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A COMPARISON OF RADIOLOGICAL RISK ASSESSMENT METHODS FOR ENVIRONMENTAL RESTORATION*

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Presented at the 38th Annual Meeting
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ABSTRACT

Evaluation of risks to human health from exposure to ionizing radiation at radioactively contaminated sites is an integral part of the decision-making process for determining the need for remediation and selecting remedial actions that may be required. At sites regulated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), a target risk range of 10^{-4} to 10^{-6} incremental cancer incidence over a lifetime is specified by the U.S. Environmental Protection Agency (EPA) as generally acceptable, based on the reasonable maximum exposure to any individual under current and future land use scenarios. Two primary methods currently being used in conducting radiological risk assessments at CERCLA sites are compared in this analysis. Under the first method, the radiation dose equivalent (i.e., Sv or rem) to the receptors of interest over the appropriate period of exposure is estimated and multiplied by a risk factor (cancer risk/Sv). Alternatively, incremental cancer risk can be estimated by combining the EPA's cancer slope factors (previously termed potency factors) for radionuclides with estimates of radionuclide intake by ingestion and inhalation, as well as radionuclide concentrations in soil that contribute to external dose. The comparison of the two methods has demonstrated that resulting estimates of lifetime incremental cancer risk under these different methods may differ significantly, even when all other exposure assumptions are held constant, with the magnitude of the discrepancy depending upon the dominant radionuclides and exposure pathways for the site. The basis for these discrepancies, the advantages and disadvantages of each method, and the significance of the discrepant results for environmental restoration decisions are presented.

1 INTRODUCTION

The National Oil and Hazardous Substances Pollution Contingency Plan (NCP) specifies requirements and procedures for undertaking response actions at contaminated sites pursuant to the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), as amended. The CERCLA addresses sites where there has been a release into the environment of a hazardous substance or of any pollutant or contaminant that may present an imminent and substantial danger to the public health or welfare. Radionuclides are defined as hazardous substances under CERCLA. More than 40 sites with radioactive contamination are currently listed on the National Priorities List (NPL) of the U.S. Environmental Protection Agency (EPA), and numerous others are being remediated under state programs and programs of the U.S. Department of Energy (DOE) and the U.S. Nuclear Regulatory Commission.

In evaluating potential risks from known or suspected carcinogens (including ionizing radiation) at contaminated sites and potential response actions, the NCP defines an "acceptable" risk range as generally between 10^{-4} and 10^{-6} lifetime excess cancer risk. Relative to this target risk range, the EPA has developed guidance for evaluating risks to human health at contaminated sites (e.g., EPA 1989a, 1991), which specifically addresses risks from radioactive contaminants in a format similar to that used to address risks from chemical carcinogens. The purpose of this study is to compare the EPA approach to radiological risk assessment to the more conventional method of estimating risk as a multiple of the radiation dose equivalent.

2 RADIOLOGICAL RISK ASSESSMENT APPROACHES

2.1 RADIONUCLIDE SLOPE FACTORS

The EPA has developed "slope factors" for estimating incremental cancer risks from known or suspected carcinogens. The slope factor represents the upper-bound probability of cancer incidence as a result of a unit exposure to a given carcinogen over a lifetime. This value is multiplied by an estimate of an individual's lifetime intake or exposure to the carcinogen to predict the incremental probability of developing cancer as a result of the exposure. Slope factors are specified for various contaminants of interest in the *Integrated Risk Information System* (IRIS) and the *Health Effects Assessment Summary Tables* (HEAST).

Slope factors for radionuclides were first published in HEAST in 1991 and were extensively revised in 1992 (EPA 1992). Values are presented separately for inhalation, ingestion, and external exposure pathways. The radionuclide slope factors for ingestion and inhalation exposures are best estimates of the age-averaged lifetime risk of excess cancer incidence (fatal plus nonfatal cancers) per unit of activity ingested or inhaled, respectively; slope factors for external exposure are best estimates of the age-averaged lifetime risk of

excess cancer incidence for each year of exposure to a unit activity concentration of photon-emitting radionuclides distributed uniformly in a thick layer of soil. These values are combined with site-specific media concentration data and exposure assumptions to estimate lifetime cancer risk to current or future receptors at a site from radionuclide exposure.

In developing the slope factors for radionuclides, contemporary dosimetric methods are used to estimate absorbed dose as a function of time from a chronic unit intake (inhalation or ingestion) or exposure (external exposure) over a lifetime. These estimates of absorbed dose are combined with cancer risk factors through a life table analysis, which accounts for competing risks (risks other than that from incremental radiation exposure). Radiation risk factors reflected in the current slope factors (EPA 1992) are based largely on the 1980 report of the National Research Council's Committee on the Biological Effects of Ionizing Radiations (BEIR III; National Academy of Sciences [NAS] 1980), and incorporate age-, sex-, and organ-specific considerations where available. Mortality data used in these estimates are those for the U.S. population in 1969-1971. (Note: Both the risk factors and mortality data have been updated recently by the EPA, and pending revisions of the slope factors are expected to incorporate these more recent data.)

2.2 DOSE-TO-RISK FACTORS

An alternative approach commonly used to estimate incremental cancer risk from radiation exposure involves estimating the dose equivalent (Sv or rem) to a receptor resulting from exposure to the radioactive contaminants at a site and multiplying by a risk factor per unit dose equivalent. Generally, the effective dose equivalent (or effective dose) is used for this purpose. Radiation risk factors have been developed for a variety of endpoints by authorities, including the BEIR Committee, International Commission on Radiological Protection (ICRP), National Council on Radiation Protection and Measurements, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and EPA. To facilitate comparison with estimates of risk computed with the slope factor approach, incremental cancer incidence (including both fatal and nonfatal cancers) is selected as the appropriate endpoint of interest for this analysis.

Estimates of risk per unit dose are summarized in Table 2.1. An excess cancer incidence risk of 6×10^{-4}/rem (6×10^{-2}/Sv) has been selected for use in this analysis. This estimate is considered most consistent with the recent recommendations of the ICRP (1991), EPA (1989b), and BEIR V (NAS 1990, with adjustment for a dose-rate-effectiveness factor of 2 and an assumed lethality fraction of 60% for radiation-induced cancers).

TABLE 2.1 Estimates of Radiation Risk per Unit Dose

Source	Cancer Risk per 10^6 person-rem[a]	Risk Endpoint	Comments[b]
ICRP (1991), Publication 60	600	Fatal cancers plus nonfatal cancers	Population average: DDREF=2; RBE_α=20
BEIR V report (NAS 1990)	800	Fatal cancers	Low-LET only. Reduction by DDREF of 2 to 10 is suggested for low-level exposures.
EPA (1989b)	622	Cancer incidence	Low-LET only; RBE_α=8 should be applied for high-LET.
UNSCEAR (1988)	710	Fatal cancers	Low-LET only. Reduction by DDREF of 2 to 10 is suggested for low-level exposures.
National Radiation Protection Board (1988)	450	Fatal cancers	For United Kingdom population. Assumes DDREF=2 for breast and DDREF=3 for all other sites.
BEIR III report (NAS 1980)	169-403	Fatal cancers	Low-LET only.

[a] Cancer risk per 10^6 person-rad for sources other than ICRP. All estimates assume relative risk model except for leukemia and bone.

[b] DDREF = dose and dose-rate-effectiveness factor; RBE_α = relative biological effectiveness for alpha radiation; LET = linear energy transfer.

3 COMPARATIVE ANALYSIS

3.1 BASIS FOR DIFFERENCES IN RISK ESTIMATES

The two methods, slope factors and dose-equivalent-risk factors, may produce dissimilar estimates of incremental cancer risk from exposure to radionuclides in the environment. These discrepancies are largely attributable to the underlying dosimetric and toxicological assumptions in the two methods.

3.1.1 Competing Risks

All persons are exposed to risks from a variety of sources other than incremental radiation exposure (e.g., disease and accidents). These competing risks, which are normally much larger than radiological risks and vary significantly as a function of age, are accounted for in the calculation of radionuclide slope factors by using mortality statistics of the U.S. population. The probability of dying at a particular age from competing risks is

calculated from the mortality rate at that age for all causes, as specified in actuarial life tables for the U.S. population. Those persons dying from these competing causes are not susceptible to radiation-induced cancer even if they have been exposed to radiation from the site in question. Under the alternative method, the integral of the effective dose equivalent from all exposure pathways over a specified period (e.g., 50 years) following initial radiation exposure is multiplied by the selected radiation risk factor to estimate excess cancer risk, without allowance for competing risks; "excess" cancer risks estimated using this approach, therefore, may include individuals who will die from competing causes before the radiation-induced cancer can be expressed. Thus, risks calculated with the slope factor approach will be systematically lower than those computed with the dose-equivalent-risk factor approach (all other factors being equal), with the magnitude of the difference dependent on the specific mortality statistics used (e.g., 1969-1971 U.S. population).

3.1.2 Relative Biological Effectiveness

In the calculation of dose equivalent, a quality factor of 20 is applied for alpha particles to account for the increased biological effectiveness relative to low-linear-energy-transfer (low-LET) radiation. The radionuclide slope factors, however, are computed by using absorbed dose and applying a relative biological effectiveness (RBE) factor of 8 for high-LET radiation. Thus, risk estimates for high-LET radiation under the two methods differ systematically by this ratio (20:8). (Note: Proposed revisions to the EPA methodology include adoption of an RBE value of 20 in conjunction with a dose-rate-effectiveness factor of 2, which would attain consistency with ICRP [1991] recommendations.)

3.1.3 Relative Organ Weighting

Organ/tissue weighting factors specified by the ICRP (1979, 1991) are used in computing the effective dose equivalent; these factors represent the estimated proportion of the total stochastic risk resulting from each organ or tissue. The effective dose equivalent is then multiplied by the selected radiation risk factor to estimate excess cancer risk. Under the slope factor approach, absorbed dose estimates for specific organs are coupled with organ-specific risk factors separately for low-LET and high-LET radiation, and the individual organ risks are subsequently summed to estimate total excess cancer risk. The relative magnitudes of the EPA organ-specific risk coefficients do not correspond directly to the ICRP weighting factors. The magnitude of this discrepancy depends on the specific radionuclides and exposure pathways of concern — i.e., on the dose distribution among body organs. Table 3.1 summarizes the relative organ weighting factors used in each approach.

3.1.4 Genetic Effects

The dose to gonads is a very important component of the effective dose equivalent (Table 3.1); estimates of radiation-induced health risk derived from the effective dose

TABLE 3.1 Comparison of Relative Organ Weighting Factors

ICRP Organ Weighting Factors		EPA Normalized Organ Risk Factors (Low-LET only)	
Organ	Factor	Organ	Factor
ICRP (1979), Publication 30		***EPA (1989b)***	
Gonads	0.25	Pulmonary lung	0.18
Breast	0.15	Breast	0.14
Red bone marrow	0.12	Liver	0.13
Lung	0.12	Stomach	0.12
Thyroid	0.03	Leukemia (red marrow)	0.11
Bone surfaces	0.03	Pancreas	0.09
Remainder	0.30	Intestine[a] (SI + ULI + LLI)	0.06
		Urinary (kidneys and bladder)	0.05
ICRP (1991), Publication 60		Thyroid	0.02[b]
		Bone	0.006
Gonads	0.20	Other	0.11
Red bone marrow	0.12		
Colon	0.12		
Lung	0.12		
Stomach	0.12		
Bladder	0.05		
Breast	0.05		
Liver	0.05		
Esophagus	0.05		
Thyroid	0.05		
Skin	0.01		
Bone surfaces	0.01		
Remainder	0.05		

[a] SI = small intestine; ULI = upper large intestine; LLI = lower large intestine.

[b] Reduced by a factor of 3 for iodine-131 and iodine-129.

equivalent reflect both cancer risk and genetic effects. Although the radionuclide slope factors do consider ovarian and testicular cancer risks, no genetic risk component is included in the slope factor. This component is addressed separately by the EPA.

3.1.5 Lung Definition

For radionuclide slope factors, the lung cancer risk is calculated on the basis of the dose to the pulmonary lung only, with an assumed mass of 570 g. For the effective dose equivalent, the lung dose normally considers a composite of the pulmonary, tracheobronchial, and lymphatic regions of the lung, with a total mass of 1,000 g.

3.1.6 Integration Period

As noted above, the committed effective dose equivalent (for internal exposures) is an integral of the effective dose equivalent over a fixed period of time following initial exposure; the radiation-induced cancer risk is then computed as the product of the committed effective dose equivalent and the radiation risk factor. In the development of radionuclide slope factors, however, organ-specific dose rates for low-LET and high-LET radiation are calculated as a function of time, and the radiation risk during each year is computed by using the absorbed dose rates for that year with age-averaged, organ-specific risk models. By adjusting for the competing risks noted previously, the use of a fixed integration period is avoided.

3.1.7 Other Differences

In addition to the systematic differences in the two methods summarized above, there are differences in radionuclide-specific assumptions in the dosimetric models and parameters selected for use. Such differences include gastrointestinal-tract-to-blood absorption factors and uptake and retention models for body organs.

3.2 COMPARISON OF RISK ESTIMATES

The relative differences in estimates of excess cancer incidence risk from exposure to several radionuclides of common interest are summarized in Table 3.2. Comparisons are provided for inhalation, ingestion, and external exposure. Dose conversion factors (DCF) for this analysis are taken from DOE (1988) for inhalation and ingestion, and from Kocher and Sjoreen (1985) for external exposure. The DCF is used in conjunction with a radiation risk factor (RF) of 6×10^{-4} excess cancers per person-rem (6×10^{-2}/person-Sv).

Except for tritium (inhalation and ingestion) and cobalt-60 (inhalation), the risk estimates computed using the effective dose equivalent risk factor are greater than the corresponding slope factor estimate. The relative magnitude of difference between the two methods ranges from 1.4 to 26 for external exposure, from 0.7 to 140 for ingestion, and from 0.5 to 50 for inhalation.

For most radionuclides, differences are more pronounced for the ingestion and inhalation pathways; for external exposures, risk estimates show the greatest discrepancies for low-energy photon emitters. The relatively more consistent risk estimates for the external exposure pathway appear reasonable in that several of the factors noted in Section 3.1 relate primarily to internal dose (e.g., RBE value for high-LET radiation, integration period, and lung definition).

TABLE 3.2 Comparison of Slope Factor and Dose Equivalent Risk

Radionuclide[a]	Relative Magnitude of Estimated Radiation Risks by Exposure Pathway[b] (DCF×RF : Slope Factor)		
	External	Ingestion	Inhalation
Hydrogen-3	-	0.7	0.5
Carbon-14	-	1.4	2.2
Cobalt-60	1.6	1.0	0.6
Strontium-90+D	-	2.3	2.2
Cesium-137+D	1.5	1.1	1.0
Lead-210+D	16.	6.1	3.2
Radium-226+D	1.5	5.5	1.6
Radium-228+D	1.7	7.2	3.9
Actinium-227+D	1.9	26.	50.
Thorium-228+D	1.4	8.2	2.4
Thorium-230	20.	25.	6.6
Thorium-232	25.	140	34.
Protactinium-231	5.0	72.	22.
Uranium-234	2.5	10.	3.0
Uranium-235+D	2.2	9.4	2.9
Uranium-238+D	2.1	5.4	1.4
Neptunium-237+D	2.2	11.	10.
Plutonium-238	26.	10.	4.6
Americium-241	5.7	11.	9.8
Curium-244	24.	8.6	7.4

[a] "+D" indicates that contributions to risk from short-lived radioactive decay products (half-life <0.5 year) are included.

[b] DCF = dose conversion factor; RF = radiation risk factor.

4 CONCLUSIONS

Radionuclide slope factors have been developed by the EPA for the specific purpose of estimating potential cancer risks from radioactive contaminants at Superfund sites in a manner consistent with that used for evaluating chemical risks. Estimates of excess cancer risk generated with the slope factor approach may differ significantly (up to 2 orders of magnitude) from estimates computed as the product of the effective dose equivalent and a radiation risk factor (cancer risk per unit dose). These differences may be primarily attributed to the consideration of competing risks and age-dependent radiation risk models in the development of the slope factors, the different distributions of relative weights assigned to individual organ risks in the two methods, the different RBE values for high-LET radiation, and the differences in dosimetric assumptions.

For radiological risk assessments of contaminated sites, the EPA's radionuclide slope factors appear to have several advantages compared with conventional dose conversion factors, particularly in providing a consistent basis for evaluating risks from chemical and radioactive contaminants at a site. This approach incorporates age-dependent risk models and accounts for competing risks of death based on mortality statistics for a real population. The method also eliminates some overly conservative assumptions inherent in the calculation of committed effective dose equivalents.

Risk estimates computed with the slope factor approach generally will be less conservative (lower) than those computed with conventional dose conversion factors and risk factors, but will still provide an estimate of the reasonable maximum incremental risk. Overly conservative estimates of excess risk may, in some cases, provide an inappropriate basis for remedial action decisions and result in unnecessary expenditures of scarce resources.

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