6E-3	2.0E-2	-		.02
Fe							4.0E-3	4.3E-4	1.0E-3	4.0E-3 (4.0E-4)	1.0E-3	.001
Fr							3.0E-2	3.4E-3	-	-		.03
Ga							4.0E-3	1.7E-4	-	-		.003
Gd							1.0E-2	1.7E-3	2.5E-3	-		.002
H							0.0	0.0	4.8	4.8 (4.8E-1)	4.8	-
Hf							3.5E-3	3.6E-4	-	-		.003
Hg							9.0E-1	8.6E-2	3.8E-1	-		.3
Ho							1.0E-2	1.7E-3	2.6E-3	-		.002
I	3.4E-3 (3.4E-4)	5.0E-2 (6.9E-3)	3.4E-3 (3.4E-4)	2.0E-2 (2.8E-3)	2.0E-2 (2.2E-3)	1.0E-2 (9.1E-3)	1.0	4.3E-1	2.0E-2	1.0 (1.0E-1)	1.0	.02
In							4.0E-3	1.7E-4	3.0E-3	-	-	.003
Ir							5.5E-2	6.4E-3	3.0E-2	-	-	.03

Table C-1. Comparison of Selected Biv Values for the Radionuclide NESHAPS, RESRAD, NUREG/CR-5512, PRESTO, NCRP and the NRC Yucca Mountan Report (continued)

ELEMENT	Selected NUREG/CR-5512 values (pCi/g dry per pCi/g dry)**		NRC CNWRA 95-018 (pCi/g dry per pCi/g dry)**				NESHAPS (EPA 1989)		RESRAD (Yu 1993) (pCi/g fresh per pCi/g dry)	PRESTO ((pCi/g dry per pCi/g dry)		NCRP (1996) for fresh vegetables
	Leafy Vegetables	Root Vegetables	Leafy Vegetables	Other Vegetables	Fruit	Grain	Pasture (pCi/g dry plant per pCi/g dry soil)	Vegetables (pCi/g fresh vegetables per pCi/g dry soil)	Applies to both pasture and crops	Leafy Vegetables and Pasture**	Grain	
K							1.0	2.4E-1	3.0E-1	-	-	.3
Kr							0.0	0.0	0	-	-	0
La							1.0E-2	1.7E-3	-	-	-	.002
Mn							2.5E-1	2.1E-2	3.0E-1	2.5E-1 (2.5E-2)	5.0E-2	.3
Mo							2.5E-1	2.6E-2	1.3E-1	-	-	.1
N							3.0E+1	1.3E+1	7.5	-	-	7.5
Na							7.5E-2	2.4E-2	5.0E-2	-	-	.05
Nb			5.0E-2 (5.0E-3)	1.7E-2 (2.4E-3)	1.7E-2 (1.8E-3)	1.7E-2 (1.5E-2)	2.0E-2	2.1E-3	1.0E-2	2.0E-2 (2.0E-3)	5.0E-3	.01
Nd							1.0E-2	1.7E-3	2.4E-3	-	-	.002
Ni	2.8E-1 (2.8E-2)	6.0E-2 (8.3E-3)	1.8E-1 (1.8E-2)	3.0E-2 (4.2E-3)	3.0E-2 (3.3E-3)	3.0E-2 (2.7E-2)	6.0E-2	2.6E-2	5.0E-2	6.0E-2 (6.0E-3)	6.0E-2	.05
Np	1.3E-2 (1.3E-3)	9.4E-3 (1.3E-3)	6.9E-2 (6.9E-3)	2.7E-2 (3.8E-3)	2.7E-2 (2.9E-3)	2.7E-2 (2.4E-2)	1.0E-1	4.3E-3	2.0E-2	4.3E-3 (4.3E-4)	4.3E-3	.02
O							0.0	0.0	-	-	-	.6
P							3.5	1.5	1.0	-	-	1
Pa							2.5E-3	1.1E-4	1.0E-2	-	-	.01
Pb	5.8E-3 (5.8E-4)	3.2E-3 (4.4E-4)	1.1E-3 (1.1E-4)	4.4E-3 (6.1E-4)	6.4E-3 (7.0E-4)	4.7E-3 (4.3E-3)	4.5E-2	3.9E-3	1.0E-2	-	-	.004
Pd							1.5E-1	1.7E-2	1.0E-1	-	-	.1
Pm							1.0E-2	1.7E-3	2.5E-3	-	-	.002
Po							2.5E-2	1.7E-3	1.0E-3	-	-	.001

Table C-1. Comparison of Selected Biv Values for the Radionuclide NESHAPS, RESRAD, NUREG/CR-5512, PRESTO, NCRP and the NRC Yucca Mountan Report (continued)

ELEMENT	Selected NUREG/CR-5512 values (pCi/g dry per pCi/g dry)**		NRC CNWRA 95-018 (pCi/g dry per pCi/g dry)**				NESHAPS (EPA 1989)		RESRAD (Yu 1993) (pCi/g fresh per pCi/g dry)	PRESTO ((pCi/g dry per pCi/g dry)		NCRP (1996) for fresh vegetables
	Leafy Vegetables	Root Vegetables	Leafy Vegetables	Other Vegetables	Fruit	Grain	Pasture (pCi/g dry plant per pCi/g dry soil)	Vegetables (pCi/g fresh vegetables per pCi/g dry soil)	Applies to both pasture and crops	Leafy Vegetables and Pasture**	Grain	
Pr							1.0E-2	1.7E-3	2.5E-3	-	-	.002
Pu	3.9E-4 (3.9E-5)	2.0E-4 (2.8E-5)	3.4E-4 (3.4E-5)	2.3E-4 (3.2E-5)	2.3E-4 (2.5E-5)	8.6E-6 (7.8E-6)	4.5E-4	1.9E-5	1.0E-3	4.5E-4 (4.5E-4)	4.5E-5	.001
Ra	7.5E-2 (7.5E-3)	3.2E-3 (4.4E-4)	8.0E-2 (8.0E-3)	1.3E-2 (1.8E-3)	1.3E-2 (1.4E-3)	1.2E-3 (1.1E-3)	1.5E-2	6.4E-4	4.0E-2	1.5E-2 (1.5E-3)	1.5E-3	.04
Rb							1.5E-1	3.0E-2	1.3E-1	-	-	.2
Re							1.5	1.5E-1	-	-	-	.2
Rh							1.5E-1	1.7E-2	1.3E-1	-	-	.03
Rn							0.0	0.0	0	-	-	0
Ru	5.2E-1 (5.2E-2)	2.0E-2 (2.8E-3)					7.5E-2	8.6E-3	3.0E-2	7.5E-2 (7.5E-3)	2.0E-2	.03
S							1.5	6.4E-1	6.0E-1	-	-	.6
Sb							2.0E-1	1.3E-2	1.0E-2	-	-	.01
Sc							6.0E-3	4.3E-4	2.0E-3	-	-	.002
Se			2.5E-2 (2.5E-3)	2.5E-2 (3.5E-3)	2.5E-2 (2.7E-3)	2.5E-2 (2.3E-2)	2.5E-2	1.1E-2	1.01E-1	-	-	.1
Sm							1.0E-2	1.7E-3	2.5E-3	-	-	.002
Sn							3.0E-2	2.6E-3	2.5E-3	-	-	.3
Sr	1.6 (1.6E-1)	8.1E-1 (1.1E-1)					2.5	1.1E-1	3.0E-1	2.5 (2.5E-1)	2.5E-1	.3
Tb							1.0E-2	1.7E-3	2.6E-3	-	-	.002
Tc	4.4E1 4.4	1.1 (1.5E-1)	7.6E1 (7.6)	1.1E1 (1.5)	1.1E1 (1.2)	7.3E-1 (6.6E-1)	9.5	6.4E-1	5.0	9.5 (9.5E-1)	1.50	5

Table C-1. Comparison of Selected Biv Values for the Radionuclide NESHAPS, RESRAD, NUREG/CR-5512, PRESTO, NCRP and the NRC Yucca Mountan Report (continued)

	Selected NUREG/CR-5512 values (pCi/g dry per pCi/g dry)**		**NRC CNWRA 95-018 (pCi/g dry per pCi/g dry)****				**NESHAPS (EPA 1989)**		**RESRAD (Yu 1993) (pCi/g fresh per pCi/g dry)**	**PRESTO ((pCi/g dry per pCi/g dry)**		**NCRP (1996) for fresh vegetables**
ELEMENT	**Leafy Vegetables**	**Root Vegetables**	**Leafy Vegetables**	**Other Vegetables**	**Fruit**	**Grain**	**Pasture (pCi/g dry plant per pCi/g dry soil)**	**Vegetables (pCi/g fresh vegetables per pCi/g dry soil)**	**Applies to both pasture and crops**	**Leafy Vegetables and Pasture****	**Grain**	
Te							2.5E-2	1.7E-3	6.0E-1	-	-	.1
Th	6.6E-3 (6.6E-4)	1.2E-4 (1.7E-5)	1.1E-2 (1.1E-3)	3.1E-4 (4.3E-5)	3.1E-4 (3.4E-5)	3.4E-5 (3.1E-5)	8.5E-4	3.6E-5	1.0E-3	-	-	.001
Tl							4.0E-3	1.7E-4	2.0E-1	-	-	.2
U	1.7E-2 (1.7E-3)	1.4E-2 (1.9E-3)	2.3E-2 (2.3E-3)	1.1E-2 (1.5E-3)	1.1E-2 (1.2E-3)	1.3E-3 (1.2E-3)	8.5E-3	1.7E-3	2.5E-3	8.5E-3 (8.5E-4)	4.0E-3	.002
W							4.5E-2	4.3E-3	1.8E-2	-	-	.8
Xe							0.0	0.0	0	-	-	0
Y							1.5E-2	2.6E-3	2.5E-3	-	-	.002
Zn							1.5	3.9E-1	4.0E-1	-	-	.4
Zr							2.0E-3	2.1E-4	1.0E-3	-	-	.001

* As part of other investigations, Bob Watters performed a literature review of the measured soil to plant transfer factors for selected radionuclides (Cs, Ra, and Pb).

** Fresh to dry weight ratios reported by Peterson in Till and Meyer are 8 to 12 (10) for leafy vegetables, 4 to 13 (7.2) for root vegetables, 1.1 for grains, 5.7 to 15 (9.2) for fruit, 1 for nuts, 3.5 to 10 (5.9) for legumes, 1.1 for grains, 4.5 for fresh forage, and 1.1 for dry forage.

Table C-2. Soil-to-Plant Transfer Factors Reported in IAEA 1994

Element	Crop		N	Expected Value Median (dry)	Expected Value Median (fresh)	Mean of Median (fresh)	Minimum of Median	Maximum of Median	Upper 95th Percentile Conf. (dry)	Upper 95th Percentile Conf. (fresh)	Mean of Upper 95th Percentile Conf. (fresh)
Na				3.00E-01							
Cr				1.00E-03							
Mn	Cereals	Grain	80	3.00E-01	2.58E-01				4.50E+00	3.87E+00	
	Alfalfa	Fodder	4	9.80E+00	1.86E+00				4.90E+01	9.31E+00	
	Clover	Fodder	32	1.50E+00	2.85E-01				1.50E+01	2.85E+00	
	Maize	Fodder	20	8.00E-02	2.48E-02				4.00E-01	1.24E-01	
	Grass		100	6.80E-01	6.80E-02				6.80E+00	6.80E-01	
	Bean	Pod	76	1.90E-01	4.75E-02				1.90E+00	4.75E-01	
	Carrot	Root	2	1.90E+00	5.89E-01				1.90E+01	5.89E+00	
	Radish	Root	8	2.60E-01	2.34E-02						
	Potato	Tuber	24	4.70E-02	9.87E-03				4.70E-01	9.87E-02	
	Cabbage		24	2.40E-01	2.88E-02				3.60E+00	4.32E-01	
	Lettuce		7	8.60E-01	6.88E-02				1.30E+01	1.04E+00	
	Spinach		69	5.60E-01	4.48E-02				8.40E+00	6.72E-01	
Total			**446**			**2.76E-01**	**9.83E-03**	**1.86E+00**			**2.31E+00**
Fe				4.00E-03							
Co	Cereals	Grain	62	3.70E-03	3.18E-03				1.50E-01	1.29E-01	
	Alflafa	Fodder	4	1.10E+00	2.09E-01				1.10E+01	2.09E+00	
	Clover	Fodder	32	9.40E-02	1.79E-02				9.40E-01	1.79E-01	
	Maize	Fodder	96	1.90E-02	5.89E-03				3.80E-01	1.18E-01	
	Grass		112	5.40E-02	5.40E-03				2.20E+00	2.20E-01	
	Bean	Pod	138	3.00E-02	7.50E-03				6.00E-01	1.50E-01	
	Carrot	Root	2	1.30E-01	2.08E-02						
	Radish	Root	8	1.20E-01	1.08E-02				1.20E+00	1.08E-01	
	Potato	Tuber	64	6.00E-02	1.26E-02				6.00E-01	1.26E-01	
	Cabbage		33	4.40E-02	5.28E-03				4.40E-01	5.28E-02	
	Lettuce		4	2.80E-01	2.24E-02				2.80E+00	2.24E-01	
	Spinach		129	2.90E-01	2.32E-02				2.90E+00	2.32E-01	
	Mixed green veg.		166	2.00E-01	1.60E-02				2.00E+00	1.60E-01	
Total			**850**			**2.77E-02**	**3.18E-03**	**2.09E-01**			**3.16E-01**

Table C-2. Soil-to-Plant Transfer Factors Reported in IAEA 1994 (continued)

Element	Crop		N	Expected Value Median (dry)	Expected Value Median (fresh)	Mean of Median (fresh)	Minimum of Median	Maximum of Median	Upper 95th Percentile Conf. (dry)	Upper 95th Percentile Conf. (fresh)	Mean of Upper 95th Percentile Conf. (fresh)
Ni	Wheat	Grain	48	3.00E-02	2.58E-02				3.00E-01	2.58E-01	
	Clover	Fodder	31	5.10E-01	9.69E-02				5.20E+00	9.88E-01	
	Grass		41	1.80E-01	1.80E-02				1.80E+00	1.80E-01	
Total			**120**			**4.69E-02**	**1.80E-02**	**9.69E-02**			**4.75E-01**
Cu				8.00E-01							
Zn	Barley	Grain	22	8.80E-01	7.57E-01				2.60E+00	2.24E+00	
	Wheat	Grain	48	1.60E+00	1.38E+00				4.80E+00	4.13E+00	
	Maize	Fodder	20	5.60E-01	1.74E-01				1.70E+00	5.27E-01	
	Grass		84	9.90E-01	9.90E-02				3.00E+00	3.00E-01	
	Bean	Pod	66	7.10E-01	1.78E-01				2.10E+00	5.25E-01	
	Potato	Tuber	22	3.50E+01	7.35E+00				1.10E+00	2.31E-01	
	Broccoli		22	8.20E-01	9.02E-02				2.50E+00	2.75E-01	
	Spinach		68	3.30E+00	2.64E-01				9.90E+00	7.92E-01	
Total			**352**			**1.29E+00**	**9.02E-02**	**7.35E+00**			**1.13E+00**
Rb				9.00E-01							
Sr	Cereals	Grain	81	1.20E-01	1.03E-01				6.60E-01	5.68E-01	
	Cereals	Grain	81	2.10E-01	1.81E-01				1.40E+00	1.20E+00	
	Cereals	Grain	4	2.00E-02	1.72E-02				2.00E-01	1.72E-01	
	Fodder		36	1.90E-01	3.61E-02				1.90E+00	3.61E-01	
	Fodder		50	1.00E+00	1.90E-01				1.00E+01	1.90E+00	
	Fruit		12	2.00E-01	1.20E-02				8.00E-01	4.80E-02	
	Grass		70	1.10E+00	1.10E-01				2.90E+00	2.90E-01	
	Grass		115	1.70E+00	1.70E-01				7.80E+00	7.80E-01	
	Grass		4	3.40E-01	3.40E-02				3.40E+00	3.40E-01	
	Pea, bean	Pod	95	1.30E+00	3.25E-01				4.90E+00	1.23E+00	
	Pea, bean	Pod	56	2.20E+00	5.50E-01				9.40E+00	2.35E+00	
	Root crops	Root	11	1.10E+00	2.42E-01				1.10E+01	2.42E+00	
	Root crops	Root	23	1.40E+00	3.08E-01				1.40E+01	3.08E+00	
	Tubers (potato)		39	1.50E-01	3.15E-02				1.30E+00	2.73E-01	
	Tubers (potato)		113	2.60E-01	5.46E-02				1.40E+00	2.94E-01	

Table C-2. Soil-to-Plant Transfer Factors Reported in IAEA 1994 (continued)

Element	Crop		N	Expected Value Median (dry)	Expected Value Median (fresh)	Mean of Median (fresh)	Minimum of Median	Maximum of Median	Upper 95th Percentile Conf. (dry)	Upper 95th Percentile Conf. (fresh)	Mean of Upper 95th Percentile Conf. (fresh)
	Tubers (potato)		2	2.00E-02	4.20E-03				2.00E-01	4.20E-02	
	Green veg. exc. spinach		65	2.70E+00	2.16E-01				1.00E+01	8.00E-01	
	Green veg. exc. spinach		49	3.00E+00	2.40E-01				3.00E+01	2.40E+00	
	Green veg. exc. spinach		2	2.60E-01	2.08E-02				2.60E+00	2.08E-01	
	Hop		1	8.00E-01	6.88E-01						
Total			**909**			**1.77E-01**	**4.20E-03**	**6.88E-01**			**9.87E-01**
Y				1.00E-02							
Zr				1.00E-03							
Nb	Bean, pod			1.70E-02	4.25E-03						
	Rape			5.00E-02	6.00E-03						
Total						**5.13E-03**	**4.25E-03**	**5.00E-02**			
Mo				8.00E-01							
Tc	Cereals	Grain	7	7.30E-01	6.28E-01				3.70E+00	3.18E+00	
	Fodder		14	8.10E+00	1.54E+00				8.10E+00	1.54E+00	
	Grass		18	7.60E+01	7.60E+00				7.60E+02	7.60E+01	
	Pea, bean	Pod	5	4.30E+00	1.08E+00				4.30E+01	1.08E+01	
	Turnip	Root	1	7.90E+01	9.48E+00						
	Potato	Tuber	7	2.40E-01	5.04E-02				2.40E+00	5.04E-01	
	Cabbage		4	1.20E+01	1.44E+00				1.20E+02	1.44E+01	
	Lettuce		2	2.00E+02	1.60E+01				2.00E+03	1.60E+02	
	Spinach		4	2.60E+03	2.08E+02				7.80E+03	6.24E+02	
Total			**62**			**2.73E+01**	**5.04E-02**	**1.60E+01**			**1.11E+02**
Ru	Wheat	Grain	2	5.00E-03	4.30E-03						
	Cabbage		2	2.00E-01	2.40E-02						
	Not specified			4.00E-02	4.00E-02					4.00E-02	
Total			4			**2.28E-02**	**4.30E-03**	**4.00E-02**			

Table C-2. Soil-to-Plant Transfer Factors Reported in IAEA 1994 (continued)

Element	Crop		N	Expected Value Median (dry)	Expected Value Median (fresh)	Mean of Median (fresh)	Minimum of Median	Maximum of Median	Upper 95th Percentile Conf. (dry)	Upper 95th Percentile Conf. (fresh)	Mean of Upper 95th Percentile Conf. (fresh)
Rh				9.00E-01							
Ag	Radish	Root	6	1.30E-03	1.17E-04				1.30E-02	1.17E-03	
	Lettuce		6	2.70E-04	2.16E-05				2.70E-03	2.16E-04	
	Tomato	Fruit	6	8.00E-04	4.80E-05				8.00E-03	4.80E-04	
	Not specified			1.50E-01	1.50E-01						
Total			**18**			**3.75E-02**	**2.16E-05**	**1.50E-01**			**6.22E-04**
Sb	Radish	Root	6	5.60E-04	5.04E-05				2.80E-03	2.52E-04	
Te				7.00E+00							
I	Grass		14	3.40E-03	3.40E-04				3.40E-02	3.40E-03	
	Not specified			2.00E-02	2.00E-02						
Total			**14**			**1.02E-02**	**3.40E-04**	**2.00E-02**			
Cs	Cereals	Grain	220	1.00E-02	8.60E-03				1.00E-01	8.60E-02	
	Cereals	Grain	132	2.60E-02	2.24E-02				2.60E-01	2.24E-01	
	Cereals	Grain	14	8.30E-02	7.14E-02				8.30E-01	7.14E-01	
	Fodder		173	1.70E-02	3.23E-03				1.70E-01	3.23E-02	
	Fodder		22	2.90E-01	5.51E-02				2.90E+00	5.51E-01	
	Fodder		2	3.00E-01	5.70E-02				3.00E+00	5.70E-01	
	Grass		246	1.10E-01	1.10E-02				1.10E+00	1.10E-01	
	Grass		229	2.40E-01	2.40E-02				2.40E+00	2.40E-01	
	Grass		21	5.30E-01	5.30E-02				5.30E+00	5.30E-01	
	Pea, bean	Pod	124	1.70E-02	4.25E-03				1.40E-01	3.50E-02	
	Pea, bean	Pod	63	9.40E-02	2.35E-02				7.50E-01	1.88E-01	
	Root crops	Root	18	4.00E-02	8.80E-03				4.00E-01	8.80E-02	
	Root crops	Root	17	1.10E-02	2.42E-03				1.10E-01	2.42E-02	
	Tubers (potato)		67	7.00E-02	1.47E-02				7.00E-01	1.47E-01	
	Tubers (potato)		79	1.70E-01	3.57E-02				1.70E+00	3.57E-01	
	Tubers (potato)		3	2.70E-01	2.32E-01				2.70E+00	2.32E+00	
	Mixed green veg.		165	1.80E-01	1.44E-02				1.70E+00	1.36E-01	
	Mixed green veg.		90	4.60E-01	3.68E-02				4.50E+00	3.60E-01	
	Mixed green veg.		2	2.60E-01	2.08E-02				2.70E+00	2.16E-01	

Table C-2. Soil-to-Plant Transfer Factors Reported in IAEA 1994 (continued)

Element	Crop		N	Expected Value Median (dry)	Expected Value Median (fresh)	Mean of Median (fresh)	Minimum of Median	Maximum of Median	Upper 95th Percentile Conf. (dry)	Upper 95th Percentile Conf. (fresh)	Mean of Upper 95th Percentile Conf. (fresh)
	Rice (irr.) soil-to-plant			5.00E-03	4.30E-03						
	Tomato fruit		2	2.20E-01	1.32E-02						
Total			**1689**			**3.41E-02**	**2.42E-03**	**2.32E-01**			**3.65E-01**
Ba				3.00E-02							
La	Maize	Fodder	6	3.00E-05	9.30E-06				1.50E-04	4.65E-05	
	Bean	Pod	4	4.20E-04	1.05E-04				2.10E-03	5.25E-04	
	Carrot	Root	6	1.00E-03	1.60E-04				5.00E-03	8.00E-04	
	Tapioca	Root	6	1.60E-03	6.08E-04				8.00E-03	3.04E-03	
	Potato	Tuber	8	2.90E-04	6.09E-05				1.50E-03	3.15E-04	
	Mixed green veg.		8	5.20E-03	4.16E-04				5.20E-02	4.16E-03	
Total			**38**			**2.27E-04**	**9.30E-06**	**4.16E-04**			**1.48E-03**
Ce				3.00E-02							
Pr				2.00E-02							
Nd				2.00E-02							
W				1.00E-01							
Pb	Cereals	Grain	3	4.70E-03	4.04E-03				4.70E-02	4.04E-02	
	Fodder		2	1.10E-03	2.09E-04						
	Mixed roots	Root	1	2.00E-02	4.40E-03						
	Potato flesh	Tuber	2	1.30E-03	2.73E-04				1.30E-02	2.73E-03	
	Mixed green veg.		6	1.00E-02	8.00E-04				2.00E-01	1.60E-02	
Total			**14**			**1.94E-03**	**2.09E-04**	**4.40E-03**			**1.97E-02**
Pol	Wheat grain			2.30E-03	1.98E-03						
	Potato			7.00E-03	1.47E-03						
	Vegetables			1.20E-03	1.44E-04						
	Grass			9.00E-02	9.00E-03						
Total						**3.15E-03**	**1.44E-04**	**9.00E-03**			

Table C-2. Soil-to-Plant Transfer Factors Reported in IAEA 1994 (continued)

Element	Crop		N	Expected Value Median (dry)	Expected Value Median (fresh)	Mean of Median (fresh)	Minimum of Median	Maximum of Median	Upper 95th Percentile Conf. (dry)	Upper 95th Percentile Conf. (fresh)	Mean of Upper 95th Percentile Conf. (fresh)
Ra	Maize	Grain	11	1.20E-03	6.60E-04				6.00E-03	3.30E-03	
	Grass		35	8.00E-02	8.00E-03				4.00E-01	4.00E-02	
	Bean	Pod	8	7.00E-03	1.75E-03				3.50E-02	8.75E-03	
	Carrot	Root	6	1.10E-02	1.76E-03				5.50E-02	8.80E-03	
	Tapioca	Root	3	2.10E-02	7.98E-03				1.10E-01	4.18E-02	
	Potato	Tuber	18	1.10E-03	2.31E-04				5.50E-03	1.16E-03	
	Collard		6	1.00E-01	8.00E-03				5.00E-01	4.00E-02	
	Tomato		2	6.10E-03	3.66E-04						
	Mixed green veg.		9	4.90E-02	3.92E-03				9.80E-01	7.84E-02	
Total			**98**			**3.63E-03**	**2.31E-04**	**8.00E-03**			**2.78E-02**
Th	Maize	Grain	9	3.40E-05	1.87E-05				8.50E-04	4.68E-04	
	Maize	Fodder	2	7.50E-03	2.33E-03				1.90E-01	5.89E-02	
	Grass		20	1.10E-02	1.10E-03				1.10E-01	1.10E-02	
	Bean	Pod	5	1.20E-04	3.00E-05				1.20E-03	3.00E-04	
	Carrot	Root	7	3.00E-04	4.80E-05				7.50E-03	1.20E-03	
	Radish	Root	1	3.90E-02	3.51E-03				3.90E-01	3.51E-02	
	Tapioca		6	6.20E-05	2.36E-05				6.20E-04	2.36E-04	
	Potato	Tuber	10	5.60E-05	1.18E-05				5.60E-04	1.18E-04	
	Sweet Potato	Tuber	1	2.90E-05	3.19E-06						
	Mixed green veg.		8	1.80E-03	1.44E-04				7.20E-02	5.76E-03	
Total			**69**			**7.21E-04**	**3.19E-06**	**3.51E-03**			**1.26E-02**
U	Cereals	Grain	2	1.30E-03	1.12E-03						
	Rice	Grain									
	Grass		31	2.30E-02	2.30E-03				2.30E-01	2.30E-02	
	Mixed roots	Roots	13	1.40E-02	3.08E-03				1.40E-01	3.08E-02	
	Potato	Tuber	2	1.10E-02	2.31E-03						
	Mixed green veg.		13	8.30E-03	6.64E-04				8.30E-02	6.64E-03	
Total			**61**			**1.89E-03**	**6.64E-04**	**3.08E-03**			**2.01E-02**

Table C-2. Soil-to-Plant Transfer Factors Reported in IAEA 1994 (continued)

Element	Crop		N	Expected Value Median (dry)	Expected Value Median (fresh)	Mean of Median (fresh)	Minimum of Median	Maximum of Median	Upper 95th Percentile Conf. (dry)	Upper 95th Percentile Conf. (fresh)	Mean of Upper 95th Percentile Conf. (fresh)
Np	Cereals	Grain	142	2.70E-03	2.32E-03				8.30E-02	7.14E-02	
	Clover	Fodder	40	8.10E-03	1.54E-03				1.20E-01	2.28E-02	
	Maize	Fodder	114	2.10E-02	6.51E-03				2.80E-01	8.68E-02	
	Grass		20	6.90E-02	6.90E-03				5.70E-01	5.70E-02	
	Bean	Pod	21	1.80E-02	4.50E-03				5.70E-02	1.43E-02	
	Carrot	Root	2	3.50E-02	5.60E-03						
	Radish	Root	4	2.60E-02	2.34E-03						
	Onion	Root	1	3.30E-02	3.63E-03						
	Potato	Tuber	98	6.70E-03	1.41E-03				1.40E-01	2.94E-02	
	Cabbage		2	2.40E-02	2.88E-03						
	Cucumber		4	2.50E-02	1.25E-03						
	Leek		3	1.10E-01	1.21E-02						
	Mixed green veg.		15	3.70E-02	2.96E-03						
Total			**466**			**4.15E-03**	**1.25E-03**	**1.21E-02**			**4.69E-02**
Pu	Cereals	Grain	152	8.60E-06	7.40E-06				4.20E-01	3.61E-01	
	Clover, alfalfa	Fodder	104	8.00E-04	1.52E-04				5.10E-02	9.69E-03	
	Maize	Fodder	114	7.50E-05	2.33E-05				2.90E-03	8.99E-04	
	Grass		19	3.40E-04	3.40E-05				6.50E-01	6.50E-02	
	Bean	Pod	20	6.10E-05	1.53E-05				1.50E-04	3.75E-05	
	Carrot	Root	2	4.40E-03	7.04E-04						
	Radish	Root	4	7.70E-04	6.93E-05						
	Onion	Root	1	8.70E-05	9.57E-06						
	Mixed roots	Root	7	9.10E-04	2.00E-04						
	Potato, swede	Tuber	122	1.50E-04	1.65E-05				5.60E-02	6.16E-03	
	Cabbage		14	4.10E-05	4.92E-06						
	Cucumber		4	9.00E-05	4.50E-06						
	Leek		3	6.40E-04	7.04E-05						
	Mixed veg.		27	7.30E-05	5.84E-06						
Total			**593**			**9.41E-05**	**4.50E-06**	**7.04E-04**			**7.38E-02**

Table C-2. Soil-to-Plant Transfer Factors Reported in IAEA 1994 (continued)

Element	Crop		N	Expected Value Median (dry)	Expected Value Median (fresh)	Mean of Median (fresh)	Minimum of Median	Maximum of Median	Upper 95th Percentile Conf. (dry)	Upper 95th Percentile Conf. (fresh)	Mean of Upper 95th Percentile Conf. (fresh)
Am	Cereals	Grain	111	2.20E-05	1.89E-05				7.70E-01	6.62E-01	
	Clover	Fodder	32	7.10E-04	1.35E-04				3.10E-03	5.89E-04	
	Maize	Fodder	109	2.70E-04	8.37E-05				1.20E-02	3.72E-03	
	Grass		20	1.20E-03	1.20E-04				1.70E-01	1.70E-02	
	Bean	Pod	20	3.90E-04	9.75E-05				7.90E-04	1.98E-04	
	Carrot	Root	2	2.20E-03	3.52E-04						
	Radish	Root	4	1.40E-03	1.26E-04						
	Onion	Root	1	1.60E-04	1.76E-05						
	Potato	Tuber	116	2.00E-04	4.20E-05				1.70E-01	3.57E-02	
	Cabbage		14	2.00E-04	2.40E-05						
	Mixed green veg.		13	6.60E-04	5.28E-05						
Total			**442**			**9.72E-05**	**1.76E-05**	**3.52E-04**			**1.20E-01**
Cm	Cereals	Grain	115	2.10E-05	1.81E-05				2.90E-04	2.49E-04	
	Maize	Fodder	109	2.10E-04	6.51E-05				1.20E-02	3.72E-03	
	Grass		20	1.10E-03	1.10E-04				3.60E-03	3.60E-04	
	Bean	Pod	20	7.50E-04	1.88E-04				1.60E-03	4.00E-04	
	Mixed roots	Root	6	1.30E-03	2.86E-04						
	Onion	Root	1								
	Potato	Tuber	92	1.50E-04	3.15E-05				2.40E-03	5.04E-04	
	Mixed green veg.		15	7.70E-04	6.16E-05						
Total			**378**			**1.09E-04**	**1.81E-05**	**2.86E-04**			**1.05E-03**

Note: The fresh wt. Values were derived using Table V in IAEA 1994. The following coefficients were used for food items which did not have coefficients reported in IAEA 1994:

Mixed green veg.	0.08 (spinach)	Collard	0.08 (spinach)	Mixed roots	0.22 (beats)	Vegetables	0.12 (cabbage)
Broccoli	0.11 (cauliflower)	Hop	0.86 (cereal grain)	Fruit	0.06 (tomato)	Rape	0.12 (cabbage)
Green veg.	0.08 (spinach)	Root crops	0.22 (beats)	Rice	0.86 (cereal grain)		

Table C-3. Comparison of Selected Biv Values

ELEMENT	RESRAD (Yu 1993) (pCi/g fresh per pCi/g dry) Applies to Both Pasture and Crops	IAEA 1996 (fresh wt, Mean Aof the Median Values)	IAEA 1996 (fresh wt, Mean of Upper 90th Percentile Level)	NCRP (1996) for Fresh Vegetables
Ac	2.5E-3			.001
Ag	1.5E-1			.004
Am	1.0E-3	9.72e-05	.12	.001
Ar	0			0
As	8.0E-2			.08
At	-			.2
Ba	5.0E-3			.01
Be	4.0E-3			.004
Bi	1.0E-1			.1
Br	7.6E-1			.4
C	5.5			-
Ca	5.0E-1			.5
Cd	3.0E-1			.5
Ce	2.0E-3			.002
Cf	1.0E-3			.001
Cm	1.0E-3	1.09e-04	1.10e-03	.001
Co	8.0E-2	.028	.316	.08
Cr	2.5E-4			.01
Cs	4.0E-2	.034	.365	.2
Cu	1.3E-1			.05
Eu	2.5E-3			.002
F	2.0E-2			.02
Fe	1.0E-3			.001
Fr	-			.03
Ga	-			.003
Gd	2.5E-3			.002
H	4.8			-
Hf	-			.003
Hg	3.8E-1			.3
Ho	2.6E-3			.002
I	2.0E-2			.02
In	3.0E-3			.003
Ir	3.0E-2			.03
K	3.0E-1			.3
Kr	0			0
La	-	2.27e-04	1.48e-03	.002
Mn	3.0E-1	.276	2.31	.3
Mo	1.3E-1			.1
N	7.5			7.5

Table C-3. Comparison of Selected Biv Values (continued)

ELEMENT	RESRAD (Yu 1993) (pCi/g fresh per pCi/g dry) Applies to Both Pasture and Crops	IAEA 1996 (fresh wt, Mean Aof the Median Values)	IAEA 1996 (fresh wt, Mean of Upper 90th Percentile Level)	NCRP (1996) for Fresh Vegetables
Na	5.0E-2			.05
Nb	1.0E-2			.01
Nd	2.4E-3			.002
Ni	5.0E-2	.047	.475	.05
Np	2.0E-2	4.15e-03	4.69e-02	.02
O	-			.6
P	1.0			1
Pa	1.0E-2			.01
Pb	1.0E-2	.0019	.020	.004
Pd	1.0E-1			.1
Pm	2.5E-3			.002
Po	1.0E-3			.001
Pr	2.5E-3			.002
Pu	1.0E-3	9.41e-05	.0738	.001
Ra	4.0E-2	3.63e-03	.0278	.04
Rb	1.3E-1			.2
Re	-			.2
Rh	1.3E-1			.03
Rn	0			0
Ru	3.0E-2			.03
S	6.0E-1			.6
Sb	1.0E-2			.01
Sc	2.0E-3			.002
Se	1.01E-1			.1
Sm	2.5E-3			.002
Sn	2.5E-3			.3
Sr	3.0E-1	.177	.987	.3
Tb	2.6E-3			.002
Tc	5.0	27.1	111	5
Te	6.0E-1			.1
Th	1.0E-3	7.21e-04	.0126	.001
Tl	2.0E-1			.2
U	2.5E-3	1.89e-03	.020	.002
W	1.8E-2			.8
Xe	0			0
Y	2.5E-3			.002
Zn	4.0E-1			.4
Zr	1.0E-3			.001

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APPENDIX D

AN ASSESSMENT OF THE RADIATION SENSITIVITY OF AQUATIC ORGANISMS

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OVERVIEW

An attempt was made in this report to assess the scientific literature regarding the effects of ionizing radiation on aquatic organisms. An exhaustive review of such a broad topic would have been beyond the intended scope of this report. Instead, prominent reviews and selected individual studies were identified which are representative of the literature and are relevant to an assessment of the DOE interim dose limit of 1 rad-d^{-1} to native aquatic organisms. The DOE has selected this dose rate limit to protect native animal aquatic organisms from exposure to radioactive material discharged to natural waterways.

Radionuclide contaminants with long half-lives have the potential for exposing generations of aquatic organisms from internal and external exposure pathways. In assessing the dose-response relationship for various biological organismal and population endpoints, however, investigators have frequently used external sources of cobalt-60 or cesium-137. These external gamma-ray sources are not only easier to use under controlled laboratory conditions, but permit accurate estimates of dose and dose rates delivered to organisms when compared to aqueous radionuclide contaminants. This is especially true for radionuclides whose metabolic significance may vary drastically with particular life stages. One exception is tritium in the form of tritiated water, which is not metabolized and distributes itself externally and internally in a constant concentration. At equilibrium, dose and dose rate estimates to soft tissue are, therefore, directly proportional to external water concentrations.

Acute Exposure Studies. Numerous controlled laboratory studies have been conducted in which aquatic organisms have been subjected to relatively high doses delivered in a very short time. Although acute radiation exposure studies can not directly derive an acceptable exposure dose rate limit, these studies are, nevertheless, useful in establishing the relative sensitivity among aquatic organisms in relation to other terrestrial organisms including man. Acute studies are equally useful in defining changes in radiosensitivity at various life stages.

In Section D2 of this report, summary results are presented for acute exposure conditions which assess mortality, developmental, reproductive, and physiological effects. Experiments indicate that the radiosensitivity of aquatic vertebrates is not too dissimilar to that of terrestrial mammals, and, like mammals, aquatic vertebrates exhibit enhanced sensitivities during embryogenesis and early growth stages. In general, invertebrates tend to be at least one or more orders of magnitude less sensitive to the effects of radiation. A unique and complicating aspect of aquatic studies is that absolute dose-response relationships are difficult to quantify. This is due to the complex influence of environmental factors that modify the impact of radiation exposure. For instance, unlike mammals, the metabolic activity of aquatic organisms is largely dictated by ambient temperature which affects the response to a given radiation exposure. Thus, even a modest shift in temperature can significantly shift the dose-response curve for most biological endpoints.

Chronic Exposure Studies. Sections D3 and D4 summarize controlled laboratory studies that have been undertaken to study the impact of chronic radiation exposure on select species of aquatic organisms. There have also been a few field studies in which aquatic organisms have been subjected to chronic radiation in their natural environment. Collectively, these studies support the following conclusions:

- Reproductive and early developmental stages of aquatic organisms are most sensitive to chronic irradiation
- Aquatic vertebrates are considerably more radiosensitive than invertebrates
- Although some effects have been observed among individual members of a population at chronic dose rates of about 1 rad-d^{-1}, to date, no significant population effects have been observed at these levels

These conclusions, however, have not been reached without some reservations (Sections D5 and D6). Investigators almost universally recognize that our present day data base is far from complete and most certainly not without flaws. When considering ecosystems, populations are of more interest than individuals, and a clear understanding of radiation effects that operate at the population level must, therefore, be established. Little, for instance, is known about the modification of radiation effects by ecological factors such as competition for survival/food, temperature, and other normal stresses which are characteristically not accounted for in controlled laboratory environments. Even when a natural environment is available for study, such as the White Oak Lake, there are unresolved difficulties such as (1) obtaining suitable controls, (2) assessing the impact of earlier higher dose rates, and (3) establishing a dose response relationship from limited dose-rate data.

Lending credibility to the limited data on aquatic organisms is that the data generally conform with scientific expectations that can be extrapolated from knowledge of radiation effects on terrestrial/mammalian systems for which an abundance of data exists. This expectation is not unreasonable since evolutionary commonalities exist at the organ, cellular, and molecular levels.

Thus, it is not surprising that the estimated mutation rate of 2×10^{-7} per rad per locus for the guppy and the doubling dose of 54 rads in the rainbow trout are highly representative of values established for mammals inclusive of humans.

The National Council on Radiation Protection and Measurement in its recent assessment (NCRP 1991; Report No. 109, "Effects of Ionizing Radiation on Aquatic Organisms") stated:

> *. . . it seems highly likely that chronic irradiation at dose rates in the lower portion of the 10 - 100 mGy-d*$^{-1*}$ *range, in particular, would not have a significant effect on the exposed population unless these were already at risk due to over exploitation (e.g., fishing) or to exposures to other environmental stressors.*
>
> *. . . Adoption of a reference level of 0.4 mGy-h*$^{-1**}$ *appears to represent a reasonable compromise based on current information, i.e., considering both the nature of the effects observed at this dose rate and the limited amount of information on effects of radiation in natural populations, including interactions between ionizing radiation and ecological conditions.*

It is also important to point out that a dose-rate limit of 1 rad-d^{-1} is likely to apply to a limited percentage of a population group within a given ecosystem. Contaminated environments are most frequently the result of point discharges that generate a varying dose field within the ecosystem. A heterogeneous dose field implies that the mean population exposure may be considerably lower than exposure at the point of discharge either because the population of sessile organisms exists throughout the varying dose field, or because mobile organisms experience a time-varying dose rate as they migrate within the environment.

Thus, on the basis of currently available data, it appears that the dose-rate limit of 1 rad-d^{-1} is not likely to result in significant impacts on aquatic populations. This tentative conclusion is supported by the failure to demonstrate significant effects at this dose rate. Moreover, even when organismal changes have been demonstrated at moderate (but above 1 rad-d^{-1}) dose rates, their impact on the overall population size was either insignificant or could not be demonstrated in a laboratory environment. The general consensus among scientists is that the resultant radiation stress of 1 rad-d^{-1} is likely to be a minor stress in relationship to other natural and anthropogenic stresses that regulate and limit population sizes within a given ecosystem.

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* 10 mGy is equal to 1 rad

** 0.4 mGy-h^{-1} is equal to about 1 rad per day.

D1.0 INTRODUCTION

D1.1 Statement of Purpose

To protect native aquatic organisms, the Department of Energy (DOE), under DOE Order 5400.5, limits radiation exposure dose rates to 1 rad per day from radioactive material in liquid wastes discharged to natural waterways. The dose rate limit of 1 rad per day is consistent with guidance issued by the IAEA and the NCRP. The primary objective of this Appendix is to provide an overview of the literature in order to determine the appropriateness of the 1 rad per day dose rate limit, as a value that corresponds to the lowest observed adverse effect level (LOAEL).

D1.2 Background Information

Past practices of discharging radioactive effluents either directly to rivers, lakes, and oceans, or storage and shallow land burial of wastes have the potential for contaminating aquatic environments. Many radionuclide contaminants may enter the aquatic food chain and are metabolized and concentrated in select species. Other radionuclides may remain or concentrate in abiotic compartments of an ecosystem (e.g., silt). Radiation exposure to aquatic organisms may, therefore, result from internal and external sources involving multiple exposure pathways.

Radiation protection standards, including those involving natural resources, have been developed principally to protect human health. The underlying philosophy is that radiation standards that adequately protect humans also protect the environment and all other life forms. The National Academy of Sciences (NAS 1972) BEIR I Committee stated that:

> *Evidence to date indicates that probably no other living organisms are very much more radiosensitive than man so that if man as an individual is protected, then other organisms as populations would be most unlikely to suffer harm.*

A similar viewpoint was expressed by the International Commission on Radiological Protection in its 1977 Report No. 26:

> *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 is thought likely to be*

adequate to protect other species, although not necessarily individual members of those species.

The last sentence reflects a qualitative difference in how we perceive risks for humans compared to other species. For humans, radiation standards reflect the high value that is placed on the individual. The risk of injury or death of a few humans is considered highly undesirable and/or unacceptable. For non-humans, the loss of a few or many (provided that there is a large overall population) is not considered a limiting factor for setting standards but rather the response and maintenance of endemic populations.

Experimental studies to date have shown that fertility and fecundity* of the organisms and embryonic development are the most sensitive stages of the radiation response. It is precisely these attributes that are important in determining the viability of the population and, in turn, the homeostasis of the ecosystem at large.

It is well documented that radionuclides in the environment can be expected to produce substantially higher doses to certain organisms than to people inhabiting and/or deriving sustenance from the same environment. It must also be recognized that contaminant induced radiation exposure is but one of many stresses placed on aquatic populations by human activities. However, determining the mode of interaction of radiation (i.e., antagonistic, additive, or synergistic) with other environmental contaminants or stressors is difficult to assess under conditions of chronic exposure.

The International Atomic Energy Agency (IAEA) sponsored several conferences in the early 1970s aimed at limiting the release of radioactive wastes into marine environments. A panel of experts assessed radiation exposure to aquatic organisms from a wide variety of taxonomic groups and proposed models for doses received from natural background radiation, fallout from nuclear tests, and radioactive waste disposal practices. As a second major objective, the panel reviewed and discussed scientific thought on the effects on aquatic populations and ecosystems resulting from radiation dose received by individual members of a given species. The IAEA panel issued its findings in 1976 (IAEA Technical Reports Series No. 172, "Effects of Ionizing Radiation on Aquatic Organisms and Ecosystems").

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* Fecundity is a measure of the production of viable eggs.

Over the last two decades, a number of other reviews of the effects of radiation on aquatic organisms have been published (Polikarpov 1966; Templeton 1971; Chipman 1972; Ophel 1976; Templeton 1976; Woodhead 1976; Blaylock and Trabalka 1978; IAEA 1979; Egami 1980; NRCC 1983; Woodhead 1984; Anderson and Harrison 1986). These detailed reviews considered field studies and laboratory experimental data from both the marine and freshwater environments. By far, the largest amount of data has been collected on marine species. Where reasonable comparisons can be made, however, there is a lack of evidence that significant differences in response to radiation exist between marine and freshwater organisms (IAEA 1976). Moreover, a survey of the published literature indicates that the majority of cited references deal with acute exposures of select organisms studied under controlled laboratory conditions using external sources such as ^{60}Co or ^{137}Cs.

Nevertheless, radiation studies on aquatic populations in which radionuclides have been introduced into the water medium are documented in the literature, but are very difficult to interpret with regard to a dose-response relationship. In fact, these studies have provoked considerable debate among individuals and scientific groups (Blaylock and Trabalka 1978; Woodhead 1984; Anderson and Harrison 1986; IAEA 1976; NRCC 1983). A common deficiency of these studies is that they utilize an insufficient range of radionuclide concentrations to construct a dose-effect curve. But a more serious problem is that estimates of absorbed dose to the organisms are very difficult to assess and, in most instances, have not been provided. Consequently, studies which fail to provide dose/dose rate estimates were not included in this report.

Most recently, the National Council on Radiation Protection and Measurements (NCRP) was requested by the U.S. Department of Energy to review the literature on the effects of radiation on aquatic organisms and to provide a report which reflects our most current understanding of such effects. The DOE also requested that the NCRP provide guidance for a standard for the protection of populations of aquatic species. This request originated from concerns that deleterious effects may be occurring in freshwaters affected by DOE operating facilities and that the DOE has not adopted an acceptable standard for protecting aquatic organisms residing in those environments.

On August 30, 1991, the NCRP issued its report (NCRP Report No. 109, "Effects of Ionizing Radiation on Aquatic Organisms: Recommendations of the National Council on Radiation Protection and Measurement").

The report was prepared by an ad hoc committee of scientific experts (i.e., Scientific Committee 64-9), which reviewed, analyzed, and interpreted the existing body of literature. The focus of their report was limited to truly aquatic organisms (e.g., fish, crustaceans, molluscs, and benthic invertebrates). A considerable amount of data presented in this report has been extracted from NCRP Report No. 109.

D1.3 DOE Policy and Interim Standards

It is the policy of DOE to implement legally applicable radiation protection standards and to consider and adopt, as appropriate recommendations by authoritative organizations, e.g., the National Council on Radiation Protection and Measurement (NCRP), the International Commission on Radiological Protection (ICRP), and the International Atomic Energy Agency (IAEA).

DOE Order 5400.5 defines the requirements for radiation protection of the public and the environment. Specifically, the Order states:

> *To protect native animal aquatic organisms, the absorbed dose to these organisms shall not exceed 1 rad per day from exposures to the radioactive material in liquid wastes discharged to natural waterways.*

D1.4 Basic Ecological Concepts and Principles

Ecology is one of the major divisions of biology fundamental to all life. The word ecology is derived from the Greek root "oikos" meaning house; therefore, it is the study of houses or for practical purposes, environments. A more modern definition of ecology is the "study of the structure and functions of nature."

One method of assessing ecological concern is to conceptualize the levels of organization common to biology. Ecology is principally concerned with the study of four items: populations, communities, ecosystems, and the biosphere. A population is defined as any group of organisms. A community includes all the organisms of any given size geographical area; if the nonliving (abiotic) segment of the community is included, it is then known as an ecosystem. Finally, the biosphere is the sum totality of the earth, air, sea, and fresh water in which the ecosystems operate, as well as the organisms themselves.

As one proceeds from the cellular level to the biosphere, some attributes become more complex; others, however, become less complex. As an example, the amount of material removed from the water by an individual algal cell is quite variable; however, the amount removed by a large population of algal cells is more constant and can be mathematically modeled. A possible explanation of this is that as one individual slows down or speeds up, another individual appears to do the reverse. This compensatory mechanism, or system or checks and balances, is referred to as homeostasis. An interesting example of homeostasis is found in estuaries, where rivers empty into oceans. At this point, the physical and chemical make-up of the water system is constantly changing drastically due to tides; yet the biological community is extremely stable. To be able to understand this phenomenon, it is not only necessary to study the whole organism, but its parts and its changing environment as well. The level of organization that lends itself best to this type of study is the ecosystem.

D1.4.1 The Ecosystem

When considered from a functional point of view, an ecosystem has two basic components: the autotrophic component and the heterotrophic component. Autotrophic organisms (autotroph means self-nourishing) are able to synthesize protoplasm from inorganic compounds and to fix light energy. Heterotrophic organisms (heterotrophic means other-nourishing), on the other hand, utilize the complex materials synthesized by the autotrophs.

From a structural standpoint, an ecosystem may further be considered as having four components: abiotic substances, producers, consumers, and decomposers. The abiotic substances are merely the basic compounds and elements of the particular environment; the producers are the autotrophic organisms (largely the green plants); the consumers (sometimes referred to as macroconsumers) are heterotrophic organisms, mostly animals which utilize the organics present and ingest other plants and animals; and the decomposers (sometimes referred to as microconsumers) are heterotrophic organisms, mostly bacteria and fungi which break down the complex organic materials present and release simpler compounds for use by the autotrophs.

To understand the relation of structure and function in an ecosystem, it is necessary to develop a method of classification for this interplay. One method commonly used is called the trophic structure, where trophic means food, and each trophic levels (food level) is distinct and different.

D1.4.2 Trophic Structure and Energy Flow

The number of organisms that occur and the rate at which organisms in an environment metabolize is a direct function of the amount and rate at which energy flows. In effect, carbon, hydrogen, oxygen, and nitrogen may circulate between living and nonliving materials and can be used more than once. Energy can only be used once; it is then converted to heat, another energy form, and is lost from the local environment.

The movement or transfer of food from one organism to another in plants and the eating and being-eaten-by of animals is known as the food chain. Those organisms that obtain their foodstuffs in the same number of steps as other organisms are said to belong to the same trophic level. Green plants occupy the first trophic level, as they are the primary producers. Those organisms that eat plants, called herbivores, would be on the second trophic level. Those organisms that eat the herbivores are on the tertiary trophic level, and so on. It should be realized that this classification is functional, not species specific, and that an organism can occur on more than one trophic level. A greatly simplified food web is shown in Figure D-1, where part of a lake ecosystem is shown and notations are made of the trophic levels at which the different organisms are operating.

In looking at the fresh water food chain presented in Figure D-1, one notices that a very large group is missing, the decomposers or the microconsumers. In all ecosystems, some production is consumed by plants and/or animals belonging to this group. Dead organic material makes up the foodstuffs for this group which contains bacteria, fungi, mites, millipedes, worms, and molluscs. These organisms are often found so intimately associated that it is impossible to determine their individual effects on organic breakdown.

There are many different ecosystems that can be described. Each of these ecosystems is unique with respect to the organisms present, trophic structure, and overall community metabolism. The following major ecosystems can be described: oak-hickory forest, coniferous forest, prairie, desert, poplar forest, agricultural, pond, river, swamp, salt marsh, estuarine, near-shore ocean, and open ocean. In this report, only aquatic and possibly marine ecosystems are of relevance.

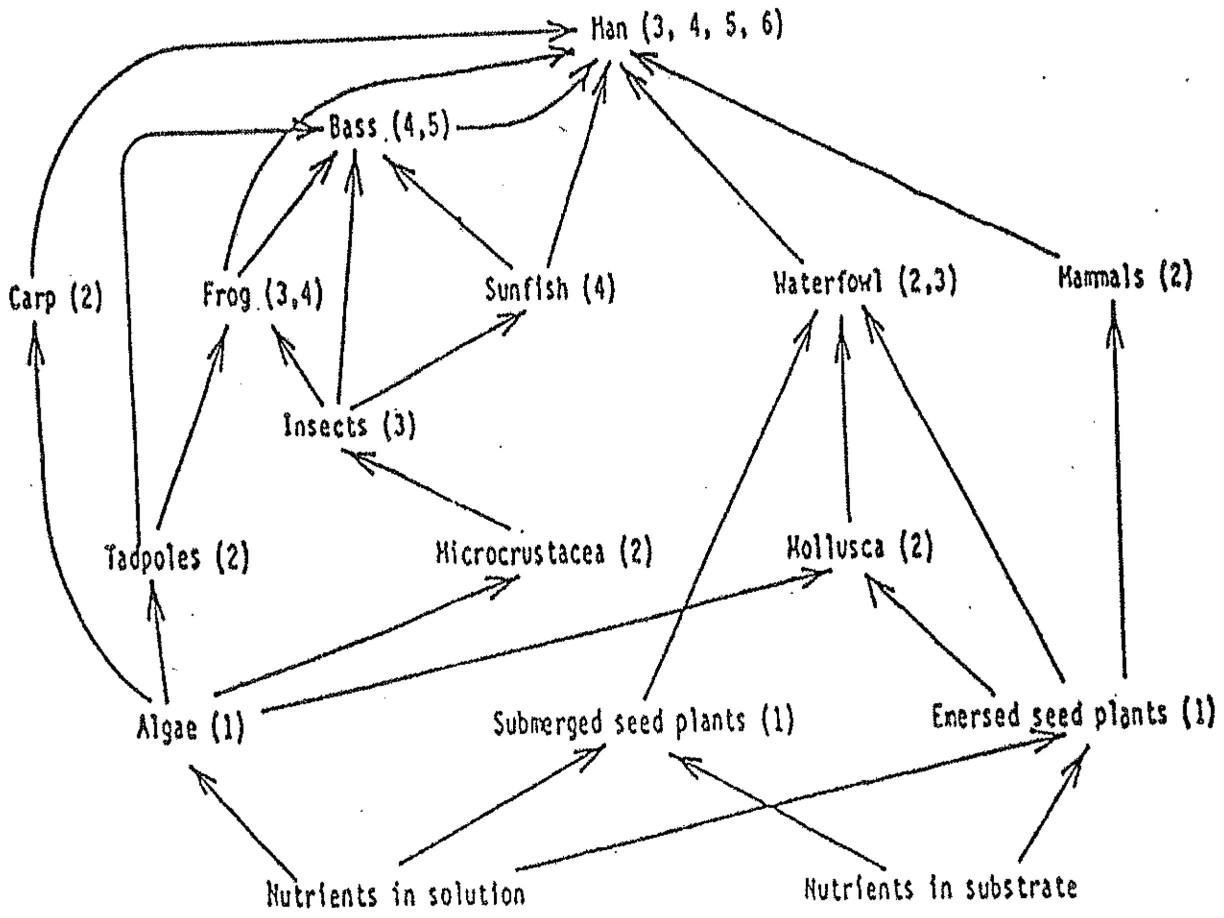

Figure D-1. A Simplified Lake Ecosystem (the parenthesized numbers note the trophic level)

D1.4.3 Aquatic and Marine Ecosystems

This group contains the pond, river, swamp, salt marsh, estuarine, near-shore ocean, and open ocean ecosystems. These systems, owning principally to nomenclature, appear more complicated to the nonecologist than terrestrial systems. To describe these systems, the communities and populations found in the generalized aquatic and marine ecosystem are listed and defined below. It should be noted that not all of these groups or organisms will be found in all ecosystems.

Benthic Community. This community consists of those organisms that live in and on the substrate. Selected typical population groups and types of organisms that may be found are discussed below.

> **Periphyton** - Periphyton are those organisms that grow on underwater substrates (attached) or burrow into the river bottom. This group includes but is not limited to: bacteria; yeasts and molds; algae; protozoa; coelenterates; sponges; corals.
>
> **Macroinvertebrates** - These are animals that live in and on the substrate and can be seen with the unaided eye. This group includes but is not limited to: flatworms; roundworms; segmented worms; molluscs; crustaceans; insects.

Lotic Community. This community is made up of those organisms that live in or spend most of their life in the water as opposed to the substrate. Selected typical population groups and types of organisms that may be found are discussed below.

> **Plankton** - Plankton are organisms suspended in a body of water and are incapable of sustained mobility against the water current. Most plankton are microscopic. This group includes but is not limited to: bacteria; yeasts and molds; phytoplankton; zooplankton (protozoa, rotifera, microcrustacea); ichthyoplankton (fish eggs, fish larval forms).
>
> **Macrophyton** - Macrophyton are aquatic plants with true leaves, stems, and/or roots. This groups includes the following organisms types: floating (float on surface, unattached); submerged (attached to the substrate, typically only leaves or reproductive structures, may not be under water); emersed (rooted in shallow water, with most of the plant being out of the water).
>
> **Macroinvertebrates** - These are the animals that live in or may be found in or on the water. This group includes but is not limited to: flatworms; roundworms; segmented worms; macrocrustacea; insects.
>
> **Vertebrates** - Vertebrates are those organisms with backbones that spend all or much of their life in running water. This group includes but is not limited to: fishes; turtles; frogs; snakes; mammals.

To summarize the above groups, a generalized trophic structure is presented in Figure D-2. It should be noted that all the communities are represented and that the food web begins with the primary producers, goes up to the herbivores, and then to the carnivores, so that three distinct groups and four trophic levels are represented.

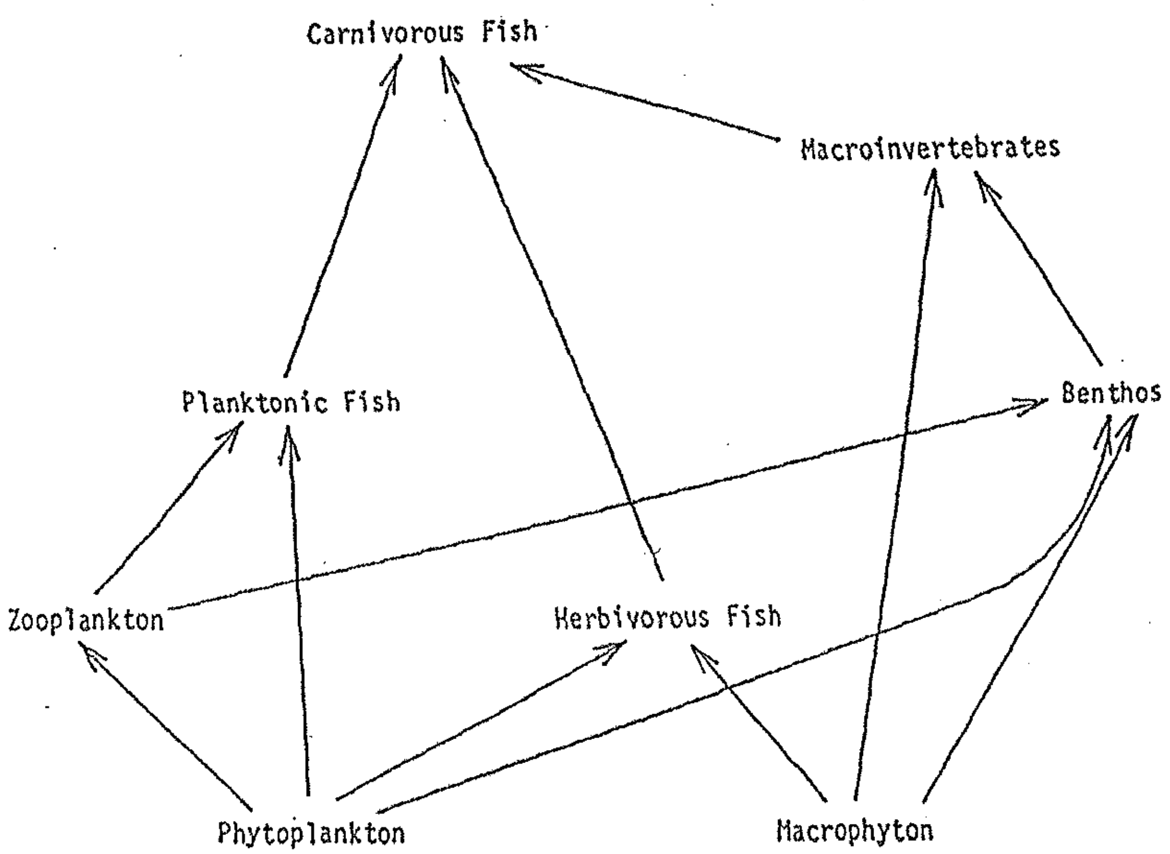

Figure D-2.Generalized Major Trophic Structure of Water Systems

D2.0 EFFECTS DUE TO ACUTE EXPOSURE

The effects of radiation on living systems are complex and involve interactions with individual atoms and molecules. The consequences of such interactions may be observable at the levels of macromolecules (i.e., chromosomes) and cells. Damage to somatic cells can affect the physiologic function of tissues, organs, or the whole organism. Damage to reproductive cells can induce deleterious mutations in future generations and, for sufficiently high exposures, may result in lowered reproductive capacity leading to population extinction.

It is fully recognized that environmental contamination from routine effluents and waste do not result in acute exposures with measurable effects. Research on the effects of acute exposures to radiations of aquatic organisms, nevertheless, provides important information which improves our understanding of chronic low-level exposure. In effect, the major difference between acute and chronic exposure is limited to the impact of time which allows for cellular repair and/or accelerated replacement of damaged cells. For example, a sufficiently large acute exposure, which may be lethal, may have minimal consequences if given over a longer period allowing repair/replacement of somatic cells of a tissue(s). Similarly, acute doses that might render an organism sterile may only have minor or transient reproductive impacts if spread out over time. By their nature, acute radiation data can be obtained in a short period of time under controlled laboratory conditions and provide useful information regarding: (1) relative sensitivities among species, (2) relative sensitivities at various stages of life stages/maturation for a given specie, and (3) the potentially complex and modifying interactions between radiation and other environmental conditions. Ecologically significant biological endpoints that are common to acute and chronic radiation exposure, include mortality, reproductive capacity, developmental and physiological effects.

D2.1 Mortality

A major reference point in radiation biology is to assess the upper limit of radiation sensitivity expressed in terms of lethality. Common measurement of this biological endpoint for mammalian systems is the determination of radiation dose that is required to kill 50% of the organism within a 30-day period (i.e., $LD_{50/30}$). Information regarding the lethal dose response for various aquatic organisms has been reviewed by several authors (Chipman 1972; Templeton 1976; Rice 1974; Ophel 1976; Blaylock 1978; Anderson 1986) and is summarized in Table D-1.

In general, lower forms of aquatic organisms show a considerably reduced sensitivity to acute radiation exposure than terrestrial mammals. (For humans, a mid-lethal exposure is estimated at about 400 rem.)

Table D-1. Relative Sensitivities of Aquatic Organisms as Measured by Acute Lethal Dose-50

Organism	Range of LD_{50} (rad)
Microorganism	
bacteria	4,500 - 735,000
algae	3,000 - 120,000
protozoans	10,000 - 600,000
Invertebrates	
crustaceans	1,500 - 57,000
molluscs	20,000 - 109,000
echinoderms*	20,000 - 200,000
Vertebrates	
fish	5,600 - 100,000
amphibians	< 1,000 - 10,000

* A phylum of marine organisms which includes starfish, sea urchins, sea cucumbers, etc.

D2.2 Reproductive Capacity

Beyond mortality, the effects of radiation on reproductive potential is the second most important parameter for assessing the relative radiosensitivity of a given specie. Like mortality, complete sterilization would lead to the elimination of a given specie within an ecosystem. Although the invertebrate germ cells appear to be less sensitive to radiation than those of mammals, doses as low as a few hundred rads in some species result in reduced egg production (Hoppenheit 1973; Anderson 1986), and doses greater than 1000 rads can cause irreversible damage to reproductive tissue resulting in permanent sterility in fish (Egami 1979).

D2.3 Developmental and Physiological Effects

Consistent with higher life-forms, there is a period of heightened radiosensitivity preceding and concurrent with organogenesis. Stages in decreasing order of sensitivity are (1) newly fertilized eggs, (2) early gastrulation, (3) early cleavage, and (4) post-organogenesis. During the most sensitive embryonic stages, doses as low as 15 rads demonstrated observable developmental disturbances in salmon embryos (Bonham 1963; Donaldson 1957). Eggs at 24 hours post-fertilization showed an LD-50 of 90 rads. At 32-cell stage, the LD-50, depending on water temperature, ranged from 100 rad (at 13.3°C) to 300 rads (at 11.3°C); hatchability of eggs irradiated after organogenesis was not affected by experimental doses in the range of 500 - 16,000 rad (Frank 1973). For invertebrates comparable disturbances in embryonic development required doses which were higher by at least one order of magnitude (Blaylock 1978).

D2.4 Physiological Effects

The interaction of radiation with biomolecules and the resultant acute changes at the cellular, tissue, and organismal level are numerous and well documented in the literature. In review, all cells may potentially be damaged by radiation, but some cell types are more susceptible to radiation injury than others. In general, immature and rapidly dividing cells are most sensitive while non-dividing and fully differentiated cells are least sensitive to radiation. Cellular injury to the nucleus prevents the cell from dividing properly or not at all. For stem cells whose primary purpose is to provide new cells by controlled cell division, a reduction or cessation in cell division may result in short-term physiological changes that for high doses may be lethal and for lowest doses predispose an organism to other environmental stresses which affect survival.

Among the most sensitive mammalian cells, for example, are those of the blood-forming tissues, which produce red and white blood cells. A reduction or cessation of stem cell division can lead to anemia, impaired blood clotting, hemorrhage, and most significantly infection from viruses, bacteria, and parasites. For mammals, inclusive of humans, hemopoietic doses in excess of 100 rads result in classical signs and symptoms that are collectively referred to as the "bone marrow syndrome."

The mammalian model for the effects of acute radiation exposure on blood-forming tissues has been applied in studies of fish. Past studies of fish have investigated changes in (1) cellular and sub-cellular morphology, (2) tissue cellularity, and (3) functional expressions with regard to immunological competence (Lockner 1972; Cosgrove 1975; Preston 1959; Shechmeister 1962). Relative to the mammalian models, the results of these studies showed that the hemopoietic tissues of fish were considerably more radiation resistant.

D2.5 Summary

Numerous scientific studies have been conducted in which aquatic organisms have been exposed to acute doses of radiation under controlled laboratory conditions. For acute radiation exposure studies, relevant biological endpoints include (1) organismal death, (2) reproductive capacity, and (3) developmental and physiological changes which affect the organisms life span or its ability to cope with other environmental stresses (e.g., natural fluctuations in environmental conditions; resistance to pathogens/parasites; etc.). In general, these studies show that adult fish exhibit radiation sensitivities that are lower than those of terrestrial mammals. Invertebrates tend to have an even lower sensitivity to radiation by at least one or more orders of magnitude when compared to fish. The most sensitive periods in the life cycle of aquatic organisms are the early embryonic stages.

It is logical to expect the lower radiation sensitivity of aquatic cold-blooded organisms relative to warm-blooded mammals since the former exist at considerably lower temperature which affects the impact of radiation-induced biochemical lesions.

Classical studies cited more than 50 years ago have firmly established the interrelationship between cellular metabolic rate and radiation sensitivity (Alexander and Bacq 1961). Dramatic increases in radiosensitivities can be observed for modest increases in ambient water temperature. In addition to ambient water temperature, metabolic activity (and, therefore, radiosensitivity) can also be affected by other factors such as salinity, water chemistry, food/nutrients, etc. Other factors thought to influence radiation sensitivity among species are nuclear volume to cellular volume of critical cell lines, number of chromosomes, and biochemical differences. For example, most invertebrates maintain their intracellular osmotic pressure by means of amino acids or small peptides (Alexander and Bacq 1961). Vertebrates, on the other hand, maintain their osmotic balance almost entirely by the segregation of Na^+, K^+, Cl^-, Ca^{++}, Mg^{++}, HCO_3^-, $H_2PO_4^-$, and SO_4 in intra- and extra-cellular fluids. Differential concentrations of these inorganic ions within and external to mammalian cells are achieved by a membrane-bound active transport mechanism that is relatively sensitive to radiation damage.

D3.0 EFFECTS DUE TO CHRONIC EXPOSURE

Radionuclide contaminants in the environment can enter the complex geochemical and biological components of an aquatic ecosystem and result in chronic internal and external exposures of individual organisms. Under conditions of chronic exposures, biological damage may result that is similar to that of acute exposure; however, considerably larger cumulative doses are required to produce injurious effects. This incremental tolerance to radiation is a function of dose rate and is due to the combined effects of repair mechanisms within individual cells and the ability of critical tissues to replace damaged or dead cells with new cells. Cellular repair mechanisms involving the vital nucleic acids (i.e., DNA and RNA) are well documented in the literature and need no further discussion. Equally well documented is the homeostatic regulation of cell proliferation/replacement of specific radiosensitive cells and tissues. Among the most radiosensitive cells are blood cells, cells of the digestive tract, and reproductive germ cells. Within limits of exposure, irreparable cell/tissue damage is compensated by the enhanced mitotic activity of the corresponding pool of stem cells. The existence of repair mechanisms and homeostatic modulation suggests that there is a chronic exposure dose rate at which no significant effects occur. Identifying the maximum dose rate below which no significant effects to the population are likely to occur would provide valuable information with respect to setting limits for environmental contamination. In this section, major studies on chronic irradiation of aquatic organisms are summarized which provide a tentative reference value for defining such a limit.

Effects at low dose rates, however, are difficult to detect in natural populations where other environmental factors affecting population dynamics may far exceed the subtle effects of lower dose rates. To complicate matters, the traditional methods of linear extrapolation from observable high dose/dose-rate effects commonly used to estimate radiation induced stochastic effects, such as cancer, are largely inappropriate for the biological endpoints affecting population dynamics and ecosystems. With the exception of population genetic effects, somatic cell injury leading to organismal mortality, physiological, reproductive, and developmental effects are generally threshold dependent.

D3.1 Mortality Studies on Vertebrates

In controlled laboratory studies, Chinook salmon exposed to 0.5 rad per day, as embryos through the time of release as smolts to their natural environment, showed no significant excess mortality

(Donaldson 1964; 1970). These studies took advantage of the migratory habit and the fecundity of Chinook salmon to make a continuing long-term study of the effect on a population of chronic low-level gamma-irradiation from a ^{60}Co source during embryonic development. Eggs were first irradiated at dose rates ranging from 0.5 rad-d^{-1} to 20 rads-d^{-1} from shortly after fertilization until feeding commenced. The fingerlings were reared and then allowed to migrate to sea; those that returned to the hatchery during the second year were precocious males; and during the third and fourth years following irradiation both male and female adults returned. Various crosses were made and some of the eggs and larvae obtained from irradiated fish were re-irradiated.

This series of long-term experiments involving large numbers of fish (96,000 to 256,000 fingerlings were released per experiment) indicate that irradiation at rates between 0.5 rad-d^{-1} and 5.0 rads-d^{-1} (total of 355 rads) from the fertilization stage to the feeding stage produced no damage to the stock sufficient to reduce the reproductive capability over a period of several generations. In fact, irradiated females returned to the laboratory site of release to spawn in greater numbers than controls producing a larger number of viable eggs. This potential hormetic effect at low dose rates was lost at higher dose rates. Exposing embryos up to the time of release to dose rates ranging from 0.5 rad-d^{-1} to 47.5 rads-d^{-1}, Hershberger (1978) and Woodhead (1984) observed a lower return of spawning adult females at dose rates equal to or greater than 9.5 rads-d^{-1}.

Several mortality studies of guppies have also been conducted under various chronic exposure conditions defined by radiation source, dose rate, duration of exposure, and stage of development. Specific parameters and results of these studies are summarized in Table D-2.

D3.2 Mortality Effects on Invertebrates

An important member of freshwater ecosystems is the "water flea," _Daphnia pulex_. These small planktonic crustacea represent a vital link in the aquatic food chain. A reduction in population mortality was observable only for chronic exposure dose rates of 1150 rads-d^{-1} (Marshall 1962). Another common organism of aquatic ecosystems are snails. The pond snail, _Physa heterstropha_, showed reduced survival for chronic exposure dose rates in excess of 240 rads-d^{-1} (Cooley 1971). For marine invertebrates threshold mortality values have been cited for blue crabs (Engel 1967), clams, and scallops (Baptist 1976). Table D-3 summarizes the exposure conditions and threshold population mortality dose rates for these invertebrates.

Table D-2. Laboratory Studies of Mortality in Fish Under Chronic Exposure Conditions

Species/Stage	Exposure Conditions			Observation	Reference
	Source	Dose Rate (rads/day)	Duration (Days)		
Oncorhychus tschawytscha (Chinook Salmon)					
• embryos to alevins	^{60}Co	0.51	61-69	• No excess mortality; • Increased return of spawning females; • Increased no. of viable eggs	Donaldson 1964; 1970
• embryos to alevins	^{60}Co	0.5-47.5	71-86	There were fewer returning spawning adults at dose rates ≥ 9.5 rads/day	
Poecilia reticulata (Guppies)					
• embryos	^{137}Cs	4.1-30.5	up to 988	No excess mortality	Woodhead 1977
• embryos	tritiated H_2O	5-100	17	No excess mortality	Erickson 1973
• 1 week old hatchlings	tritiated H_2O	10-210	21-30	No excess mortality	Erickson 1973

Table D-3. Mortality of Aquatic Invertebrates Under Laboratory Conditions

Organism/Life Stage	Exposure Conditions			Observation	Reference
	Source	Dose Rate (rads/day)	Duration (Days)		
Freshwater					
• *Daphnia pulex*/all life stages (Water flea)	^{60}Co	412-1370	20-25	Increased mortality rate observed only for dose rates ≥ 1150 rads/day	Marshall 1962
• *Physa heterostropha*/adults (Pond snail)	^{60}Co	24-600	168	Reduced survival at dose rates ≥ 240 rads/day	Cooley 1971
Marine					
• *Callinectes sapidus*/juveniles (Blue crab)	^{60}Co	77-696	70	Lowered survival observed at 696 rads/day only	Engel 1967
• *Argopecten irradians*/ juveniles (Scallop)	^{60}Co	0.14-890	84	No observable reduction in survival	Baptist 1976
• *Mercenaria mercenaria*/ juveniles (Clam)	^{60}Co	1.4-890	426	Observed lowered survival at dose rates ≥ 380 rads/day	Baptist 1976

In summary, mortality/survival studies of aquatic organisms indicate that invertebrates are at least one or more orders of magnitude less sensitive than vertebrates. For the more sensitive vertebrates, deleterious effects on survival have not been demonstrated at dose rates below 10 rads-d^{-1}.

D3.3 Chronic Exposure and Reproductive Effects

The production of sexual cells (ova and spermatozoa) may be divided into three periods: a period of cell multiplication; a period of cell growth; and a period of maturation. During the first period, germ cells (spermatogonia in testis, ovogonia in ovary) divide a number of times in the same way as somatic cells. During the rather long second period, the sexual cells do not divide, but the volume of the cytoplasm increases and the diploid cell prepares itself for meiosis. During the last period, cell division in male and female sexual cells occurs without prior chromosome replication leading to mature haploid male and female reproductive cells.

The most radiosensitive cells are the gonia (i.e., first period), especially the spermatogonia, while the mature sexual cells are markedly less sensitive (Rackham 1984). Thus, an organism exposed to sufficient doses of radiation may remain fecund until it has exhausted its stock of mature cells. Temporary, early reduction in primary spermatogonia has been observed at dose rates as low as 1 rad-d^{-1} in fish exposed to tritiated water and 2.8 rads-d^{-1} from external gamma radiation (Hyodo-Taguchi 1977; 1980). Atrophy of male reproductive tissues was observed in adult mosquitofish, *Gambusia affinis*, irradiated for 47 days to dose rates ranging from 31.2 rads-d^{-1} to 130 rads-d^{-1} (Cosgrove 1973). In a general population of female guppies, *Poecilia reticulata*, impaired oogenesis was observed for all dose rates ranging from 4.1 rads-d^{-1} to 30.5 rads-d^{-1} (Woodhead 1977). For higher dose rates, impaired oogenesis was not only more pronounced but appeared at shorter time intervals following the onset of chronic exposure.

Laboratory population of the aquatic snail, *Physa heterostropha*, were exposed to chronic gamma-irradiation during their life span at dose rates up to 120 rads-d^{-1}. Partial gonadal atrophy was observed in a limited number of snails only at the highest doses. Table D-4 summarizes the above-cited studies involving effects of chronic radiation on the reproductive tissues of aquatic species. It is not a coincidence that all but one of these laboratory studies involved the use of an external gamma radiation source. There have, in fact, been numerous studies in which radiation exposure effects were assessed for a variety of radionuclides that had been added to the water medium at various concentrations. Most of these studies have a limited value, however, for assessing regulatory dose rate criteria due to the difficulty and uncertainties in converting radionuclide concentrations in water with exposure estimates. For metabolically active radionuclides, exposure varies not only among tissues but for a given tissue with time (i.e., embryologic/developmental stage). Among the few radionuclides for which these concerns do not apply is tritium (H-3) in the form of tritiated water (HTO). The dispersal of tritiated water into an aquatic system is governed by the same processes that control the transport and distribution of ordinary water. Thus, tritiated water will exist in intra- and extra-cellular fluids in the same concentration as in the general medium.

As a result, internal exposure is essentially uniform among tissues, and dose rates are directly proportional to water concentration and are readily calculated. A potential limitation of using tritiated water is the potential impact of chemical transmutation by a small percentage of tritium which may become organically bound to critical macromolecules. This concern is addressed in a later section of this report.

Fecundity studies have been conducted under laboratory conditions for several species of fish and invertebrates. Fecundity of the guppy exposed to dose rates of 4.1, 9.6, and 30.5 rads-d^{-1} neonatal stage to adulthood was reduced at all dose rates as indicated by a decreased brood size and increased frequency of sterile adults (Woodhead 1977). Significant increases in the percentages of unfertilized eggs and sterile offsprings were the result of matings involving unirradiated females and irradiated male medaka, *Oryzias latipes*, at dose rates ≥ 6.5 rads-d^{-1} for 60 days (Hyodo-Taguchi 1980). Under laboratory conditions, egg and egg capsule production were progressively reduced in the pond snail at dose rates between 48 rads-d^{-1} and 600 rads-d^{-1} (Cooley and Miller 1971); and for population birth rates greater than 460 rads-d^{-1}, decreased population birth rates were observed for the water flea, *Daphnia pulex*. These and other studies of aquatic fecundity are summarized in Table D-5.

D3.4 Studies of Natural Populations

In rare instances, aquatic ecosystems have been contaminated and have provided study data of natural populations. The radioactively contaminated White Oak Lake at the Oak Ridge National Laboratories has been studied by several authors. White Oak Lake served as the final settling basin for radioactive waste from the Oak Ridge National Laboratory.

Doses from internal emitters have been estimated from measurements of amounts of radionuclides in specific tissues by Blaylock (1969) with _Gambusia affinis_ and Cooley and Nelson (1970) with _Physa heterostropha_. Blaylock estimated doses from five internal emitters (^{60}Co, ^{65}Zn, ^{90}Sr, ^{106}Ru, ^{137}Cs) as well as gamma doses from bottom sediments of White Oak Lake. The combined dose to *Gambusia* from internal emitters was about 1.75 rads-yr^{-1}, and total external gamma was 10.9 rads-d^{-1}. The calculations for the snail (Cooley and Nelson 1970), involving internal doses and doses from the surrounding water and algae, as well as radiations from bottom sediments are about as complete as one would expect to encounter in this type of analysis. The snails were estimated to receive about 0.65 rad-d^{-1} from all sources.

Over the years, several studies have been conducted on the reproductive aspects of the mosquitofish to dose rates greater than 1 rad-d^{-1} in the early 1960s and falling to 0.35, 0.18, and 0.06 rads-d^{-1} by 1965, 1971, and 1975, respectively (Blaylock 1969; Trabalka and Allen 1977; Blaylock and Frank 1980).

Blaylock (1969) was the first to study the fecundity of a population of mosquitofish, _Gambusia affinis_, in White Oak Lake. These fish had been exposed for about 100 generations to continuous irradiation from radioactive wastes in bottom sediments. However, there was no evidence that the radioresistance of these fish had been selectively enhanced over this period of time (Blaylock and Mitchell 1969). At the time of the study, the dose rate to fish was estimated to be 10.9 rads-d^{-1}. Brood size is positively correlated with body size, so Blaylock compared regressions of log transformations of the numbers of viable embryos on body lengths. Non-irradiated fish were collected from a pond about two miles upstream from White Oak Lake (and above the point of entry of radioactive wastes). The slopes of these regressions were the same, but the intercepts differed significantly. Blaylock's analysis showed that, in general, the number of viable embryos produced by the control fish was only about 60-70% of that produced by irradiated fish in White Oak Lake. However, the irradiated fish produced over twice as many dead embryos and more abnormal embryos (based on examination of over 7800 embryos).

In summary, the mosquitofish studies of Blaylock and others showed a surprising response: A significantly larger brood size occurred in the irradiated as compared to the unirradiated population, although significantly more dead embryos and physical abnormalities were observed in the irradiated broods. The authors suggested that the increased fecundity represents a means by which a natural population, having a relatively short life cycle and producing a large progeny, can adjust rapidly to an increased environmental stress caused by radiation; and the decreased embryo viability may well be attributable to a genetic load of radiation-induced recessive lethal mutations.

Cooley and Nelson (1970) examined responses of the snail, *Physa heterestropha*, to continuous irradiation in the laboratory (see also Cooley and Miller 1971; Cooley 1973b) and in a small waste-contaminated seep near White Oak Lake. Laboratory experiments were conducted at two temperatures (15 and 25°C) and effects were generally intensified at the higher temperature. At 25°C, fecundity decreased at dose rates ranging from 1 to 25 rads-hr^{-1}. At 15°C, 5 rads-hr^{-1} significantly decreased fecundity, but lower rates did not. The life span of adult snails was shortened by dose rates above 1 rad-hr^{-1} at 25°C. In 1970, an experiment was conducted in a small pond adjoining White Oak Lake. Snails occupying this area had been exposed to continuous irradiation since 1954. In 1970, the dose rate was estimated at around 0.65 rad-d^{-1}, but in the past it had been appreciably higher. At the beginning of the experiment, three containers, each stocked with 70 snails from North Springs (the control population), were placed in East Seep. Each of three other containers were stocked with 70 snails from the East Seep. Egg capsules were collected every five days from each container. The control snails produced more capsules per snail, but irradiated snails had a higher average number of eggs per capsule. When the total numbers of eggs produced per snail were compared, the two populations did not differ significantly. Cooley and Nelson concluded that, whereas continued radiation exposure had reduced the frequency of capsule production, there had been a compensatory increase in the number of eggs per capsule.

D3.5 Effects on Growth and Development

Pertinent biological endpoints commonly used to assess the effects of radiation on growth and development include (1) the rate of growth as determined by physical dimensions and weight, (2) the final mature size and weight, (3) survival rate into adulthood, and (4) physical abnormalities involving the gills, eyes, etc. Exposure of coho salmon embryos and hatchlings to a dose rate of 0.42 rads-d^{-1} produced an increased incidence of defects involving the gills.

However, chinook salmon embryos, *Oncorhynchus tschawytscha*, exposed to dose rates of 0.51 rads-d^{-1} exhibited higher body weights at the time of their release to a natural environment (Donaldson 1964). In another study of chinook salmon embryos irradiated at dose rates between 0.5 rad-d^{-1} and 47.5 rads-d^{-1}, growth rates of smolts were assessed (Hershberger 1978). No significant differences were observed for dose rates below 9.5 rads-d^{-1}. Above 9.5 rads-d^{-1}, the reduction of growth rate was, in general, more pronounced with increasing dose rates.

Growth and developmental effects have been studied in several species of fish reared in tritiated water (Erickson 1973; Strand 1973b; Walden 1973). Dose rates of up to 210 rads-d^{-1} resulted in no consistent growth and developmental effects in guppies. No observable effects were apparent in a population of rainbow trout exposed to 2 rads-d^{-1}. A measurable and significant reduction in the mean eye diameter, however, was observed in stickieback, *Gasterosteus aculeatus*, for exposure dose rates above 200 rads-d^{-1}. Table D-6 summarizes growth and development effects among select fish species chronically exposed to external radiation and tritiated water under laboratory conditions. Growth and developmental effects have also been studied on a natural population of mosquitofish at White Oak Lake over a several year period (Blaylock 1969). During that time the dose rate was reduced to about 0.35 rad-d^{-1}. Although an increased frequency of abnormal embryos was observed at this low dose rate, there is almost universal consensus among researchers that results cannot be attributed exclusively to radiation and/or to radiation levels corresponding to the time of the study. The NCRP (1991) cautioned that ". . . Radiation exposure regimes at the time that studies were conducted (1960s and 1970s)" have sometimes been recorded by reviewers (and authors) without recognition of the potential impacts of earlier exposures to anthropogenic [man-made] radiation levels orders of magnitude greater (and of the resulting radiation-induced genetic load accumulated). . . . In no case, including examples cited from research on White Oak Lake populations, can results be attributed exclusively to effects of ionizing radiation."

Radiation impacts on growth and development have also been studied on aquatic invertebrates. Several studies of the freshwater flea, *Daphnia pulex*, (Marshall 1962; 1966; 1967) and the pond snail, *Physa heterostroha*, (Cooley 1971) indicate threshold dose rates of about 400 rads-d^{-1} and 240 rads-d^{-1}, respectively. Among marine invertebrates, impaired growth and development in blue crabs, scallops, and clams were not observed for dose rates less than about 400 rads-d^{-1} (Engel 1967; Baptist 1976).

Table D-6. Developmental Effects in Fish from Chronic Exposure Radiation Under Laboratory Conditions

Species/Stage	Exposure Conditions			Observation	Reference
	Source	Dose Rate (rads/day)	Duration (Days)		
Oncorhynchus kisutch (Coho salmon)					
• embryos and alevins	^{60}Co	0.42	91	Increased number of ocular defects	Donaldson and Bonham 1964
Oncorhychus tschawytscha (Chinook Salmon)					
• embryos	^{60}Co	0.51	61-69	• Increased weight of smolts; • Inconclusive results on F_1 generations from returned fish (released as smolts)	Donaldson 1964; 1970
• embryos	^{60}Co	0.5-47.5	71-86	Lower rate of growth (smolts) at dose rates ≥ 9.5 rads/day	Hershberger 1978
Poecilia reticulata (Guppies)					
• embryos	tritiated H_2O	10-100	17	No consistent pattern of effects on growth and development, but males exposed to 1.85 rads/l were twice the weight of controls at 21 weeks of age	Erickson 1973
• 1 week old juveniles	tritiated H_2O	100-210	21-30	No consistent pattern of effects on growth and development	Erickson 1973
Salmo gairdneri (Rainbow trout)					
• embryos	tritiated H_2O	2	20	No effect on growth of larvae by end of 149 day observation period	Strand 1973(b)
Gasterosteus (Stickieback)					
• embryos	tritiated H_2O	100-410	7	Significant reduction in mean eye diameter at 3.7 and 7.4 rads/l	Walden 1973

D3.6 Physiological and Pathological Effects of Chronic Exposure

Under conditions of chronic exposure, somatic cell lines that are more radiosensitive than others may contribute directly or indirectly to impaired health and disease. Among the most sensitive somatic cells are those of the blood forming tissues (i.e., hemopoietic stem cells and their differentiated cell progeny). Mitotic inhibition and/or interphase cell death among these cells can lead to a host of conditions that affect the life span or survival of an organism. Biological endpoints relating to blood forming tissues can be assessed at various levels inclusive of (1) histological changes within hemopoietic tissues, (2) reduced immuno-competency towards infectious agents, and (3) reduced life span/survival.

Cosgrove, et al. (1975) studied histological changes of hemopoietic tissues located in the kidney and spleen of the mosquitofish, *Gambusia affinis*. Adult populations of fish exposed to a dose rate of about 12.5 rads-d^{-1} (^{60}Co) for 37 days showed no observable histological changes. Mild hemopoietic atrophy of the spleen and kidney of some fish were observed for dose rates in excess of 36 rads-d^{-1} and exposure duration in excess of 128 days.

A more quantitative endpoint for hemopoietic damage is the measurement of antibody titer to a specific infectious organism. Strand, et al. (1973a) subjected rainbow trout embryos, *Salmo gairdnerii*, to tritiated water resulting in dose rates of 0.2 rad-d^{-1} and 2 rads-d^{-1}. Antibody titers in juveniles and yearlings were measured in response to a challenge with the pathogen chondrococuus columaris. At the higher dose rate, the corresponding reduced antibody titer suggested evidence of a generalized state of immune suppression.

The quantity of body water was studied in adult medaka fish, *Oryzias latipes*, exposed to dose rates of 2.8 rads-d^{-1} to 210 rads-d^{-1}. A small decrease in percentage of body water was observed for higher dose rates which was attributed to failure of fish to maintain the normal proportion of soft tissue to skeletal mass (Kaufman 1973). This shift is normally seen as an effect of aging and in the irradiated fish population may, therefore, reflect a hastened aging process. A reduction in life span has also been observed in the pond snail for dose rates corresponding to 25 rads-d^{-1} (Cooley 1971).

D4.0 CYTOGENETIC AND GENETIC EFFECTS

Radiation may damage the genetic material of individual cells. Genetic damage to somatic cells can lead to a variety of disorders inclusive of cancer in the irradiated host organism, but is of minor concern in non-humans. Of potential concern is the genetic damage to reproductive cells which may result in mutations among future offsprings of the irradiated organisms. Genetic damage can be assessed by analyzing chromosomes within individual cells (cytogenetic studies) or observing discernable mutations in offsprings. Because reproductive cells are not readily studied for chromosomal damage, cytogenetic analyses frequently use somatic cells as surrogate models.

Over the past several decades, numerous studies have been undertaken to assess the effects of radiation and of radioactive contaminants on the hereditary material contained in somatic and reproductive cells of aquatic organisms. Most of these studies are cytogenetic and have been cited in several major reviews (IAEA 1976; Kligerman 1979; Anderson 1986; NCRP 1991).

D4.1 Cytogenetic Studies

A standard cytogenetic technique involves the analysis of chromosomes within individual cells arrested during metaphase when chromosomes appear as discrete structures that can be counted and assessed for morphological changes. In standard metaphase cytogenetic studies, individual chromosomes may be karyotyped (i.e., systematically characterizing individual chromosomes of a single cell by the overall length of chromosomes and by the lengths of the short arm and long arm of the chromosomes as dictated by the position of the centromere). Gross cytogenetic damage can be quantified by morphological changes that include formation of chromosomal fragments, translocation, dicentrics, abnormal chromosomal numbers, polyploidy, endoreduplication, etc. For aquatic organisms, however, there are two major limitations for applying standard cytogenetic techniques. The first difficulty is that many aquatic species have karyotypes represented by large numbers of small chromosomes. (This is in contrast to mammalian karyotypes that characteristically have fewer numbers of chromosomes which vary in size/morphology and are, therefore, readily distinguishable for karyotyping.) A second limitation for chronic exposure studies is that the organism is studied in the adult stage when mitotic activity of suitable cell lines has been drastically reduced. For these technical reasons, only a limited number of cytogenetic studies of aquatic organisms have been performed using standard metaphase karyotyping.

Standard metaphase chromosomal analysis has been attempted by several investigators. Kligerman, et al. (1975) selected the mud-minnow, _Umbra limi_, for studies on the effects of x-rays on chromosomal breakage. Although the investigators demonstrated the presence of visible chromosomal breaks, no dose-response relationship was discernable. Subsequently, metaphase cytogenetic studies of the mud-minnow were undertaken by other investigators. Mong and Berra (1979) studied the cytogenetic effects on gill and spleen cells and reported a dose-dependent increase in "aberrant" metaphases for cumulative doses between 330 to 940 rads. Suyanna and Etoh (1983) studied the effects of x-irradiation on the fish lymphocytes and reported an increase in chromosomal dicentrics formation at the lowest dose applied of 48 rads. The observed cytogenetic dose-response curve and level of sensitivity of fish lymphocytes is similar to mammalian inclusive of human lymphocytes, which are generally regarded as one of the most radiosensitive cell lines.

Owing to the difficulty of chromosomal analysis during metaphase, other investigators have attempted to quantify cytogenetic damage by scoring the presence of micronuclei in peripheral blood erythrocytes following exposure to radiation. (Unlike human red blood cells which do _not_ contain a nucleus/chromosomes, the erythrocytes of many other species are nucleated.) Micronuclei are either acentric (i.e., without a centromere) fragments or entire chromosomal strands. Upon cell division, the lack of a centromere prevents spindle attachment of these chromosomal structures which are then expelled from the cell nucleus and released to the cellular cytoplasm. By means of a stain, these extranuclear chromosomal structures can be identified microscopically. The manifestation of micronuclei in the cytoplasm of a cell during interphase requires, therefore, that a cell undergo at least one cell division following radiation exposure.

Siboulet (1984) studied the larvae of the newt, _Pleurodels waltl_, following exposure of 6 to 120 rads of x-rays. An increased induction of micronuclei in peripheral blood erythrocytes was observed at the lowest doses shortly after exposure. This indicator of cytogenetic damage was greatly reduced when cells were analyzed 10 days following an acute exposure and returned to baseline levels 18 days post-irradiation. Siboulet noted that the sensitivity of the micronuclei assay technique is highly dependent on the larvae stage. Optimum radio-sensitivity coincides with rapid cell division of peripheral blood erythrocytes.

Attempts to use the micronuclei assay technique in assessing chromosomal damage in irradiated fish, however, failed to demonstrate its usefulness even for high exposure doses (Jaylet 1986).

A number of cytogenetic studies have also been conducted on aquatic invertebrates. Blaylock (1966) investigated chromosomal abnormalities in a natural population of midges, *Chironomus tentaus*, that inhabited White Oak Lake. Chromosomes of the giant salivary gland of midge larvae showed an elevated frequency of damage during the earlier years when dose rates at White Oak Lake were estimated at 0.63 rad-d^{-1}. Renewed studies 10 years later when dose rates declined to 0.03 rad-d^{-1} failed to show an observable effect.

Laboratory studies of worm larvae reported observable increases in cytogenetic damage at threshold doses of 60 rads (Harrison 1985) and 200 rads (Pesch 1980).

D4.2 Genetic Effects

The ability of radiation to induce chromosomal damage in germ cells is similar to that of somatic cells. However, most gene mutations, unlike gross chromosomal aberrations of cytogenetic studies, may not be microscopically visualized.

Genetic mutations occurring in the germ cells of an irradiated organism may express themselves as dominant or recessive, lethal or sub-lethal mutations. The range of possible mutational effects encompass virtually every aspect of biochemical and physiological control mechanisms associated with normal functions of an organism. While dominant mutations may manifest themselves in the first generation, recessive mutations may be postponed for many generations.

In comparison to the number of genetic studies on other organisms, data on radiation mutation rates in aquatic organisms are very limited. Literature reviews of genetic studies involving aquatic species suggest a mutation rate of about 10^{-3} to 10^{-4} per gamete per rad (Woodhead 1984; Blaylock 1978; Schroeder 1979). Purdom (1966) studied the mutation rate in the guppy, *Lebistes reticulaatus*. His study indicates that the specific locus mutation rate in the guppy is probably not greater than 2×10^{-7} per rad per locus. These mutation rates are strikingly similar to terrestrial mammals, including humans.

For example, in a series of studies involving irradiated rainbow trout spermatozoa and eggs, the resultant increased frequency of malformed eyes in offsprings indicated that approximately 54 rads of acute exposure were required to double the natural occurrence of the mutation. This value is close to the doubling dose value for humans estimated at about 100 rem (NAS 1990, BEIR V). In a comparative study on *Chironomus riparius* involving acute versus chronic exposure conditions, Blaylock (1971; 1973) demonstrated that the frequency of chromosomal damage was approximately one order of magnitude lower under chronic exposure conditions. Chronic exposure, which is more representative of exposure conditions created by environmental contamination, is likely to result in lowered chromosomal sensitivity due to the presence of repair mechanisms.

Under conditions of long-term exposure involving sequential generations, it is logical to expect an increase in the frequency of mutant genes in the irradiated population. The increment in frequency of gene mutation does not continue indefinitely, but reaches a new equilibrium value above its normal level, which is proportional to the dose rate. This phenomenon is due to the concurrent elimination of mutant genes, which is also proportional to their induction rate. Thus, as the number of such genes in the irradiated population increases, the number being eliminated will also increase. With time, an equilibrium condition is reached in which continued chronic radiation induces new mutations that will be exactly equal to their new rate of elimination. It follows that cessation of irradiation will ultimately return the mutation frequency to pre-irradiation levels.

Studies by Blaylock (1969) and Trabalka (1978) on the mosquitofish that inhabited White Oak Lake indicated that the frequency of recessive deleterious mutations had, in fact, increased in the genome of species. Nevertheless, the increased genetic stress did not appear to have had a detrimental impact on the population size. This is consistent with conclusions derived by others which assume that the genetic stress associated with dose rates of less than 1 rad-d^{-1} will not result in deleterious effects at the population level (NRCC 1983; IAEA 1976; Blaylock 1978).

D4.3 Transmutation Effects

A frequently voiced concern uniquely associated with some contaminant radionuclides (and, therefore, not addressed by external gamma radiation studies) involves the transmutation effect and its potential for inducing molecular disorientation. The potential impact of chemical transmutation is of particular concern for genetic macromolecules of DNA and RNA. Chemical transmutation refers to when a radioactive isotope emits a beta particle, it also undergoes chemical transformation due to the change in atomic number. For example, when tritium (H-3) undergoes radioactive decay, it becomes helium (He-3), which is a chemically inert gas. Another radionuclide of transmutational concern is carbon-14. When such atoms are incorporated in critical molecules such as DNA, the resulting change in atomic number, recoil, or excitation may give rise to biologic effects, including mutation, beyond those induced by the attendant ionizing radiation. A legitimate question, therefore, is whether or not dose-response values, involving cytogenetic/genetic effects derived under experimental conditions of external radiation, might seriously underestimate the hazards presented by these potential radionuclide contaminants.

It is well established that a small percentage of H-3, when introduced in the environment as inorganic tritiated water (HTO), will become organically bound through a simple exchange mechanism. The tritium atom of a water molecule is exchanged for a hydrogen atom formerly attached to an organic molecule. In living tissues, about 80% of organically-bound hydrogen exists as exchangeable hydrogen, which under long-term exposure readily assumes equilibrium with tritium. At equilibrium, the total number of organically-bound tritium atoms is proportional to the ratio of available tritium atoms to hydrogen atoms.

The remaining 20% of organically-bound hydrogen is non-exchangeable. Non-exchangeable hydrogen is primarily bound to carbon. Nevertheless, tritium can become metabolically incorporated into an organic molecule as non-exchangeable hydrogen. The primary step is the photosynthetic conversion by aquatic plant organisms of carbon dioxide and H_2O/HTO in the presence of sunlight to hexose. The process by which tritium may subsequently be incorporated as non-exchangeable hydrogen in aquatic animals (or other species) involves the ingestion of organically-bound food stuffs. Tritium has been extensively investigated for its transmutational potential effects when it is organically bound to specific locations within the DNA molecule (i.e., ^{3}H-5-cytosine, ^{3}H-6-thymidine, and ^{3}H-2-adenine) (Person 1976, Kaplan 1965, Kieft 1969, Carsten 1976). These and other studies have been reviewed by the National Committee on Radiation Protection and Measurement (1979) with the resultant conclusion:

> *. . . it is reasonably conservative to assume, for the purpose of practical hazards considerations, that there is no significant transmutation effect for tritium incorporated in DNA, and that one may estimate hazards solely on the basis of absorbed beta dose . . .* (NCRP 1979, Report No. 63)

Similar conclusions were reached by the National Academy of Sciences BEIR I and BEIR III Committees. In the first report (NAS 1972, BEIR I Report), the Committee concluded:

> *. . . that the genetic effects of decays of H-3, C-14, and P-32 can, in fact, be attributed almost entirely to their beta radiation and that the contribution from transmutation is so small in comparison that it is justified to consider the main effect to come from the radiation emitted when the isotope disintegrates.*

In the Committee's subsequent report (NAS 1980, BEIR III), evidence was acknowledged which indicated a modest transmutational effect when H-3 and C-14 occupied highly specific locations within DNA. Nevertheless, the committee concluded that it still seems unlikely that neither H-3 nor C-14 decay are significantly underestimated by considering only the ionizing radiation dose accumulated by germ-line cells.

D5.0 RADIATION EFFECTS ON ECOSYSTEMS REQUIRING DOSE-RATE CONSIDERATIONS

Applicable dose and dose rate criteria for aquatic organisms are qualitatively different from those normally applied to human and, in a quantitative sense, to terrestrial animals. For human populations, a great value is placed on the health and well-being of the individual. Thus, radiation exposure limits for general populations are entirely based on stochastic effects involving cancer induction, in-utero effects, and genetic damage to future offsprings of irradiated individuals. All stochastic effects are, therefore, based on genetic damage to either somatic cells (i.e., cancer and in-utero effects) or reproductive germinal cells. In contrast, for endemic aquatic organisms, it is the collective somatic and genetic damage to the population rather than the individual which is of concern. Somatic cell damage involves the large-scale death of radiosensitive cell lines. Of primary concern is the capacity of individual populations of species to maintain a steady-state relationship through reproduction and competition in the face of the "stress" imposed by a given radiation environment. If exposures are limited to protect fertility and fecundity, it is most unlikely that other effects such as immune competency will be detrimental to the steady-state survival of a population.

In most aquatic organisms in which reproductive rates are generally high and on which selective pressures are strong, the value of a few or even thousands of individuals to the whole population, however, may be totally insignificant.

In previous sections, data were cited which showed that, under carefully controlled laboratory conditions, detectable histological effects on gonads of guppies were evident at dose rates as low as 0.04 rad-h^{-1} (or about 1 rad-d^{-1}); and consistently damaging effects of irradiation during the development of salmon eggs were apparent at dose rates of 0.4 rad-h^{-1} (or about 10 rads-d^{-1}). Yet, scientific consensus predicts that population effects are highly unlikely for chronic irradiation dose rates in the lower portion of the 1 - 10 rads-d^{-1} range. Stated somewhat differently, even when biological effects have been observed for specific exposure conditions, their overall impact on an ecological system may, nevertheless, be of little consequence. This implies that in addition to fertility and fecundity, there are other factors that determine population size in natural environments.

D5.1 Other Factors Affecting Population Size

The population impact of somatic effects during the most sensitive life-stages (i.e., embryonic and juvenile stages) is only partly dictated by the fecundity of a particular specie. In most aquatic organisms, inclusive of fish, reproductive potentials are high. It is generally assumed that less than one percent of viable zygotes are normally expected to mature long enough to reproduce. Among fish, most of the mortality occurs within the first several months of life in the larval state, and only 1 in 10,000 survive long enough to reach the age of one year (IAEA 1976). For organisms of high fecundity, recruitment into the adult population is not rigidly tied to total number of eggs, zygotes, or hatchlings but is frequently based on other regulatory mechanisms such as the availability of food. These homeostatic regulating mechanisms are often natural stressors which, in combination, tend to modulate population dynamics over a relatively wide range of a given stress.

For example, survival of fish larvae is thought to be primarily dependent upon the availability of phytoplankton and zooplankton, except at the extremes of the range of a species, where hydrological conditions become of major importance (Cushing 1972). The spawning time of fish in temperate waters is fixed, but the production of plankton is not, because its timing is largely dependent upon the amount of sunlight. Therefore, the hatching of fish eggs may or may not coincide with the time of optimum food production. In years when the plankton production cycle coincides with hatching of eggs, food is plentiful and an above average percentage of larvae will mature and survive. Conversely, when these two events are out of phase, food for the larvae will be less abundant and result in reduced survival. An important observation, however, is that even under conditions of optimum food availability, only a small fraction of fish larvae will survive. Thus, there is a density-dependent mortality that reduces the population of fish larvae to a level which can be supported by the available food supply (Cushing 1971). Thus, an observable but minor radiation stress which would result in a reduction of viable eggs, spermatozoa, and/or zygotes would result in fewer hatched eggs and fewer larvae competing for food. The decreased stress from reduced food competition is, however, compensated by enhanced survival of hatchlings with the result that the adult population number remains unchanged. Correspondingly, in the contaminated environment of White Oak Lake, an increased incidence of dead embryos of mosquitofish was observed as a result of dose-rates which are estimated to have been about 1 rad-d^{-1}. Yet, this observable genetically-induced mortality had no detectable effects on the overall population of mosquitofish. The minimum egg production, zygote formation, and number of hatchlings required for maintaining a normal adult population remains uncertain. Some fish stocks have been almost eliminated by the stress of commercial fishing. The north-east Arctic cod stock proved to be viable, however, even when the spawning potential was reduced to approximately 5% of its maximum recorded level (Garrod 1974).

The resilience and viability of cod stock that had been reduced to 5% of its spawning potential suggests that the radiation stress of 1 rad-d^{-1} at the White Oak Lake is not likely to represent an upper dose rate value with no measurable population consequence unless those populations are already at risk from other natural or anthrogonic stresses, inclusive of commercial/sport fishing. Laboratory studies of *Daphnia pulex* irradiated and "exploited" at various rates support this conclusion. Although relatively tolerant to radiation dose rates, one extinction occurred at the lowest dose rate tested. Population extinction occurred at a dose rate of about 0.5 rad-d^{-1} when the population was exploited at the highest rate of 90% per day (Marshall 1967). It can be assumed, however, that with exception of commercial activities relating to fishing or the uncontrolled discharge of chemical toxins, aquatic organisms are not likely to be stressed/exploited to a level at which radiation exposure at 1 rad-d^{-1} would be likely to adversely affect the normal population balance.

The National Council on Radiation Protection and Measurement in its recent assessment (NCRP 1991; Report No. 109, "Effects of Ionizing Radiation on Aquatic Organisms") stated:

> *. . . it seems highly likely that chronic irradiation at dose rates in the lower portion of the 10 - 100 mGy-d^{-1*} range, in particular, would not have a significant effect on the exposed population unless these were already at risk due to over exploitation (e.g., fishing) or to exposures to other environmental stressors.*
>
> *. . . Adoption of a reference level of 0.4 mGy-h^{-1**} appears to represent a reasonable compromise based on current information, i.e., considering both the nature of the effects observed at this dose rate and the limited amount of information on effects of radiation in natural populations, including interactions between ionizing radiation and ecological conditions.*

It is also important to point out that a dose-rate limit of 1 rad-d^{-1} is likely to apply to a limited percentage of a population group within a given ecosystem. Contaminated environments are most frequently the result of point discharges that generate a varying dose field within the ecosystem. A heterogeneous dose field implies that the mean population exposure may be considerably lower than exposure at the point of discharge either because the population of sessile organisms exist throughout the varying dose field, or because mobile organisms experience a time-varying dose rate as they migrate within the environment.

D5.2 Conclusion

On the basis of currently available data, it appears that the dose-rate limit of 1 rad-d^{-1} is not likely to result in significant impacts on aquatic populations. This tentative conclusion is supported by the failure to demonstrate significant effects at this dose rate. Moreover, even when organismal changes have been demonstrated at moderate (but above 1 rad-d^{-1}) dose rates, their impact on the overall population size was either insignificant or could not be demonstrated in a laboratory environment. It is the general consensus among scientists that the resultant radiation stress of 1 rad-d^{-1} is likely to be a minor stress in relationship to other natural and anthropogenic stresses which regulate and limit population sizes within a given ecosystem.

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[*] 10 mGy is equal to 1 rad

[**] 0.4 mGy-h^{-1} is equal to about 1 rad per day.

D6.0 COMPATIBILITY OF DOE DOSE-RATE CRITERION WITH EPA'S GENERIC ECOLOGICAL ASSESSMENT METHODOLOGY

In 1989, EPA issued a report that provides guidance on designing, implementing, and interpreting ecological assessments of hazardous waste sites (EPA 1989). Among the many topics addressed, the report discusses the scientific basis for assessing adverse ecological effects at hazardous waste sites (HWSs) and presents methods for evaluating the on-site and off-site ecological effects of HWSs. Its stated objective of an ecological assessment is to quantify specific effects at an HWS. Specific ecological effects refer principally to population - and community - level effects on terrestrial and aquatic biota and biological processes.

An evaluation of compatibility between DOE's dose-rate criteria with EPA's ecological assessment methodology is restricted to a comparison between the methodologies employed by scientific studies on which DOE criteria are based and those recommended by the EPA.

Sections D2, D3, and D4 of this report summarized scientific data on which DOE established its interim dose-rate limits of 1 rad-d^{-1}. For reasons of simplicity and the near absence of suitable field study conditions, the data primarily reflect studies conducted under laboratory conditions. For all the obvious benefits which can be assigned to controlled laboratory conditions, there are serious limitations in extrapolating such data to natural environments. The dose-response relationship as measured by individual responses (i.e., mortality, reproduction, growth and development, and genetic mutations) may in some cases be underestimated and in other cases overestimated when radiation stress is induced in the absence of other stresses that normally exist in a natural environment. Even more important is that observable individual effects in the laboratory may not have any impact on the whole population in a natural setting. The concept of individual "biomarkers" is generally seen by environmental toxicologists as a potentially powerful tool for assessing environmental contaminants. The underlying concept is that selected endpoints measured in individual organisms, typically comprised of biochemical or physiological responses, can provide sensitive indices of exposure and stresses and potentially provide an early warning system for adverse ecological effects.

Thus, it may be assumed that dose-rate criteria, which are based on individual "biomarkers," are conservative since nominal, but observable, changes in death, reproduction, and growth of individuals may not necessarily be linked to effects at the biological levels of organization of greatest ecological concern (i.e., population, community, and ecosystem levels).

The EPA, in its 1989 report, has identified four common endpoints of ecological concern: (1) species richness and relative abundance; (2) indicator species; (3) biological indices; and (4) guild structure.

Species Richness and Relative Abundance. Species richness (the number of species in a community) and relative abundances (the number of individuals in any given species compared to the total number of individuals in the community) are structural endpoints commonly measured in field assessments of periphyton, plankton, macro-invertebrates, and fish. Estimates of relative abundance or species richness may yield readily interpretable information on the degree of contamination of an aquatic habitat (Sheehan 1984b; Lamberti 1985; Hellawell 1986). Loss of a particular species from an ecosystem can be critical when that species plays a important role in community or ecosystem functions such as predation (Paine 1969) or grazing (Giesy 1979).

Measures of species richness and relative abundance are taken by sampling known substrate areas or water volumes. Richness measures have not always been taken to the species level, especially in monitoring invertebrate communities. Taxonomic, fiscal, and time constraints have often predicated the need for rapid bioassessment (Hilsenhoff 1988; Plafkin 1988) involving taxonomic identifications only to family and genus.

Indicator Species. The presence or absence of "indicator species" is commonly used to assess adverse effects to ecological communities (Karr 1986; Hilsenhoff 1988; Plafkin 1988). The concept was originally derived from the saprobian system, in which certain species and groups were found to generally characterize stream and river reaches subject to organic wastewaters; increasing anthropogenic organic matter in aquatic habitats serves to fill the energy requirements of "tolerant" species, while reducing the numbers of "sensitive" species that respond negatively to competition, predation, or decreased dissolved oxygen (Kolkwitz 1902; Gaufin 1958; Sheehan 1984a).

Experience has shown that the indicator species concept lacks broad applicability to all types of pollution. Sheehan (1984a) indicated that communities do not respond to organic wastes (e.g., sewage) in the same way they respond to toxic chemicals. Organic sewage stimulates certain species by increasing their food supply; other species consequently diminish as a result of interspecific interactions. Toxic chemicals or radioactive contamination, on the other hand, tend to affect all members of a community. Furthermore, species selection may occur in aquatic habitats that are chronically polluted with low levels of contaminants over sufficiently long periods. In such instances, certain species that ordinarily appear to be quite "sensitive" may seem to "tolerant" due to decreases in predation or competitive pressures (Hersh 1987).

However, the indicator species concept can be applied to the assessment of ecological effects if enough care is taken to limit the breadth of its application. Some species may be found upstream from the contaminated site or in habitats known to be unaffected by contamination seepages. The indicator species concept has been applied in assessment techniques for a variety of hazardous effluents (Courtemanch 1987; Sheehan 1984b). Karr (1981) applied the indicator species concept in the Index of Biotic Integrity (IBI), in which fish community composition is used as a measurement of environmental quality.

Biological Indices. Biological indices can be used to mathematically reduce taxonomic information to a single number or index, to simplify data for interpretation or presentation. Indices derived from direct measures of the presence of taxa have been extensively developed, reviewed, and critiqued (Sheehan 1984a; Hellawell 1986). Indices can be classified among several types: evenness (measuring how equitably individuals in a community are distributed among the taxa present); diversity (calculating the abundance of individuals in one taxon relative to the total abundance of individuals in all other taxa); similarity (comparing likeness of community composition between two sites); and biotic indices (examining the environmental tolerances or requirements of individual species or groups).

Guild Structure. Community data generated at the species level can be analyzed according to guild structure. Guilds, or functional feeding groups, are classifications based on the manner in which organisms obtain their food and energy. Invertebrates can be classified among such functional groups as collector-gathers, piercers, predators, scrapers, and shredders (Merritt 1984; Cummins 1985); and fish can be classified as omnivores, insectivores, and piscivores (Karr 1986). Shifts in community guild structure reflect changes in the tropic-dynamic status of an aquatic ecosystem. For example, contaminant influences from an HWS may eliminate or reduce periphyton and thus concomitantly reduce the relative abundance of scrapers (herbivores) in relation to other invertebrate guilds such as collector-gathers. Changes may also occur with a guild, such as when a contaminant alters the level of competition between two species that compete for a common resource (Petersen 1986). Generally, the effects must be fairly strong to enable the measurement of changes in guild structure.

The Need for Additional Data

By definition, the EPA-cited ecological endpoints may only be applied to field studies of natural populations and are, therefore, inapplicable to studies cited in Sections D2, D3, and D4 of this report. In the absence of suitable field study data, laboratory studies, on which interim dose-rate limits are based, provide a suitable alternative that is most likely to yield a conservative dose-rate limit.

Dose-rate criteria which are more defensible than those currently used by the DOE must await additional research data. Future research intended to improve our current understanding of radiation effects on aquatic individuals, populations, and ecosystems must not only expand the scope of past studies but employ improved study methodologies. Recommendations include the following:

- Parallel experiments between individuals and populations of the same species should be considered in order to provide a correlation between individual and population responses and to assess possible interaction of radiation effects with other environmental factors/stresses.
- Research should identify sensitive, but relevant, biomarkers which would allow assessment at low dose rates in order to eliminate uncertainties associated with extrapolation from high dose rate data to low dose rate.
- A greater diversity of natural species should be studied. In past instances, studies have focused on organisms that are easy to "culture" or maintain under laboratory conditions, but which have uncertain or minor ecological significance. It is obvious that even a major population impact on some species may have minimal ecological impacts. Conversely, a seemingly minor population impact on a specie that has a vital ecological role may have a serious ecological impact.
- Perhaps the least documented/understood effect of chronic radiation is the potential long-term effect of radiation-induced mutations. Research should focus on the genetic effects of radiation singly and in combination with other stressors. Attempts should also be made to correlate cytogenetic aberrations with population damage (population size, biomass, fecundity, biological fitness, etc.).

In the meantime, the implementation of the interim dose rate limit of 1 rad-d^{-1} in itself may pose a significant problem. It is rarely practical to obtain estimates of the radiation dose rate to organisms in a contaminated, but otherwise natural, environment by direct measurements. Direct measurements might include (1) measurements of radionuclide concentrations in water and within tissues of specific organisms and (2) direct measurements of external measurement within the contaminated body of water. The difficulties with such measurements, however, is the microdosimetry of alpha and beta emitting internal contaminants, the estimation of variability/errors introduced by uncertainties regarding external exposure due to the behavior of mobile animals in a nonuniformly contaminated environment, and the logistical complications imposed by the requirement for a capture-recapture protocol if a passive dosimeter (e.g., LiF TLD) is to be used for in-situ measurements.

Collectively, these complex problems imply dependence on suitable computer models for relating radionuclide-specific contamination levels with dose-rates to select populations of aquatic species in an ecosystem. The IAEA in Technical Report Series No. 288 (IAEA 1988) defined a model (i.e., GESAMP VII Model) that specifies dose rates to specific groups of marine organisms from (1) radionuclide concentrations in water or (2) point source discharge rates at various distances. The GESAMP VIII Model, however, may not be an appropriate model for freshwater environments due to differences in dilution/concentration mechanisms caused by water flow and the mobility/migration of aquatic species relative to a source term of contamination.

The NCRP Report 109 (NCRP 1991) has identified three separate modeling approaches: (1) CRITR, (2) EXREM III, and (3) BIORAD. The CRITR was developed for applications of effluent discharges into surface waters. It provides a simplified means of calculating the concentrations of radionuclides in water, sediment, and two groups of organisms using a restricted number of parameters relating to the discharge and the receiving body of water. Thus, the value of the CRITR model is primarily one of conducting a preoperational assessment phase of any waste management project involving potential discharges.

EXREM III and BIORAD models allow for the determination of the concentration of a radionuclide within an organism on the basis of the radionuclide's concentrations in water using a "concentration factor." No means of estimating the concentrations in sediment are given. The dose rate to the organism from the radionuclides in the water is derived from the mean dose rate in an infinite, uniformly contaminated source.

In summary, these two models have serious limitations with regard to establishing regulatory compliance with interim standards. Undoubtedly, improved dosimetry models must be developed that allow users to more easily and accurately estimate exposure dose rates, which are based on water concentrations, from all pathways.