A REVIEW OF THE SUPERFUND RISK ASSESSMENT APPROACH FOR QUANTIFYING RADIATION RISKS

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ABSTRACT

When the Environmental Protection Agency (EPA) calculates the risk of developing cancer from radiation exposure at Superfund sites containing radioactive material, it must consider the risks from ingestion and inhalation of radioactivity as well as from external irradiation. This paper will focus on the derivation and application of slope factors for estimating the age-averaged lifetime excess cancer incidence (including fatal and nonfatal radiogenic cancers) per unit intake or exposure to the radionuclides of concern from these three exposure pathways.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

INTRODUCTION

As part of the National Oil and Hazardous Substances Pollution Contingency Plan or NCP [40 CFR Part 300] (1), the U.S. Environmental Protection Agency (EPA) must ensure that Superfund sites are protective of human health and the environment before they can be released for unrestricted use by the public. Protective of human health is generally defined in the NCP as presenting a lifetime excess cancer risk of 10^{-4} to 10^{-6} due to exposures to all hazardous materials on a site.

EPA provides guidance for risk assessment to those parties responsible for remediation at Superfund sites. This paper reviews the Superfund risk assessment approach for quantifying radiation risks. It will consider the derivation and application of slope factors which are the basis of this method of risk estimation.

To determine the lifetime risk from a radionuclide present in the environment, such as at a Superfund National Priorities List (NPL) site, several things must be determined. To determine how a radionuclide might reach a potentially exposed individual, measurements and models are used to estimate the amount of a particular radionuclide present at the site; its chemical form; its physical form (i.e., in what matrix it exists); and its movement within the environment (i.e., "fate and transport" or pathway modeling). Three exposure pathways are considered - ingestion, inhalation, and external irradiation from radioactivity in soil. Once the amount of external irradiation and the quantity of a radionuclide inhaled and ingested is determined, complex dosimetry models are used to calculate the radiation dose to individual organs from each of these three pathways. Knowing the organ dose rates allows the calculation of lifetime cancer incidence risk. For any radionuclide, the total lifetime cancer incidence risks per unit of radioactivity inhaled, per unit ingested, and per unit of annual external exposure are presented as the three pathway-specific slope factors.

RADIONUCLIDE SLOPE FACTORS

EPA classifies all ionizing radiation and therefore all radionuclides as human carcinogens. Ingestion and inhalation slope factors for radionuclides are best estimates of the age-averaged, lifetime excess cancer incidence risk per unit of activity inhaled or ingested, expressed as risk/becquerel (risk/Bq) or risk/picocurie (risk/pCi). Cancer incidence includes occurrences of cancers, both fatal and nonfatal. External exposure slope factors are best estimates of the average lifetime excess cancer incidence risk for exposure to external radiation from photon-emitting radionuclides distributed uniformly in a thick layer of soil, and are expressed as risk/yr per Bq (or pCi)/gram of soil. When combined with site-specific media concentration data and appropriate exposure assumptions, slope factors can be used to estimate lifetime cancer risks to members of the general population due to radionuclide exposures. Agency standardized default exposure scenarios and assumptions for use in baseline risk assessment are provided in EPA guidance (2).

Derivation of Slope Factors

EPA's Office of Radiation Programs (ORP) calculates radionuclide slope factor values using health effects data and dose and risk models from a number of national and international scientific advisory commissions and organizations, including the National Academy of Sciences (NAS), the National Council on Radiation Protection and Measurement (NCRP), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and the International Commission on Radiological Protection (ICRP). A detailed discussion of ORP's approach and assumptions is provided in "Risk Assessment Methodology, Environmental Impact Statement, NESHAPS for Radionuclides, Background Information Document - Volume I" (3), referred to hereafter as the BID for NESHAPS or just the BID.

Radionuclide slope factors are calculated for each radionuclide individually, based on its unique chemical, metabolic and radioactive properties. The calculation uses EPA's computer code RADRISK (4), life table analyses, and cancer risk estimates based largely on the results of the NAS BEIR III report (5). Ingestion and inhalation slope factors for radionuclides account for:

- the amount of radionuclide transported into the bloodstream from either the gastrointestinal (GI)

tract following oral ingestion, or from the lungs following inhalation;

- the ingrowth and decay of radioactive progeny produced within the body subsequent to intake;
- the distribution and retention of each radionuclide (and its associated progeny, if appropriate) in body tissues and organs;
- the radiation dose rates delivered to body tissues and organs from the radionuclide (and its associated progeny, if appropriate); and
- the sex, age, and organ-specific risk factors over the lifetime of exposure.

The slope factors are the average risk per unit intake or external exposure for an individual in a stationary population with vital statistics (mortality rates) of the United States in 1970. (The expected lifetime for an individual in this population is about 70 years.) EPA slope factors are published in EPA's on-line Integrated Risk Information System (IRIS) and in the Health Effects Assessment Summary Tables (HEAST) (6).

EPA DOSIMETRIC MODELS AND BEIR III

Internal Dose Models

As described in Volume 1 of the BID for NESHAPS, EPA implements contemporary models to estimate absorbed dose rates as a function of time to specified organs in the body. These internal dosimetry models are primarily based on those of the International Commission on Radiation Protection (ICRP) in its Report No. 30 (7). In order to calculate the doses for particular concentrations of radionuclides in environmental media, many pathway assumptions had to be made (e.g., occupancy factors and ingestion rates). These are also presented in the BID. Estimates of the doses resulting from the deposition and retention of inhaled particulates in the lung, in particular, and their subsequent absorption into the blood and clearance into the gastrointestinal (GI) tract, are made using the ICRP Task Group Lung Model (8).

The cancer types and body organs considered to date by the EPA are listed in Table I. The ratio of lifetime risk to lifetime dose for these organs and cancer types were based on relationships (health effects models) presented by the National Academy of Sciences in its report colloquially called BEIR III (Biological Effects of Ionizing Radiation) (5). The EPA's use of the BEIR III models is described at length in the BID for NESHAPS. It is important to note that the NCP of 40 CFR Part 300 addresses cancer incidence risk; hence, the EPA uses the BID incidence models only. Also, EPA included consideration of health effects information that became available after BEIR III was published.

External Dose Models

Current external exposure slope factors are given for cancer incidence risk per unit exposure to a source of uniform activity per unit mass in soil (e.g., risk/year per Bq/gram of soil or risk $Bq^{-1}\ y^{-1}\ g$). The RADRISK (4) risk factors that form the basis of EPA's estimates of risk for radionuclide intakes and exposures include factors for exposure to a uniform concentration on the ground surface, but not for an exposure to a radionuclide *concentration* per unit volume in soil.

TABLE I

Cancer Sites and Related Organs and Tissues Considered in the EPA Risk Estimates

Cancer	Organ/Tissue
Leukemia	Red bone marrow
Bone	Bone surface (Endosteum)
Thyroid	Thyroid
Breast	Breast
Lung	Pulmonary region
Stomach	Stomach
Liver	Liver
Urinary	Urinary (= 1/3 x kidney + 2/3 x bladder)
Pancreas	Pancreas
Bowel	Intestine (= 0.2 x small intestine + 0.4 x upper large intestine + 0.4 x lower large intestine)
Other (includes esophagus and lymphoma)	Pancreas*

* The pancreas is used as a surrogate tissue for these organs.

It is possible, however, to convert the surface risk factor to a volume risk factor by means of a suitable scaling factor. A separate computer code, DFSOIL (9), is used to estimate this scaling factor by calculating the dose to air at a fixed height (1 m) above the ground for both 1) a unit concentration of a radionuclide on the surface, and 2) a unit concentration of that radionuclide in the soil volume. The quotient of the air dose per Bq/m^3 in soil divided by the air dose per Bq/m^2 on the surface approximates the ratio of the dose rates in an exposed individual from the volume and surface distributions of the contaminant, and serves as the necessary scaling factor. Since it has the units of length, the scaling factor is called the effective depth. This value is used to convert the RADRISK risk factors to volume risk factors as described. Finally, since soil concentrations are usually expressed in units of activity per unit mass, e.g. Bq/g, the volume risk factor is multiplied by the soil density ($1.43 \times 10^6\ g/m^3$) to obtain the slope factor for an activity concentration per unit mass of soil.

LIFE TABLE ANALYSES

A life table consists of data describing age-specific survival, based on mortality rates from all causes of death for a given population. This information is derived from data obtained on actual mortality rates in a real population. Actuarial life tables are used to account for the time dependence of the radiation insult, and also to allow for competing risks of death in the estimation of risk due to radiation exposure. The life table used by EPA/Superfund for the derivation of the radiological slope factors is illustrated in Table II (10). This table records the expected (in 1970) number of survivors and their expected lifetime remaining over time of an initial cohort of 100,000 persons liveborn in 1970.

Radionuclides that are ingested or inhaled today may still be irradiating an individual seventy or more years in the future.

TABLE II

Excerpt from 1970 Life Table for Initial Cohort of 100,000 Persons Liveborn in 1970*

AGE (y)	Persons Surviving	Person-Years of Life Remaining
0	100,000	70.756×10^5
2	97,876	68.787×10^5
4	97,724	66.831×10^5
10	97,460	60.976×10^5
16	97,181	55.135×10^5
20	96,716	51.257×10^5
25	96,000	46.439×10^5
35	94,482	36.911×10^5
46	91,144	26.674×10^5
50	88,972	23.070×10^5
53	86,838	20.432×10^5
63	75,236	12.265×10^5
78	41,192	3.269×10^5

*Note that life expectancy at birth in 1970 was 70.756 yrs.

In addition, damage from radiation received today may not express itself for many years. For these reasons and others, calculation of risk from internal contamination is complicated. To determine age-averaged lifetime risk factors, a hypothetical newborn cohort of 100,000 persons is assumed to be exposed at a constant rate over its entire life. For inhaled or ingested radionuclides, dose rates to each organ of concern are calculated as a function of age. For internal dosimetry, it is important to recognize that while we assume the rate of intake of a radionuclide to be constant over time, the dose rate from that radionuclide in any particular organ will vary over time depending on its half-life and its retention in the body. For longer half-life isotopes, the result will generally be a steadily increasing dose rate. Once determined, the average annual organ dose for each year is used to calculate the incidence risk in all succeeding years of the cohort. This risk is the sum of the products of the excess cancer incidence rate (calculated by the risk model) and the average number of surviving persons at each age of the cohort. Since the dose delivered in each year includes the contributions from the radionuclide intake in all previous years, the total risk for a lifetime intake is the same as the sum of the risks contributed by the dose in each year.

This cancer incidence calculation accounts for age at exposure, and corrects for competing causes of death within the hypothetical exposed population. That is, through use of the 1970 actuarial life table, the hypothetical population at risk is diminished each year by the number of deaths expected under baseline risk conditions in an "unexposed" population (i.e., one with no radiation exposure above normal background). Because the total number of excess cancers in the exposed cohort will be extremely small relative to the baseline cancer incidence, the 1970 actuarial life table should look almost identical to one constructed for the exposed population. Summing all the excess cancer incidences for each organ group and dividing by the original size of the cohort (100,000) yields the overall excess risk of cancer incidence to an individual for a lifetime exposure from a particular radionuclide.

This risk factor is calculated separately for each pathway. Dividing the total risk by the total activity (becquerels or picocuries) ingested or inhaled over the average individual's life gives the ingestion and inhalation slope factors in terms of age-averaged lifetime risk per Bq or pCi. For external irradiation, a slope factor is calculated as risk per year per Bq (or pCi) per gram of soil, as previously described.

FUTURE RISK METHODOLOGY

EPA recognizes that methods of risk assessment need to reflect up-to-date information regarding epidemiology, internal dosimetry, and fate and transport modeling. Currently, we are assessing new risk estimates such as those presented in BEIR V (11) which are based on revised dosimetry for the Japanese atomic bomb survivors. EPA also recognizes the need for adjusting external slope factors to account for small areas of contamination. EPA currently assumes the soil concentration to be constant for an infinite slab of infinite thickness. In addition, EPA will continue to revise the internal dosimetry models as improved dosimetric parameters become available. However, given our present understanding, major changes in cancer risks attributable to radiation are not expected.

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