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WHITE PAPER: USING RESRAD IN A CERCLA RADIOLOGICAL RISK ASSESSMENT

BUFFALO, NEW YORK

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U.S. Army Corps of Engineers
Buffalo District Office
Formerly Utilized Sites Remedial Action Program

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prepared by
Science Applications International Corporation

for
U.S. Army Corps of Engineers, Buffalo District Office, Formerly Utilized Sites Remedial Action Program

PREFACE

The United States Army Corps of Engineers (USACE) Buffalo District is using the RESidual RADioactivity (RESRAD) code to carry out its radiological risk assessments for the Formerly Utilized Sites Remedial Action Program (FUSRAP) sites in New York, Pennsylvania, and Ohio. In order to produce consistent, understandable, and reproducible results, the Buffalo District Environmental Health Section called upon Sciences Application International Corporation (SAIC) (a consultant providing technical health physics support) to write a white paper on the use of RESRAD for FUSRAP sites.

The purpose for having this paper written was two-fold: (1) to ensure a consistent risk (and dose) assessment approach across all of the FUSRAP sites for which the Buffalo District is responsible, and (2) to share our radiological risk assessment approach with Buffalo District FUSRAP partners and stakeholders, who in some cases, may be more familiar with the United States Environmental Protection Agency's (USEPA) standard Risk Assessment Guidance for Superfund (RAGS) than with the use of RESRAD. Although this paper compares standard USEPA risk assessment methods with that of RESRAD, this comparison is provided to help risk assessors understand the uncertainties, limitations, and advantages associated with each method and does not prescribe the use of one method over the other. Rather, it is simply intended to assure the proper use and interpretation of RESRAD results when RESRAD is employed.

This "white paper" is a technical paper written specifically for the use of the Buffalo District on its FUSRAP sites. Although the USACE – Hazardous, Toxic, and Radioactive Waste Center of Expertise reviewed this paper (and provided comments), this document should not be considered USACE policy or an official USACE document.

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ACRONYMS

ACF	area correction factor
ANL	Argonne National Laboratory
ASR	air-to-source ratio
Bq	becquerel
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CSF	cancer slope factor
DF	dilution factor
DOE	U.S. Department of Energy
ECRIR	Excess Cancer Risks for Individual Radionuclides
ED	exposure duration
EPA	U.S. Environmental Protection Agency
ETF	environmental transport factor
FA	area factor
FDW	fraction of drinking water
FGR-13	Federal Guidance Report No. 13
FIND	indoor time fraction
FO	usage factor
FOND	outdoor time fraction
FUSRAP	Formerly Utilized Sites Remedial Action Program
GSF	gamma shielding factor
HEAST	Health Effects Assessment Summary Tables
IR	ingestion rate
K_d	distribution coefficient
NRC	U.S. Nuclear Regulatory Commission
pCi	picocuries
PEF	particulate emission factor
RAGS	Risk Assessment Guidance for Superfund
RESRAD	RESidual RADioactivity
RME	reasonable maximum exposure
RSR	risk-to-source ratio
Se	shielding factor
SSG	soil screening guidance
Sv	sievert
Te	time factor
TERIER	Total Excess Risk for Initially Existent Radionuclides
VR	ventilation rate
WL	working level

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1.0 INTRODUCTION

1.1 PURPOSE

The purpose of this white paper is to describe how to properly use the RESidual RADioactivity (RESRAD) computer code in calculating radiological risk and how to interpret and manipulate RESRAD output. This paper discusses the use of the RESRAD code in a Comprehensive Environmental Response, Compensation, and Liability Act (CERLCA) risk assessment for radionuclides. The guidance contained herein is intended to assist the Buffalo District in evaluating sites, such as those found in the Formerly Utilized Sites Remedial Action Program (FUSRAP), containing radiologically contaminated media.

This white paper is designed to explain how to use RESRAD in place of standard Risk Assessment Guidance for Superfund (RAGS) equations while closely paralleling the RAGS methodology. The discussions presented in this white paper are intended for risk assessors that may or may not have been trained in the use of RESRAD and need additional guidance to understand the various nuances in the code and to properly interpret radiological data and RESRAD results. Specifically, the paper is organized as follows:

Section 1 – Introduction (this section),
Section 2 – RESRAD Versus Basic Equations,
Section 3 – Input Parameters,
Section 4 – Exposure Pathways,
Section 5 – Source Term Development,
Section 6 – Output Interpretation and Manipulation,
Section 7 – Sensitivity Analysis and Uncertainties
Section 8 – References.

The paper uses examples to describe general risk assessment problems using the RESRAD code, focusing on naturally occurring radionuclides in the uranium, thorium, and actinium decay series. However, guidance presented herein applies to most naturally-occurring or man-made radionuclides that may be encountered at a CERCLA site.

1.2 SCOPE

The scope of this paper is limited to the evaluation of radiological contaminants, as RESRAD is not intended for use with non-radionuclides (i.e., chemicals). It is assumed that the reader is familiar with risks assessment methods presented in RAGS (EPA 1989 and 1991), has a general working knowledge of the RESRAD code, and understands the general principles of radioactivity. As pointed out throughout this paper, a general working knowledge of RESRAD does not assure proper use of the code. The RESRAD code is relatively simple to use, but not necessarily simple to use properly. This white paper provides guidance for proper use of the code so that appropriate input parameters are used to attain risk assessment results that are correctly interpreted.

The RESRAD code is used for estimating the carcinogenic risk to human receptors from exposure to radionuclides in soil or soil-like media. RESRAD is not intended to be used with contamination inside buildings. The reader should consider using RESRAD-BUILD or other methods to address contamination within buildings. RESRAD includes methods for estimating the human health risk at a site from the inhalation pathway via suspension of contaminated soil rather than using an air dispersion (or off-site)

model. The RESRAD code assumes that the receptor stands directly over and in the center of a lens of the contaminated medium. This paper does not address the following:

- Risks to potential off-site receptors (CAP88-PC and another codes/models are more suitable for off-site scenarios);

- Exposure to carbon-14 and hydrogen-3 (tritium) although modules are included in the code;

- Exposure to materials inside buildings (reader should refer to the RESRAD-BUILD code, although RESRAD-BUILD only calculates radiological dose, not risk); and

- Probabilistic risk calculations (this paper is limited to deterministic applications).

This white paper is intended as a supplement and not a replacement for the RESRAD *User's Manual for RESRAD Version* 6 (ANL 2001) and other RESRAD reference documents prepared by Argonne National Laboratory (ANL). It is assumed that the reader has access to the RESRAD home page at http://web.ead.anl.gov/resrad/home2/ and has a copy of the User's Manual (ANL 2001) and the *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil* (ANL 1993). Both documents are available in portable document format though the RESRAD home page.

Traditional units are used in this paper [i.e., picocuries (pCi) instead of becquerels (Bq) and mrem instead of sieverts (Sv)] to be consistent with units currently used by RESRAD, United States regulations, RAGS, and other U.S. Environmental Protection Agency (EPA) guidance documents.

2.0 RESRAD VERSUS BASIC EQUATIONS

2.1 EXPOSURE PATHWAY COMPARISON

This section evaluates intake/exposure estimates using three approaches: basic (or standard) RAGS equations (EPA 1989 and 1991), Soil Screening Guidance for Radionuclides (SSG)[1] equations (EPA 2000), and RESRAD (ANL 2001). This comparison shows that the three approaches are very similar. The primary exception is that RESRAD includes built-in flexibility to evaluate environmental transport of contaminants (i.e., area factors, leaching, etc.) plus radiological decay and ingrowth. The basic RAGS/SSG equations could be modified to include environmental and radiological factors or could be supplemented with additional models. However, these components are already included in the RESRAD code, and it is likely much less time consuming to use RESRAD when considering a dynamic relatively complex exposure environment. This section shows that the standard RAGS approach is the most limiting while RESRAD provides the most flexibility. In spite of the differences, similar results could be obtained from each of the models often with only minor modifications. Differences between RESRAD and basic RAGS/SSG equations are discussed in more detail in Sections 2.1.1 through 2.1.4 as they apply to specific exposure pathways and in Section 2.1.5 as they apply to additional RESRAD functions.

This section includes five subsections, one each for the ingestion, inhalation, external gamma, and dermal contact pathways. The fifth and final section includes a discussion of other functions built into the RESRAD code that are not considered using standard RAGS or SSG methods. The discussions within the following sections are written to be generic and are intentionally medium-independent for simplicity. RESRAD equations are presented to compare against RAGS/SSG equivalents and are necessarily modified from the original equations presented in referenced ANL documents. These modifications are made to simplify the presentation while it is assumed that risk assessors can review the RESRAD manual (ANL 2001) for a more detailed description of pathway-specific equations. Where possible, parameter names are defined consistent with RESRAD terminology, otherwise names are consistent with RAGS/SSG. Although not described in detail in this section of the white paper, all three methods use intake estimates multiplied by Health Effects Assessment Summary Tables (HEAST) cancer slope factors to calculate risk.

2.1.1 Ingestion

Using both the basic RAGS and SSG approach, incidental ingestion of a given radionuclide in some environmental media (e.g., soil, sediment, drinking water) is estimated using the following basic equation:

$$Intake_{ing}\ (pCi) = C_j \times IR \times EF \times ED, \qquad \text{Eq. 2-1}$$

where:

- C_j = concentration of radionuclide "j" in some medium (pCi/g or pCi/L);
- IR = ingestion rate (g/day or L/day);
- EF = exposure frequency (days/year); and
- ED = exposure duration (years).

Using RESRAD, incidental soil ingestion of a given radionuclide in some environmental media is estimated using the following equation:

$$Intake_{ing}\ (pCi) = C_j \times IR \times (FOTD + FOND) \times ED \times ETF_j, \qquad \text{Eq. 2-2}$$

[1] SSG is intended to supercede RAGS, although RAGS is still used extensively.

where:

C_j	=	concentration of radionuclide "j" in some medium (pCi/g or pCi/L);
IR	=	ingestion rate (g/year or L/year);
FOTD	=	outdoor time fraction (dimensionless); fraction of total year exposed to contaminant while outdoors = (total hours per year exposed outdoors) / (8760 hours);
FIND	=	indoor time fraction (dimensionless); fraction of total year exposed to contaminant while indoors = (total hours per year exposed indoors) / (8760 hours);
ED	=	exposure duration (years); and
ETF_j	=	environmental transport factor radionuclide "j"; could be an area factor, a cover and depth factor, radiological ingrowth and decay, etc.

Ingestion of milk, meat, fish, produce, and water is estimated by RESRAD using the following slightly different equation:

$$Intake_{ing}\ (pCi) = C_j \times IR \times FO \times ED \times ETF_j\ , \qquad \text{Eq. 2-3}$$

where:

C_j	=	concentration of radionuclide "j" in some medium (pCi/g or pCi/L);
IR	=	ingestion rate (g/year or L/year);
FO	=	usage factor; fraction originating from a potentially contaminated medium or used by the receptor, e.g., 0.05 if 5% of produce is from an on-site garden (unitless);
ED	=	exposure duration (years); and
ETF_j	=	environmental transport factor radionuclide "j"; could be an area factor, a cover and depth factor, radiological ingrowth and decay, etc.

Both Equation 2-1 and Equation 2-2 estimate the lifetime intake of a contaminant through the soil ingestion pathway. However, there are three key differences in the RAGS/SSG versus RESRAD equations. First, the RAGS/SSG equation uses a daily ingestion rate (e.g., g/day or L/day) while RESRAD uses a yearly rate (e.g., g/year or L/year). The final product for both is the yearly rate multiplied by the exposure duration to get lifetime intake. Second, RAGS/SSG uses an exposure frequency (days/year) while RESRAD uses an occupancy fractions (total hours exposed/8760). These differences in Equations 2-1 and 2-2 amount to a simple unit conversion. Although the presentation is different, the end product is mathematically the same (e.g., g/year or L/year). Third, RAGS/SSG does not include an environmental transport factor (ETF) while RESRAD does, although additional models may be used to supplement RAGS/SSG equations. Use of the ETF enables RESRAD to account for environmental factors such as the size of the contaminated area, cover depth, erosion rate, radiological decay and ingrowth, leaching and other factors relating interactions between the contaminated medium and the environment, ultimately impacting the risk from the ingestion pathway. The RAGS/SSG equation does not include ETFs that could be used to produce a prospective risk estimate.

Equation 2-3 utilizes a usage factor (FO) in place of the RESRAD occupancy factors. This term is different from RAGS/SSG approaches but still results in a yearly intake, similar to the approach used in the RESRAD soil ingestion equation. To properly apply FO, the risk assessor must balance intake rates with the assumed product usage (see Section 4.4 for a more detailed description).

2.1.2 Inhalation

Using the basic RAGS approach, inhalation of a given radionuclide is estimated using the following equation:

$$Intake_{inh}\ (pCi) = C_j \times VR \times EF \times ED \times T_e \times CF \times \left(\frac{1}{VF} + \frac{1}{PEF}\right), \qquad \text{Eq. 2-4}$$

where:

C_j	=	concentration of radionuclide "j" in some medium (pCi/g or pCi/L);
VR	=	ventilation/inhalation rate (m^3/day);
EF	=	exposure frequency (days/year);
ED	=	exposure duration (years);
T_e	=	exposure time factor (hr/hr – e.g., 8/24 for an 8-hour workday);
CF	=	conversion factor (10^3 g/kg);
VF	=	volatilization factor (chemical-specific m^3/kg); 1/VF = 0 for most radionuclides;
PEF	=	particulate emission factor (m^3/kg).

Alternately, the SSG provides the following equation:

$$Intake_{inh}\ (pCi) = C_j \times VR \times EF \times ED \times CF \times \frac{1}{PEF} \times [ET_o + (ET_i \times DF_i)], \qquad \text{Eq. 2-5}$$

where:

C_j	=	concentration of radionuclide "j" in some medium (pCi/g or pCi/L);
VR	=	ventilation/inhalation rate (m^3/day);
EF	=	exposure frequency (days/year);
ED	=	exposure duration (years);
CF	=	conversion factor (10^3 g/kg);
PEF	=	particulate emission factor (m^3/kg); note that the volatilization factor (VF) is omitted;
ET_o	=	exposure time fraction outdoors (unitless);
ET_i	=	exposure time fraction indoors (unitless); and
DF_i	=	dilution factor for indoor inhalation (unitless).

Using RESRAD, incidental inhalation of a given radionuclide is estimated using the following equation:

$$Intake_{inh}\ (pCi) = C_j \times VR \times ASR \times ED \times [FOTD + (FIND \times DF_i)] \times ETF_j\ , \qquad \text{Eq. 2-6}$$

where:

C_j	=	concentration of radionuclide "j" in some medium (pCi/g or pCi/L);
VR	=	ventilation/inhalation rate (m^3/year);
ASR	=	air to soil concentration ratio (g/m^3), equivalent to PEF^{-1};
ED	=	exposure duration (years);
FOTD	=	outdoor time fraction (dimensionless); fraction of total year exposed to contaminant while outdoors = (total hours per year exposed outdoors) / (8760 hours);
FIND	=	indoor time fraction (dimensionless); fraction of total year exposed to contaminant while indoors = (total hours per year exposed indoors) / (8760 hours);
DF_i	=	dilution factor for indoor inhalation (unitless); and
ETF_j	=	environmental transport factor radionuclide "j"; could be an area factor, a cover and depth factor, radiological ingrowth and decay, etc.

A quick review shows that the RAGS equation (Equation 2-4) is significantly different from both the SSG equation (Equation 2-5) and the RESRAD equation (Equation 2-6). The most obvious difference is that the RAGS equation does not include a dust dilution factor (DF) for indoor receptors. DF reduces the amount if indoor dust assuming some filtering or dilution that would not be observed while outdoors.

As with the ingestion pathway, the general approach for estimating intake is different for each of the indicated equations. The RESRAD equation uses time fractions and a yearly inhalation rate while the RAGS/SSG equations use exposure frequencies and daily inhalation rates. Both yield yearly rate which are multiplied by exposure duration to estimate lifetime intake.

Equations 2-5 and 2-6 are functionally equivalent except that the RESRAD model includes an ETF and the SSG equation does not. As with the ingestion pathway, RESRAD includes the flexibility to account for environmental factors such as size of the contaminated area, cover depth, erosion, radiological decay and ingrowth, leaching and other factors relating the interactions between the contaminated medium and the environment, ultimately impacting the risk from the inhalation pathway.

2.1.3 Direct Gamma

Using the basic RAGS approach, the external exposure to radionuclides in some medium is calculated using the following equation:

$$Exposure\,(pCi \cdot year/g) = C_j \times EF \times \frac{1}{365} \times ED \times (1 - Se) \times Te, \qquad \text{Eq. 2-7}$$

where:

C_j	=	concentration of radionuclide "j" in some medium (pCi/g or pCi/L);
EF	=	exposure frequency (days/year);
365	=	number of days/year (days/year);
ED	=	exposure duration (years);
Se	=	gamma shielding factor (unitless), (1 – Se) is transmitted through shield; and
Te	=	gamma exposure time factor or fraction of day exposed (hours/24 hours).

Alternately, the SSG provides the following equation:

$$Exposure\,(pCi \cdot year\,/\,g) = C_j \times EF \times \frac{1}{365} \times ED \times ACF \times [ET_o + (ET_i \times GSF)], \qquad \text{Eq. 2-8}$$

where:

C_j	=	concentration of radionuclide "j" in some medium (pCi/g or pCi/L);
EF	=	exposure frequency (days/year);
365	=	number of days/year (days/year);
ED	=	exposure duration (years);
ACF	=	area correction factor (unitless);
ET_o	=	exposure time fraction outdoors (unitless);
ET_i	=	exposure time fraction indoors (unitless); and
GSF	=	gamma shielding factor, equivalent to (1-Se) (unitless).

Using RESRAD, the external exposure to radionuclides in some environmental media is calculated using the following equation:

$$Exposure\,(pCi \cdot year\,/\,g) = C_j \times ED \times [FOTD + (FIND \times GSF)] \times ETF_j, \qquad \text{Eq. 2-9}$$

where:

- C_j = concentration of radionuclide "j" in some medium (pCi/g or pCi/L);
- ED = exposure duration (years);
- FOTD = outdoor time fraction (dimensionless); fraction of total year exposed to contaminant while outdoors = (total hours per year exposed outdoors) / (8760 hours);
- FIND = indoor time fraction (dimensionless); fraction of total year exposed to contaminant while indoors = (total hours per year exposed indoors) / (8760 hours);
- GSF = gamma shielding factor, equivalent to (1-Se) (unitless); and
- ETF_j = environmental transport factor radionuclide "j"; could be an area factor, a cover and depth factor, radiological ingrowth and decay, etc.

Again a quick review shows that the RAGS equation (Equation 2-7) is significantly different from both the SSG equation (Equation 2-8) and the RESRAD equation (Equation 2-9). The most obvious difference is that the RAGS equation does not distinguish between indoor and outdoor exposures. The RAGS shielding factor (Se) applies regardless of location while the SSG/RESRAD gamma shielding factor (GSF) only applies while the receptor is indoors. Another difference is that the RAGS equation lacks ETFs, although additional models may be used to supplement RAGS equations. The SSG equation includes only an area correction factor (ACF) while the RESRAD equation includes a more sophisticated model which accounts for the contaminated area, cover depth, erosion, radiological decay and ingrowth, leaching, etc.

The external gamma pathway does not result in a true intake, rather, the result is radiological exposure that may occur while the receptor is in the vicinity of the contaminated medium. The general approach for estimating exposure is different for different equations. The RAGS equation (Equation 2-7) uses exposure duration and a time factor (Te) assumes the same Se for indoor and outdoor exposures. The SSG and RESRAD equations consider indoor and outdoor exposure time, although SSG still uses exposure frequencies. The RESRAD approach uses indoor (FIND) and outdoor (FOTD) occupancy fractions, calculated as the hours on-site (indoors or outdoors, respectively) divided by the total hours in the year. In all cases, however, an exposure duration (ED) term is used to yield a lifetime exposure estimate.

Equations 2-8 and 2-9 are functionally equivalent except that the RESRAD model includes a complex ETF term and the SSG equation contains only an ACF. As with the other pathways equations, the RESRAD equation integrates environmental factors such as the size of the contaminated area (same as under SSG), cover depth, erosion, radiological decay and ingrowth, leaching and other factors relating the interactions between the contaminated medium and the environment, ultimately impacting the risk from the external gamma pathway.

2.1.4 Dermal

There are no dermal slope factors for radionuclides, thus RESRAD does not include a dermal component. Omission of the dermal pathway in radiological assessments is a generally accepted and widely practiced approach given that the radiological risk from dermal exposure is negligible compared to the radiological risk from the ingestion, inhalation, and external exposure pathways.

2.1.5 Additional RESRAD Functions

Perhaps the most useful RESRAD function is the code's ability to account for dynamic conditions encountered in the environment. This capability is not found in either the standard RAGS or the SSG approach, although RAGS/SSG methods can be supplemented with additional fate and transport models. Specifically, RESRAD incorporates the following:

- Future conditions taking into account source removal by radiological decay, leaching, erosion, etc., and source buildup due to the ingrowth of decay products;
- Site-specific variables such as rainfall, soil density, etc. that may impact results;
- Source geometry taking into account the thickness and surface area of soil contamination;
- Comprehensive pathway analyses including external gamma, dust and radon inhalation, soil ingestion, groundwater and surface water ingestion, produce ingestion, meat and dairy product ingestion, and fish ingestion (see Figure 2-1 for a diagram of RESRAD pathways);
- Integrated results that simultaneously account for all potential exposure pathways; and
- Both carcinogenic risk and radiological dose estimates for comparison to appropriate regulatory limits.

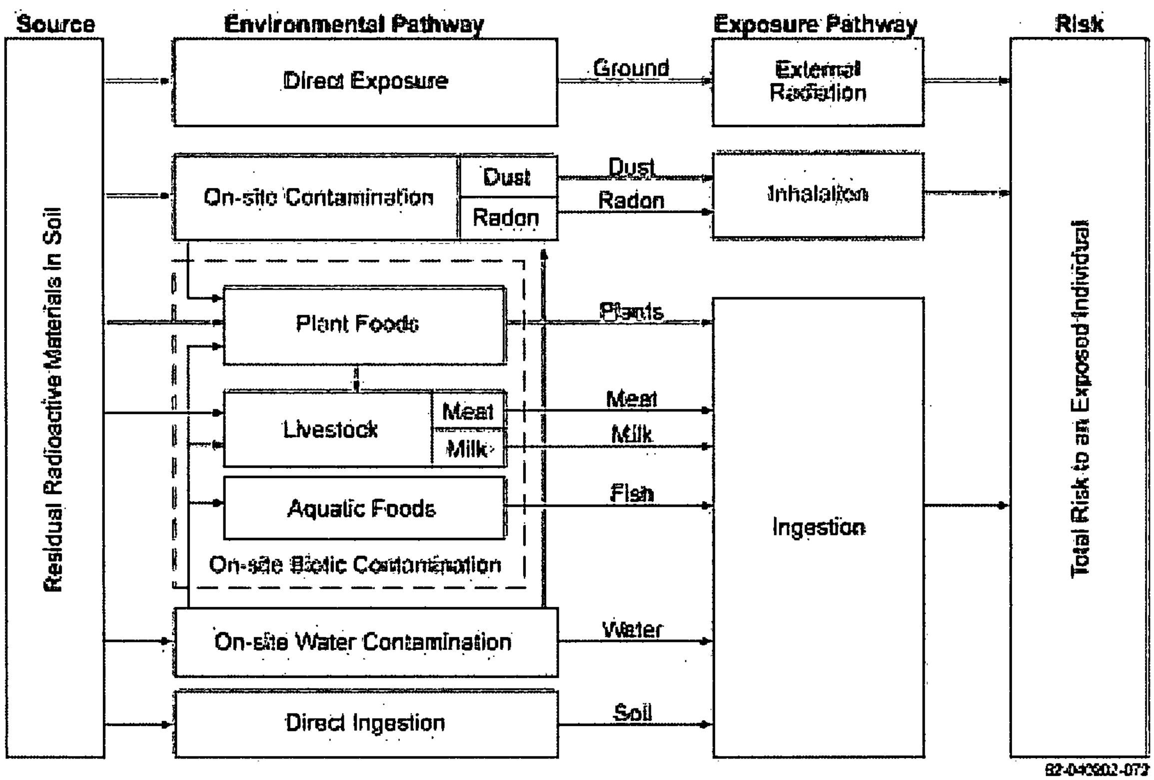

Figure 2-1. Presentation of RESRAD Pathways (modified from Figure 2.2, ANL 2001)

It is noted that produce, meat, dairy, and fish ingestion are typically excluded from even the most conservative exposure scenarios in chemical risk assessments. This is because the uncertainties in the associated environmental transport and bioaccumulation factors (e.g., from soil to cow to milk) are large and can dominate risk estimates. However, the radiological risk/dose estimates often default to include subsistence farming and fishing exposure pathways with little consideration of these uncertainties. The environmental transport and bioaccumulation factors used by RESRAD are interpreted on the same level as cancer slope factors: factors are accepted as approved point estimates in spite of large uncertainties. The RESRAD default scenario is consistent with the paradigms established by the U.S. Department of Energy (DOE) and the U.S. Nuclear Regulatory Commissions (NRC) for establishing concentration limits for radiological contaminants. Moving away from the subsistence exposure pathways requires special justification under the DOE and NRC paradigms, whereas special circumstances must exist for including meat, milk, produce, and fish in a typical CERCLA risk assessment. In either a chemical or radiological risk assessment, these special circumstances are evaluated on a site-by-site basis considering regulator input, the likelihood that a pathway is complete, plus current and projected surrounding land-use.

The ETF term in Equations 2, 3, 6, and 9 are of particular interest when comparing RESRAD to standard risk equations. RESRAD integrates all pathway-specific environmental transport into each "run" considering the variables bulleted above. Chemical contaminant concentrations in soil are generally assumed to remain constant over time, thus risk assessors typically only consider baseline conditions without any or limited ETF terms. Guidance and models do exist for predicting the environmental transport of certain chemicals in certain media, and the information generated may be used to modify standard risk models. However, this information likely does not account for radiological ingrowth and decay and may not be appropriate for use with radionuclides. It is up to the professional judgment of the risk assessor to determine which models, including RESRAD, are appropriate for use in a risk assessment. Assuming RESRAD is an acceptable model, pathway-specific ETF terms are described in more detail in Section 4 of this paper. If a risk assessor specifically does not wish to consider environmental transport but still wants to use the RESRAD model, he/she can consider only year 0 results after turning off the drinking water and farming-related pathways.

Because RESRAD calculates risk using a similar approach to RAGS and more recent guidance (i.e., SSG), its use is assumed appropriate for use in CERCLA risk assessments. Because of the added features as described in this section, RESRAD may be able to produce more defensible risk estimates using an integrated, proven approach. The RESRAD code certainly provides risk assessors with flexibility not provided by standard RAGS methods and automatically accounts for radiological decay and ingrowth. However, risk assessors should understand that RAGS may be used to produce results similar to RESRAD when supplemented with additional modeled data that accounts for environmental transport plus decay and ingrowth.

Assuming both chemical and radiological contaminants are present at a site, risk assessors should, to the extent possible, maintain consistency between risk calculations methods. Some method differences are expected such as the assumed infinite source in chemical assessments versus RESRAD-modeled finite sources for radionuclides. However, the chemical and radiological methods should be fundamentally similar and equally defensible. This is best achieved through coordination by project geologists or hydrologists, CERCLA risk assessors, and health physicist. It may be that qualified project team members will have to resolve the differences between CERLCA chemical risk assessment versus NRC/DOE-based radiological dose paradigms.

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3.0 RESRAD INPUT PARAMETERS

Section 3 includes a general description of RESRAD input parameters, specific parameter values for a range of potential exposure conditions and receptors (Section 3.1), a general description of a range of receptors commonly used in CERLCA risk assessments (Section 3.2), and a brief discussion on toxicity values and related factors (Section 3.3). The general receptor descriptions are used to justify specific parameter values.

3.1 GENERAL DISCUSSION

Table 3-1 lists RESRAD input parameters, parameter units, the RESRAD default values, radiological dose variability indicators, proposed values for specified receptors, and comments/references. This table is provided to demonstrate the flexibility a risk assessor has to incorporate site-specific and receptor-specific information into risk calculations. The parameters typically used in standard RAGS/SSG calculations are included, but, as shown, RESRAD allows for the integrated consideration of multiple pathways, environmental factors, geometry factors, and site characterization data that do not fit into standard risk calculations.

The comment column in Table 3-1 is used to explain the function of the specified parameter or otherwise indicates how the parameter is properly interpreted. This column is included because risk assessors may not recognize the difference in the RESRAD versus standard RAGS parameter definitions. Risk assessors should note that many of the parameters are related to specific pathways and may be ignored or left as default values. For example, there is little reason to insert a hydraulic conductivity if the groundwater pathway is incomplete; or alternatively, if there is site-specific information on hydraulic conductivity it could be substituted for the default value. A more detailed description for each parameter is available through the *Help* tool of the RESRAD code or may be accessed by placing the cursor in the cell of interest and pressing the Function 2 (F2) button.

Although not listed in Table 3-1, RESRAD can simultaneously estimate exposures from 74 principle radionuclides (half-lives greater than 6 months) and 53 associated radionuclides (short-lived decay products). HEAST cancer slope factors are incorporated into the code and are updated when new factors are published. The current RESRAD version (6.2) uses HEAST factors published in April of 2001.

Most of the parameters listed in Table 3-1 are site-specific and not receptor-specific. For example, the area of the contaminated zone is independent of whether the receptor is a resident, industrial worker, recreational user, etc. Certain receptor-specific and scenario-specific parameters are also listed in Table 3-1 for consideration by risk assessors. Specifically, Table 3-1 lists a range of parameter values for various receptors and exposure conditions. Recommended values are provided from several EPA guidance documents and from NRC guidance document NUREG/CR-5512 Volume 4. Some calculated values also are provided with the underlying assumptions/rational. The goal is not to provide reasonable maximum exposure (RME)[2] values for a range of potential receptors. In many cases a recommended value is not available, but is estimated based on site-specific conditions. It is also assumed that when site-specific or receptor-specific values are not provided or can not be assigned from another source, the RESRAD defaults are used. If RESRAD default parameters are not acceptable, NUREG/CR-5512 Volume 4 may be used to assign default values for some exposure parameters. The receptor-specific inputs presented in Table 3-1 are, to the extent possible, assigned based on the descriptions in the following subsections.

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[2] Parameter values may be considered either RME (typically associated with the ≥ 90th percentile) or CT (central tendency = the mean or 50th percentile) in a CERCLA risk assessment. Assessments for radionuclides (i.e., under NRC and DOE) often replace RME-based receptors with "average members of the critical group" where the critical group is defined as the group of individuals reasonably expected to receive the greatest exposure for an applicable set of circumstances. It is up the risk assessor to determine which terminology and level of conservatism is most appropriate for the site.

Table 3-1. Receptor-Specific and Scenario-Specific RESRAD Parameter Values

RESRAD Parameter	Units	RESRAD Default	Risk Variability[#]	Proposed Values	Receptor or Scenario	Comment/Reference
Area of contaminated zone	m^2	10,000	3	Site-specific[δ] 100 2000	All receptors All receptors All receptors	Intake/exposure directly proportional to surface area Corresponds to UMTRCA exposure unit Corresponds to default Class 1 MARSSIM unit; equivalent to a half acre lot.
Thickness of contaminated zone	m	2.0	1	Site-specific	All receptors	Intake/exposure can be directly proportional to thickness
Length parallel to aquifer flow	m	100	4	Site-specific	All receptors	Relevant for surface water dependent pathways
Time since placement of material	yr	0.0	-	Site-specific	All receptors	Old data may not reflect current conditions
Cover depth	m	0.0	3	Site-specific	All receptors	Cover will eliminate direct ingestion and inhalation pathways
Density of cover material	g/m^3	1.5	3	Site-specific	All receptors	See Manual Appendix A and E and DCH Section 2; omitted if cover depth = 0; consult geologist/hydrologist
Cover depth erosion rate	m/yr	0.001	5	Site-specific 0.00006 0.0006	All receptors Non-farming Farming	If cover erodes, direct ingestion and inhalation pathways are relevant See DCH Section 14; 2% slope, no farming/gardening See DCH Section 14; 2% slope, significant farming/gardening
Density of contaminated zone	g/m^3	1.5	4	Site-specific	All receptors	See Manual Appendix E and DCH Section 2; consult geologist/hydrologist
Contaminated zone erosion rate	m/yr	0.001	3	Site-specific 0.00006 0.0006	All receptors Non-farming Farming	Can erode entire contaminated lens if large enough; assumed 0.0 until cover erodes See DCH Section 14; 2% slope, no farming/gardening See DCH Section 14; 2% slope, significant farming/gardening
Contaminated zone total porosity	unitless	0.4	5	Site-specific	All receptors	See Manual Appendix E and DCH Section 3; consult geologist/hydrologist
Contaminated zone field capacity	unitless	0.2	7	Site-specific	All receptors	See Manual Appendix E; consult geologist/hydrologist
Contaminated zone hydraulic conductivity	m/yr	10	7	Site-specific	All receptors	See Manual Appendix E and DCH Section 5; consult geologist/hydrologist
Contaminated zone b parameter	unitless	5.3	7	Site-specific	All receptors	See Manual Appendix E and DCH Section 13; consult geologist/hydrologist
Average annual wind speed	m/sec	2.0	6	Site-specific	All receptors	See Manual Appendix B and DCH Section 21; consult geologist/hydrologist
Humidity in air	g/m^3	8.0	7	Site-specific	All receptors	Only relevant for tritium (hydrogen-3); see Manual Appendix L
Evapotranspiration coefficient	unitless	0.5	5	Site-specific	All receptors	See Manual Appendix E and DCH Section 12; consult geologist/hydrologist
Precipitation	m/yr	1.0	5	Site-specific	All receptors	See Manual Appendix E and DCH Section 9
Irrigation	m/yr	0.2	5	Site-specific	Farming or gardening	See Manual Appendix E and DCH Section 11
Irrigation mode	unitless	Overhead	-	Site-specific	Farming or gardening	See Manual Appendix E and DCH Section 11
Runoff coefficient	unitless	0.2	5	Site-specific 0.2 0.4 0.65 0.8	All receptors Farming Non-farming Non-farming Non-farming	See Manual Appendix E and DCH Section 10; consult geologist/hydrologist See DCH Section 10; flat, sandy, cultivated land See DCH Section 10; flat urban, area (30% impervious) See DCH Section 10; moderately steep, urban area (50% impervious) See DCH Section 10; moderately steep, built-up area (70% impervious)
Watershed area for nearby stream or pond	m^2	1E+06	5	Site-specific	All receptors	Surface water dependent pathways; see Manual Appendix E and DCH Section 17
Accuracy for water/soil computations	unitless	0.001	-	Site-specific	All receptors	Related to water/soil concentration ratios; see Manual Appendix E
Saturated zone density	g/m^3	1.5	4	Site-specific	All receptors	See Manual Appendix E and DCH Section 2; consult geologist/hydrologist
Saturated zone total porosity	unitless	0.4	4	Site-specific	All receptors	See Manual Appendix E and DCH Section 3; consult geologist/hydrologist
Saturated zone effective porosity	unitless	0.2	3	Site-specific	All receptors	See Manual Appendix E and DCH Section 4; consult geologist/hydrologist
Saturated zone field capacity	unitless	0.2	7	Site-specific	All receptors	See Manual Appendix E; consult geologist/hydrologist
Saturated zone hydraulic conductivity	m/yr	100	3	Site-specific	All receptors	See Manual Appendix E and DCH Section 5; consult geologist/hydrologist
Saturated zone hydraulic gradient	unitless	0.02	3	Site-specific	All receptors	See Manual Appendix E and DCH Section 15; consult geologist/hydrologist
Saturated zone b parameter	unitless	5.3	7	Site-specific	All receptors	See Manual Appendix E and DCH Section 13; consult geologist/hydrologist
Water table drop rate	m/yr	0.001	7	Site-specific	All receptors	See Manual Appendix E and DCH Section 18; consult geologist/hydrologist
Well pump intake depth (m below water table)	m	10	5	Site-specific	All receptors	See Manual Appendix E and DCH Section 19; consult geologist/hydrologist
Model: Nondispersion (ND) or Mass-Balance (MB)	unitless	ND	-	Site-specific	All receptors	See Manual Appendix E
Well pumping rate	m^3/yr	250	4	Site-specific	All receptors	See Manual Appendix E; consult geologist/hydrologist
Number of unsaturated zone strata [##]	unitless	1	-	Site-specific	All receptors	See Manual Appendix E; consult geologist/hydrologist
Unsaturated zone thickness	m	4.0	4	Site-specific	All receptors	See Manual Appendix E; consult geologist/hydrologist
Unsaturated zone soil density	g/m^3	1.5	7	Site-specific	All receptors	See Manual Appendix E and DCH Section 2; consult geologist/hydrologist
Unsaturated zone total porosity	unitless	0.4	7	Site-specific	All receptors	See Manual Appendix E and DCH Section 3; consult geologist/hydrologist
Unsaturated zone effective porosity	unitless	0.2	7	Site-specific	All receptors	See Manual Appendix E and DCH Section 4; consult geologist/hydrologist
Unsaturated zone field capacity	unitless	0.2	7	Site-specific	All receptors	See Manual Appendix E; consult geologist/hydrologist

Table 3-1. Receptor-Specific and Scenario-Specific RESRAD Parameter Values (continued)

RESRAD Parameter	Units	RESRAD Default	Risk Variability #	Proposed Values	Receptor or Scenario	Comment/Reference
Unsaturated zone b parameter	unitless	5.3	7	Site-specific	All receptors	See Manual Appendix E and DCH Section 5; consult geologist/hydrologist
Unsaturated zone hydraulic conductivity	m/yr	10	7	Site-specific	All receptors	See Manual Appendix E and DCH Section 13; consult geologist/hydrologist
Distribution coefficients	cm^3/g	*	4	Site-specific	All receptors	Radionuclide-specific; impacts all pathways, not just groundwater
Inhalation rate	m^3/yr	8,400	6	Site-specific	All receptors	Average over entire 365-day year; default equivalent to 0.9589 m^3/hr
				5,548	Subsistence adult	Assuming adult male rate of 15.2 m^3/day (EFH, Table 1-2)
				2,765	Subsistence child	Assuming 1-5 year old rate of 7.55 m^3/day (EFH, Table 5-23)
				5,548	Resident adult	Assuming adult male rate of 15.2 m^3/day (EFH, Table 1-2)
				2,765	Resident child	Assuming 1-5 year old rate of 7.55 m^3/day (EFH, Table 5-23)
				7,300	Industrial worker	Assuming RAGS default rate of 20 m^3/day for workers
				7,300	Maintenance worker	Assuming RAGS default rate of 20 m^3/day for workers
				7,300	Construction worker	Assuming RAGS default rate of 20 m^3/day for workers
				5,548	Recreational adult	Assuming adult male rate of 15.2 m^3/day (EFH, Table 1-2)
				5,110	Recreational teen	Avg. for 7-16 year old male of 14 m^3/day (EFH, Table 5-23)
Mass loading for inhalation	g/m^3	0.0001	5	Site-specific	Non-construction	Similar to 1/PEF; calculate region-specific PEF values using SSG Section 2
				6.0E-04	Construction	See DCH Section 35
Exposure duration	yr	30	7	Site-specific	All receptors	Same as ED in standard RAGS equations
				30	Subsistence adult	RME duration for resident (EFH, RAGS)
				6	Subsistence child	Assuming 6 years of childhood spend at site
				30	Resident adult	Duration for resident (EFH, RAGS)
				6	Resident child	Assuming 6 years of childhood spend at site
				25	Industrial worker	Duration for occupational receptor (EFH, RAGS)
				25	Maintenance worker	Duration for occupational receptor (EFH, RAGS)
				1	Construction worker	Assuming construction activities during one calendar year
				30	Recreational adult	Duration for (off-site) resident (EFH, RAGS)
				10	Recreational teen	Assumed for off-site adolescent receptor through ages 7-16
Shielding factor, inhalation	unitless	0.4	6	Site-specific	All receptors	Fraction of outdoor air that is filtered/diluted; 1.0 = no filtering/dilution
Shielding factor, external gamma	unitless	0.7	4	Site-specific	All receptors	Fraction of outdoor gamma that is shielded; 1.0 = no shielding
				0.4	Building occupant	See SSG Section 2; 60% shielding for all indoor receptors
Fraction of time spent indoors	unitless	0.5	5	Site-specific	All receptors	Fraction of 8760 hours spent indoors on-site
				0.655	Subsistence adult	16.4 hr/day for 350 days/yr for resident (EFH, Table 1-2)
				0.655	Subsistence child	16.4 hr/day for 350 days/yr for resident (EFH, Table 1-2)
				0.655	Resident adult	16.4 hr/day for 350 days/yr for resident (EFH, Table 1-2)
				0.655	Resident child	16.4 hr/day for 350 days/yr for resident (EFH, Table 1-2)
				0.20	Industrial worker	7 of 8 hours per day for 250 days per year (assumed)
				0.0	All other receptors	No indoor exposure
Fraction of time spent outdoors (on site)	unitless	0.25	5	Site-specific	All receptors	Fraction of 8760 hours spent outdoors on-site
				0.0799	Subsistence adult	2 hrs/day for 350 days/yr for resident (EFH, Table 1-2)
				0.223	Subsistence child	5 hrs/day on weekdays or 7 hrs/day on weekends for 350 days per year for children ages 3-11 (EFH, Table 1-2)
				0.0799	Resident adult	2 hrs/day for 350 days/yr for resident (EFH, Table 1-2)
				0.223	Resident child	5 hrs/day on weekdays or 7 hrs/day on weekends for 350 days per year for children ages 3-11 (EFH, Table 1-2)
				0.0285	Industrial worker	1 of 8 hrs/day for 250 days/yr (assumed)
				0.0228	Maintenance worker	4 hr/week for 50 weeks/yr (assumed)
				0.228	Construction worker	Assumes one full work-year for a supervisor-type worker
				0.0119	Recreational adult	4 hr/wk for averaged over 26 wks/yr; warm season only (assumed)
				0.0119	Recreational teen	4 hr/wk for averaged over 26 wks/yr; warm season only (assumed)
Shape factor flag, external gamma	unitless	1.0	-	Site-specific	All receptors	Default = uniform circular; see Manual Appendix A and DCH Section 50

Table 3-1. Receptor-Specific and Scenario-Specific RESRAD Parameter Values (continued)

RESRAD Parameter	Units	RESRAD Default	Risk Variability #	Proposed Values	Receptor or Scenario	Comment/Reference
Fruits, vegetables and grain consumption	kg/yr	160	2	Site-specific	Farming or gardening	Average over entire 365-day year; see EFH Volume III; grains typically milled off-site and distributed, therefore not included in on-site exposure scenarios
				469	Subsistence adult	22.4 g/kg-day (12.4 for fruit and 10 for vegetables) minus leafy vegetable rate for 60 kg adult; 60kg used because intake rate data includes child data (EFH, Table 1-2)
				118	Subsistence child	22.4 g/kg-day (12.4 for fruit and 10 for vegetables) minus leafy vegetable rate for 15 kg child (EFH, Table 1-2)
				469	Resident adult	22.4 g/kg-day (12.4 for fruit and 10 for vegetables) minus leafy vegetable rate for 60 kg adult; 60kg used because intake rate data includes child data (EFH, Table 1-2)
				118	Resident child	22.4 g/kg-day (12.4 for fruit and 10 for vegetables) minus leafy vegetable rate for 15 kg child (EFH, Table 1-2)
				N/C	All other receptors	Not used
Leafy vegetable consumption	kg/yr	14	5	Site-specific	Farming or gardening	Average over entire 365-day year; see EFH Volume III
				21.4	Subsistence adult	NUREG/CR-5512 Volume 4 default for resident farmer
				4.59	Subsistence child	Adult value scaled by child-to-adult body weight factor
				21.4	Resident adult	NUREG/CR-5512 Volume 4 default for resident farmer
				4.59	Resident child	Adult value scaled by child-to-adult body weight factor
				N/C	All other receptors	Not used
Milk consumption	L/yr	92	4	Site-specific	Farming only	Average over entire 365-day year; see EFH Volume III
				131	Subsistence adult	Rate for 12-19 year old male conservatively assumed (EFH, Table 11-15).
				153	Subsistence child	Rate averaged over 0-5 year old male and female children (EFH, Table 11-15).
				N/C	All other receptors	Not used
Meat and poultry consumption	kg/yr	63	5	Site-specific	Farming only	Average over entire 365-day year; see EFH Volume III
				130	Subsistence adult	5.1 g/kg-day for a 70 kg adult (EFH, Table 1-2)
				27.9	Subsistence child	5.1 g/kg-day for a 15 kg child (EFH, Table 1-2)
				130	Recreational adult	5.1 g/kg-day for a 70 kg adult (EFH, Table 1-2)
				78.2	Recreational teen	5.1 g/kg-day for a 42 kg adolescent (EFH, Table 1-2)
				N/C	All other receptors	Not used
Fish consumption	kg/yr	5.4	7	Site-specific	Fishing only	Average over entire 365-day year; see EFH Volume III
				62.05	Subsistence adult	Native American rate recommended by EFH, Table 1-2 (170 g/day)
				25.55	Subsistence other	Native American rate recommended by EFH, Table 1-2 (70 g/day)
				9.125	Recreational adult	Freshwater fish rate recommended by EFH, Table 1-2 (25 g/day)
				2.90	Recreational other	Freshwater fish average rate recommended by EFH, Table 1-2 (8 g/day)
Other seafood consumption	kg/yr	0.9	7	Site-specific	Fishing only	Mollusks and crustacea; Average over entire 365-day year; see EFH Volume III
Soil ingestion rate	m/yr	36.5	4	Site-specific	All receptors	Average over entire 365-day year; default equivalent to 100 mg/day
				36.5	Subsistence adult	100 mg/day for residential adult (RAGS)
				73.0	Subsistence child	200 mg/day for residential child (RAGS)
				36.5	Resident adult	100 mg/day for residential adult (RAGS)
				73.0	Resident child	200 mg/day for residential child (RAGS)
				18.25	Industrial worker	50 mg/day for industrial worker rate (RAGS)
				36.5	Maintenance worker	100 mg/day for adult rate (RAGS)
				175.2	Construction worker	480 mg/day for assuming outdoor summer activities (EFH, Table 4-16)
				36.5	Recreational adult	100 mg/day for adult rate (RAGS)
				54.75	Recreational teen	150 mg/day assuming average of adult and child rates (RAGS)
Drinking water intake	L/yr	510	3	Site-specific	All receptors	Average over entire 365-day year; default equivalent to 1.397 L/day
				869	Subsistence adult	34 ml/kg-day for 70 kg adult (EFH, Table 1-2)
				186	Subsistence child	34 ml/kg-day for 15 kg child (EFH, Table 1-2)
				869	Resident adult	34 ml/kg-day for 70 kg adult (EFH, Table 1-2)
				186	Resident child	34 ml/kg-day for 15 kg child (EFH, Table 1-2)
				N/C	All other receptors	Typically limited to above residential or farming scenarios
Contamination fraction of drinking water	unitless	1.0	-	1.0	All receptors	Typically set to 1.0; see Manual Appendix E
Contamination fraction of household water	unitless	1.0	-	1.0	Resident only	Relevant for radon calculations only; see Manual Appendix C
Contamination fraction of livestock water	unitless	1.0	-	1.0	Farming only	Typically set to 1.0; see Manual Appendix D

Table 3-1. Receptor-Specific and Scenario-Specific RESRAD Parameter Values (continued)

RESRAD Parameter	Units	RESRAD Default	Risk Variability #	Proposed Values	Receptor or Scenario	Comment/Reference
Contamination fraction of irrigation water	unitless	1.0	-	1.0	Farming or gardening	Typically set to 1.0; see Manual Appendix D
Contamination fraction of aquatic food	unitless	0.5	7	0.5	Fishing only	Typically set to 1.0; see Manual Appendix D
Contamination fraction of plant food	unitless	-1 **	-	-1	Farming or gardening	Typically contaminated surface area dependent; see Manual Appendix D
Contamination fraction of meat	unitless	-1 **	-	-1	Farming only	Typically contaminated surface area dependent; see Manual Appendix D
Contamination fraction of milk	unitless	-1**	-	-1	Farming only	Typically contaminated surface area dependent; see Manual Appendix D
Livestock fodder intake for meat	kg/day	68	5	68	Farming only	See Manual Appendix D
Livestock fodder intake for milk	kg/day	55	5	55	Farming only	See Manual Appendix D
Livestock water intake for meat	L/day	50	7	50	Farming only	See Manual Appendix D
Livestock water intake for milk	L/day	160	7	160	Farming only	See Manual Appendix D
Livestock soil intake	kg/day	0.5	6	0.5	Farming only	See Manual Appendix D
Mass loading for foliar deposition	g/m^3	0.0001	7	0.0001	Farming or gardening	See Manual Appendix E
Depth of soil mixing layer	m	0.15	5	Site-specific 0.05 0.0	All receptors Non-farming Non-farming	Relevant when contaminated thickness ≤ 0.15 m or cover thickness < 15 cm (original cover can erode to < 15 cm); default assumes tilling Assuming no-till, but some surface disturbance (e.g., industrial activities) No surface soil disturbances expected (e.g., with land-use controls or paved surfaces)
Depth of roots	m	0.9	3	Site-specific	Farming or gardening	See Manual Appendix D and DCH Section 37
Drinking water fraction from ground water	unitless	1.0	-	1.0	All receptors	Default assume 0% from surface water; set to 0.0 for 100% from surface water
Household water fraction from ground water	unitless	1.0	-	1.0	Resident only	Default assume 0% from surface water; set to 0.0 for 100% from surface water
Livestock water fraction from ground water	unitless	1.0	-	1.0	Farming only	Default assume 0% from surface water; set to 0.0 for 100% from surface water
Irrigation fraction from ground water	unitless	1.0	-	1.0	Farming or gardening	Default assume 0% from surface water; set to 0.0 for 100% from surface water
Wet weight crop yield for non-leafy	kg/m^2	0.7	5	Site-specific	Farming or gardening	See Manual Appendix D
Wet weight crop yield for leafy	kg/m^2	1.5	7	Site-specific	Farming or gardening	See Manual Appendix D
Wet weight crop yield for fodder	kg/m^2	1.1	7	Site-specific	Farming or gardening	See Manual Appendix D
Growing season for non-leafy	years	0.17	7	Site-specific	Farming or gardening	See Manual Appendix D; also see EFH Volume III for region-specific values
Growing season for leafy	years	0.25	7	Site-specific	Farming or gardening	See Manual Appendix D; also see EFH Volume III for region-specific values
Growing season for fodder	years	0.08	7	Site-specific	Farming or gardening	See Manual Appendix D; also see EFH Volume III for region-specific values
Translocation factor for non-leafy	unitless	0.1	7	Site-specific	Farming or gardening	See Manual Appendix D
Translocation factor for leafy	unitless	1.0	7	Site-specific	Farming or gardening	See Manual Appendix D
Translocation factor for fodder	unitless	0.1	7	Site-specific	Farming or gardening	See Manual Appendix D
Dry foliar interception fraction for non-leafy	unitless	0.25	7	Site-specific	Farming or gardening	See Manual Appendix D
Dry foliar interception fraction for leafy	unitless	0.25	7	Site-specific	Farming or gardening	See Manual Appendix D
Dry foliar interception fraction for fodder	unitless	0.25	7	Site-specific	Farming or gardening	See Manual Appendix D
Wet foliar interception fraction for non-leafy	unitless	0.25	7	Site-specific	Farming or gardening	See Manual Appendix D
Wet foliar interception fraction for leafy	unitless	0.25	6	Site-specific	Farming or gardening	See Manual Appendix D
Wet foliar interception fraction for fodder	unitless	0.25	7	Site-specific	Farming or gardening	See Manual Appendix D
Weathering removal constant for vegetation	1/yr	20	6	Site-specific	Farming or gardening	See Manual Appendix D
Storage time: fruits, non-leafy vegetables, and grain	days	14	7	Site-specific	Farming or gardening	Adjusts for radiological ingrowth and decay; see Manual Appendix D
Storage time: leafy vegetables	days	1.0	7	Site-specific	Farming or gardening	Adjusts for radiological ingrowth and decay; see Manual Appendix D
Storage time: milk	days	1.0	7	Site-specific	Farming or gardening	Adjusts for radiological ingrowth and decay; see Manual Appendix D
Storage time: meat and poultry	days	20	7	Site-specific	Farming or gardening	Adjusts for radiological ingrowth and decay; see Manual Appendix D
Storage time: fish	days	7.0	7	Site-specific	Fishing only	Adjusts for radiological ingrowth and decay; see Manual Appendix D
Storage time: crustacea and mollusks	days	7.0	7	Site-specific	Farming or gardening	Adjusts for radiological ingrowth and decay; see Manual Appendix D
Storage time: well water	days	1.0	7	Site-specific	Farming or gardening	Adjusts for radiological ingrowth and decay; see Manual Appendix D
Storage time: surface water	days	1.0	7	Site-specific	Farming or gardening	Adjusts for radiological ingrowth and decay; see Manual Appendix D
Storage time: livestock fodder	days	45	7	Site-specific	Farming or gardening	Adjusts for radiological ingrowth and decay; see Manual Appendix D
Thickness of building foundation	m	0.15	-	Site-specific	Building occupant	Relevant for radon calculations only; see Manual Appendix C
Bulk density of building foundation	g/cm^3	2.4	-	Site-specific	Building occupant	Relevant for radon calculations only; see Manual Appendix C
Total porosity of the cover material	unitless	0.4		Site-specific	Building occupant	Relevant for radon calculations only; see Manual Appendix C
Total porosity of the building foundation	unitless	0.1	-	Site-specific	Building occupant	Relevant for radon calculations only; see Manual Appendix C

Table 3-1. Receptor-Specific and Scenario-Specific RESRAD Parameter Values (continued)

RESRAD Parameter	Units	RESRAD Default	Risk Variability [#]	Proposed Values	Receptor or Scenario	Comment/Reference
Volumetric water constant of the cover material	unitless	0.05	-	Site-specific	Building occupant	Relevant for radon calculations only; see Manual Appendix C
Volumetric water constant of the foundation	unitless	0.03	-	Site-specific	Building occupant	Relevant for radon calculations only; see Manual Appendix C
Diffusion coefficient for radon gas in cover material	m/sec	2E+06	-	Site-specific	Building occupant	Relevant for radon calculations only; see Manual Appendix C
Diffusion coefficient for radon gas in foundation material	m/sec	3E-07	-	Site-specific	Building occupant	Relevant for radon calculations only; see Manual Appendix C
Diffusion coefficient for radon gas in contaminated zone soil	m/sec	2E-06	-	Site-specific	Building occupant	Relevant for radon calculations only; see Manual Appendix C
Radon vertical dimension of mixing	m	2.0	-	Site-specific	Building occupant	Relevant for radon calculations only; see Manual Appendix C
Average building air exchange rate	1/hour	0.5	-	Site-specific	Building occupant	Relevant for radon calculations only; see Manual Appendix C
Height of the building (room)	m	2.5	-	Site-specific	Building occupant	Relevant for radon calculations only; see Manual Appendix C
Building interior area factor	unitless	0.0	-	Site-specific	Building occupant	Relevant for radon calculations only; see Manual Appendix C
Building depth below ground surface	m	-1.0	-	Site-specific	Building occupant	Relevant for radon calculations only; see Manual Appendix C
Emanating power of Rn-222 gas	unitless	0.25	-	Site-specific	Building occupant	Relevant for radon calculations only; see Manual Appendix C
Emanating power of Rn-220 gas	unitless	0.15	-	Site-specific	Building occupant	Relevant for radon calculations only; see Manual Appendix C
Pathway – external gamma	unitless	active	-	Active	All receptors	See Manual Appendix A
Pathway – inhalation (w/o radon)	unitless	active	-	Active	All receptors	See Manual Appendix B
Pathway – plant ingestion	unitless	active	-	Active Inactive	Farming or gardening All other receptors	See Manual Appendix D Typically active for resident or subsistence farmer only
Pathway – meat ingestion	unitless	active	-	Active Inactive	Farming only All other receptors	See Manual Appendix D Typically active for subsistence farmer only
Pathway – milk ingestion	unitless	active	-	Active Inactive	Farming only All other receptors	See Manual Appendix D Typically for subsistence farmer only
Pathway – aquatic foods	unitless	active	-	Active Inactive	Fishing only All other receptors	See Manual Appendix D Typically active for subsistence farmer or recreational user only
Pathway – drinking water	unitless	active	-	Active Inactive	Resident/farmer All other receptors	See Manual Appendix E Typically active for resident or subsistence farmer only
Pathway – soil ingestion	unitless	active	-	Active	All receptors	See Manual Appendix F
Pathway – radon	unitless	active	-	Inactive	All receptors	Typically excluded from risk calculations; see Manual Appendix C

[#] From NUREG/CR-6697 Table 4.1; represents variability of radiological dose (same relationship with risk assumed) on parameter ranging from 1 (extremely sensitive) to 7 (insensitive). Dash (-) shown if no values listed in NUREG/CR-6697.

[δ] Site-specific information/data (either physical, behavioral, or metabolic) should be used whenever available. For this table, general information is provided in the Comment/Reference column when the Proposed Values is "site-specific."

[##] The unsaturated zone may contain as many as five distinct layers

* Radionuclide-specific and can be soil-type-specific. See RESRAD support documentation for potential defaults.

** Adjusted automatically by RESRAD based on the contaminated surface area.

DCH = *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil* (ANL 1993)
EFH = *Exposure Factors Handbook* (EPA 1997)
Manual = *User's Manual for RESRAD Version 6* (ANL 2001)
MARSSIM = Multi-Agency radiation Survey and Site Investigation Manual (DoD et al. 2000)
N/C = not considered
RAGS = Risk Assessment Guidance for Superfund
RME = reasonable maximum exposure
SSG = *Soil Screening Guidance for Radionuclides: Technical Background Document* (EPA 2000)
UMTRCA = Uranium Mill Tailings Radiation Control Act

3.2 GENERAL RECEPTOR DESCRIPTIONS

Section 3.2 describes receptors often evaluated in CERCLA risk assessments. RESRAD input parameters related to these receptors are listed in Table 3-1. Each receptor may represent a most conservative plausible scenario under current or potential future-use conditions, or may be considered as part of remedial alternative development (e.g., for a Feasibility Study). In any case, these receptor descriptions form the basis of the Table 3-1 input parameter values.

3.2.1 Subsistence Farmer

A subsistence farmer is often the most conservative plausible receptor in a radiological risk assessment although produce, meat, dairy, and fish ingestion are typically excluded from even the most conservative exposure scenarios in chemical risk assessments. The farmer may be a child or an adult, or can be considered a child for a fraction of the exposure duration. The farmer generally spends a significant amount of time outdoors, but overall is indoors for a larger fraction of the day (including after dark). Farmers are characterized by, on average, moderate to low activity levels (e.g., non-elevated breathing rates, soil ingestion rates, etc.). This receptor is assumed to consume any or all of the following: home-grown produce, meat and dairy products from livestock, fish from a local surface water body, and water from a well or surface water body. Soil ingestion, dust inhalation, and external exposure are also assumed to be complete exposure pathways for the subsistence farmer. Table 3-1 lists parameter values for a subsistence farmer scenario, although this scenario may not be appropriate for some sites. Parameter values for adults and children are provided, as appropriate. Parameter values for a child and an adult can be combined using the following approach:

- Define exposure duration for residential child (ED_c) and adult (ED_a);
- Likewise, define the parameter under consideration as P_c for child and P_a for adult; then
- Combined parameter values = $[(ED_c \times P_c) + (ED_a \times P_a)] / (ED_c + ED_a)$.

For example, assume the child soil ingestion rate is 200 mg/day over 6 year and the adult rate is 100 mg/day over 24 years. The time-weighted average is $[(6 \times 200) + (24 \times 100)] / (6+24) = 120$ mg/day.

3.2.2 Resident

A resident is typically the most conservative plausible non-farming receptor in a risk assessment. The resident may be a child or an adult, or can be considered a child for a fraction of the exposure duration. Residents generally spend more time indoors and are characterized by moderate to low activity levels (e.g., non-elevated breathing rates, soil ingestion rates, etc.). The resident can be a gardener that ingests homegrown produce and can consume water from a well of local surface water body. Soil ingestion, dust inhalation, and external exposure are also assumed to be complete exposure pathways for the resident. Table 3-1 lists parameter values for a resident scenario, although this scenario may not be appropriate for some sites. Parameter values for adults and children are provided, as appropriate. Parameter values for a child and an adult can be combined using the following approach:

- Define exposure duration for residential child (ED_c) and adult (ED_a);
- Likewise, define the parameter under consideration as P_c for child and P_a for adult; then
- Combined parameter values = $[(ED_c \times P_c) + (ED_a \times P_a)] / (ED_c + ED_a)$.

For example, assume the child soil ingestion rate is 200 mg/day over 6 year and the adult rate is 100 mg/day over 24 years. The time-weighted average is $[(6 \times 200) + (24 \times 100)] / (6+24) = 120$ mg/day.

3.2.3 Industrial Worker

An industrial worker can be the most conservative plausible receptor at a site that has little or no chance of undergoing residential development (e.g., a chemical factory). This receptor is considered to be a typical office/laboratory employee that works a standard work year and is characterized by moderate to low activity levels. Industrial workers are always adults and spend most of the time indoors. Complete exposure pathways typically include dust inhalation, soil ingestion, external gamma, and sometimes drinking water.

3.2.4 Maintenance Worker

A maintenance worker is typically the most conservative plausible receptor at a mostly unoccupied site (e.g., a fenced or isolated area) that must be mowed, landscaped, etc. This receptor is considered to be a typical laborer that works a fraction of the year and is characterized by moderate to high activity levels. Maintenance workers are adults and spend time indoor and outdoors depending on the site-specific description. Complete exposure pathways typically include dust inhalation, soil ingestion, and external gamma. Drinking water can be added if appropriate, but it may also be assumed that the receptor consumes water from an off-site source, particularly where site conditions do not provide a viable source of drinking water.

3.2.5 Construction Worker

A construction worker typically are not the most conservative plausible receptors. Short-term intake/exposure estimates are typically higher than other receptors since the construction worker is typically in direct contact with the contaminated media and is characterized by elevated activity levels (elevated inhalation rates, etc.). However, the construction worker is usually considered a short-term receptor receiving a one-time exposure over some fraction of one year. Construction workers are always adults and spend their time outdoors. Complete exposure pathways typically include dust inhalation, soil ingestion, and external gamma. Again, drinking water can be added if appropriate, but it may be assumed that the worker consumes water from an off-site source, particularly where site conditions do not provide a viable source of drinking water.

3.2.6 Recreational User and Inadvertent Intruders

A recreational user or inadvertent intruder can be the most conservative plausible receptor at a site that is not maintained and is generally unpopulated. This receptor can be a jogger, fisherman, hunter, or other receptor that spends a fraction of the year on-site and is characterized by low to high activity levels. These receptors can be children, teens, or adults and are typically assumed to spend all of their time outdoors. Complete exposure pathways typically include dust inhalation, soil ingestion, and external gamma, but can include incidental drinking water (from a body of surface water), game ingestion, or fish ingestion.

3.3 TOXICITY AND RELATED FACTORS

RESRAD default toxicity (i.e., cancer slope) factors are taken from Federal Guidance Report No. 13 (FGR-13) morbidity tables (EPA 1999). Factors are applied using the "+D" approach consistent with HEAST. That is, decay products with half-lives less than six months are included in the parent factor. For example, the radium-228+D slope factor includes contributions from radium-228 plus its short-lived decay product actinium-228. The code allows the user to select one of four slope tables: FGR-13 morbidity, FGR-13 mortality, HEAST 1995 morbidity, and HEAST 2000 morbidity. Slope factors used in each RESRAD "run" are listed in the *Health Risk Report* of RESRAD output.

RESRAD allows users more flexibility in the selection of dose factors and transfer factors (e.g., soil to plant). Users may create whole new libraries of dose factors using whatever criteria apply to the site. For

example, a radionuclide may be less soluble than would be assumed using the default dose factor, thus modifications are warranted and may be incorporated. RESRAD default dose factors are taken from FGR-11 (EPA 1988) and FGR-12 (EPA 1993) and again use the "+D" approach. Adjustments to transfer factors may be made in a similar fashion using site-specific or otherwise approved values. Dose and transfer factors used in each RESRAD "run" are listed in the *Summary Report* of RESRAD output.

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4.0 EXPOSURE PATHWAYS

Section 4 describes the exposure pathways evaluated in RESRAD and what risk assessors familiar with standard RAGS equations should know to properly complete RESRAD risk calculations. RESRAD exposure pathways are divided into five major headings including external gamma, inhalation (excluding radon), ingestion, drinking water, and radon. The exposure pathway descriptions are not intended to replace, but to supplement RESRAD guidance documents (e.g., ANL 2001 and ANL 1993). The intent is to point out some of the subtle differences in RAGS versus RESRAD methods and to provide some useful tools for proper implementation of the RESRAD code.

Intake equations from Section 2 are again listed for ease of reference. Select parameters from these equations are then described in more detail to give a risk assessor some insight on their proper use.

4.1 EXTERNAL GAMMA

Recalling the basic external gamma exposure equation from Section 2.1, there are four factors of particular interest: FOTD, FIND, GSF, and ETF.

$$Exposure\,(pCi \cdot year/g) = C_j \times ED \times [FOTD + (FIND \times GSF)] \times ETF_j \qquad \text{Eq. 2-9}$$

where:

- C_j = concentration of radionuclide "j" in some medium (pCi/g or pCi/L);
- ED = exposure duration (years);
- FOTD = outdoor time fraction (dimensionless); fraction of total year exposed to contaminant while outdoors = (total hours per year exposed outdoors) / (8760 hours);
- FIND = indoor time fraction (dimensionless); fraction of total year exposed to contaminant while indoors = (total hours per year exposed indoors) / (8760 hours);
- GSF = gamma shielding factor, equivalent to (1-Se) (unitless); and
- ETF_j = environmental transport factor radionuclide "j"; could be an area factor, a cover and depth factor, radiological ingrowth and decay, etc.

The outdoor time fraction (FOTD) is the fraction of time spent outdoors (on-site). This factor is calculated as the total hours outdoors (on-site) divided by the total number of hours in the year (8760). For example, if a industrial worker spends on average of 1 hour per day, 250 days per year in a contaminated area, the occupancy factor is (1×250 / 8760) = 0.0285. RESRAD assumes that there is no gamma shielding during this fraction of the year. Similarly, the indoor time fraction (FIND) is the fraction of time spent indoors (on-site). This factor is calculated as the total hours indoors (on-site) divided by the total number of hours in the year (8760). For example, assuming the same industrial worker spends on average of 7 hour per day, 250 days per year inside a structure build on or surrounded by contamination, the occupancy factor is (7×250 / 8760) = 0.200. RESRAD assumes that the gamma shielding factor applies during this fraction of the year.

The GSF represents the fraction of the external gamma that is transmitted through structure floors and walls. This is similar to the (1-Se) factor in Equation 2-7 and effectively dilutes that external gamma pathway while the receptor is indoors (on-site). For example, consider a GSF of 0.4 and the above industrial worker. The gamma levels during the 7-hour per day indoor occupancy would be reduced to 40% of the outdoor level. There would be no shielding for the 1-hour outdoor exposure (e.g., GSF = 1.0). Note that GSF is independent of any shielding that may occur from cover material. If it is assumed that

contaminated media are covered by, for example, 0.15 m (6 inches) of clean soil, RESRAD automatically accounts for any shielding from the cover then applies to the GSF for indoor exposures.

Two components of the ETF are of particular importance. They are the area of the contaminated zone and the contaminated zone thickness. The RESRAD code includes a program to adjust gamma levels dependent on the surface area and depth of contamination. In general, gamma levels (and risk) are proportional to area and depth, although as areas increase to greater than about 1,000 m^2 and as the thickness increases to greater than about 1 m, there is no additional increase in risk. As a result, an area greater than about 1,000 m^2 with a thickness of about 1 m is effectively the same as a contaminated zone of infinite area and semi-infinite thickness. Depth and cover factor equations are too complex to discuss in detail here, but are presented in ANL 2001. Note that thickness of the contaminated zone may be impacted by the erosion parameter. A thickness of 1 meter will completely erode in 1000 years using the default erosion rate of 0.001 m/year. RESRAD is a dynamic model that accounts for erosion, leaching, radiological decay, radiological ingrowth, etc. All these variables are included in the ETF term and can significantly impact risk assessment results.

4.2 INHALATION (EXCLUDING RADON)

Recalling the basic inhalation intake equation from Section 2.1, there are six factors of particular interest: VR, FOTD, FIND, DF, ASR, and ETF.

$$Intake_{inh}\ (pCi) = C_j \times VR \times ASR \times ED \times [FOTD + (FIND \times DF_i)] \times ETF_j \qquad \text{Eq. 2-6}$$

where:

- C_j = concentration of radionuclide "j" in some medium (pCi/g or pCi/L);
- VR = ventilation/inhalation rate (m^3/year);
- ASR = air to soil concentration ratio (g/m^3), equivalent to PEF^{-1};
- ED = exposure duration (years);
- FOTD = outdoor time fraction (dimensionless); fraction of total year exposed to contaminant while outdoors = (total hours per year exposed outdoors) / (8760 hours);
- FIND = indoor time fraction (dimensionless); fraction of total year exposed to contaminant while indoors = (total hours per year exposed indoors) / (8760 hours);
- DF_i = dilution factor for indoor inhalation (unitless); and
- ETF_j = environmental transport factor radionuclide "j"; could be an area factor, a cover and depth factor, radiological ingrowth and decay, etc.

The ventilation rate (VR) is the average on-site inhalation rate projected over the entire year. For example, if the average on-site inhalation rate is 1.3 m^3/hour, the yearly rate entered into RESRAD is 1.3 m^3/hr × 8760 hrs/year = 11,388 m^3/year. The rate is calculated independent of the number of hours or days on-site because of the way RESRAD applies the occupancy factor. For example, assume an industrial worker is on-site for 250 days/year and has an average on-site inhalation rate of 20 m^3/day. The yearly inhalation rate could be incorrectly calculated as 20 m^3/day × 250 days/year = 5,000 m^3/year. RESRAD would actually interpret this rate as 5000 m^3/year ÷ 365 day/year = 13.7 m^3/day, and the inhalation intake rate (and risk) would be underestimated. For RESRAD the inhalation rate is always interpreted as the on-site rate projected over a 24 × 365 = 8760 hour year.

FOTD is the fraction of time spent outdoors (on-site). This factor is calculated as the total hours outdoors (on-site) divided by the total number of hours in the year (8760). For example, if a maintenance worker spends on average of 1 hour per day, 250 days per year in a contaminated area, the occupancy factor is (1×250 / 8760) = 0.0285. RESRAD assumes that there is no airborne dust dilution (see below) during this

fraction of the year. Similarly, FIND is the fraction of time spent indoors (on-site). This factor is calculated as the total hours indoors (on-site) divided by the total number of hours in the year (8760). For example, if the same maintenance worker spends on average of 7 hour per day, 250 days per year inside a structure build on or surrounded by contamination, the occupancy factor is (7×250 / 8760) = 0.200. RESRAD assumes that the airborne dust levels are diluted or filtered during this fraction of the year.

The dust DF represents the fraction of the airborne dust that is diluted or filtered prior to inhalation by the indoor receptor. This is similar to the GSF and applies only while the receptor is indoors (on-site). For example, consider a DF of 0.4 and the above maintenance worker. The dust levels during the 7-hour per day indoor occupancy would be reduced to 40% of the outdoor level. There would be no such reduction for the 1-hour outdoor exposure (i.e., DF = 1.0). Note that the DF is independent of any reductions in airborne contamination due to cover material. If it is assumed that contamination is covered by, for example, 0.15 m (6 inches) of clean soil, dust from the contaminated zone could be eliminated, depending on the assumed mixing layer and erosion rates. Take for example a cover depth of 0.15 m, a mixing layer of 0.05 m, and an erosion rate of 0.001 m/year. At first, the mixing would not be sufficient to bring contamination to the surface. After 100 years, 0.1 m of the cover will have eroded, some mixing will occur, and some of the contaminated soil zone will become airborne. After 150 years the entire cover will be eroded away and all airborne dust will originate from the contaminated zone.

The air-to-source ratio (ASR) represents the radionuclide concentration in air divided by the concentration in soil (pCi/m^3 per pCi/g = g/m^3). This is similar to the 1/PEF term in standard RAGS equations[3], but default ASR values are typically orders of magnitude higher (i.e., more conservative). The ASR term is used in the RESRAD code as mass loading for inhalation and is usually defined based on receptor-specific information. ANL 1993 and others provide a range of possible values for a given scenario, although values can also be derived using PEF calculation methods (see EPA 2000) or using a mixture of activity-specific mass loading values from literature. As with the PEF, the ASR can be adjusted to account only for the respirable of contaminated dust. Table 4-1 presents an example mass loading calculation using NRC defaults and an assumed breakdown of receptor activities. By inserting the weighted mass load value into RESRAD, the risk assessor accounts for short periods of heavy loading during gardening activities and longer periods of ambient loading. The weighted values is adjusted by RESRAD using DF for indoor exposures.

Table 4-1. Example Weighted Mass Loading for Resident Gardener

Location	ML_k (g/m^3)	Exposure Time (hour/year)	FO_k Fraction On-site	WML (g/m^3)
Ambient	3.14E-06	18.4 hr/day × 350 days/year	0.7306	—
Gardening	4.00E-04	1 hr/day × 90 days/year	0.0103	—
				8.66E-06

ML_k = mass loading for activity/location "k"
FO_k = fraction of time spent for activity/location "k"; ΣFO_k = fraction on-site
WML = weighted mass loading = $[\Sigma(ML_k \times FO_k)] / \Sigma(FO_k)$; additional adjustments may be made to account only for the respirable fraction of generated dust

The ETF includes the area plus cover and depth factors that produce similar adjustments for all RESRAD exposure pathways. In general, inhalation intake (and risk) is related directly to the size of the area and wind speed (see Appendix B of ANL 2001). Larger areas and higher wind speeds correlate to more dust

[3] The PEF is described in RAGS Part B (EPA 1991) as the respirable concentration of particulates in air originating from contaminated soil. The derivation of the PEF is dependent on the size of the contaminated area, wind speed, and fractional vegetative cover, among other variables. However, it is independent of the type of receptor-specific activities (e.g., construction activities) that could produce various levels of dust loading.

in the air, thus larger inhalation intake and risk. Inhalation rate is also dependent on the cover depth, erosion rate, the thickness of the contaminated zone, and the mixing layer. As long as the cover depth is thicker than the mixing layer there will be no inhalation intake. Over time, however, the cover may erode, or no cover may be assumed. The relationship between depth and cover factors and intake are also presented in Appendix B of ANL 2001. RESRAD also accounts for erosion, leaching, radiological decay, radiological ingrowth, etc. All these variables are included in the ETF term and can significantly impact risk assessment results.

4.3 INGESTION – SOIL

Recalling the basic soil ingestion intake equation from Section 2.1, there are four factors of particular interest: IR, FOTD, FIND, and ETF.

$$Intake_{ing}\ (pCi) = C_j \times IR \times (FOTD + FOND) \times ED \times ETF_j\ , \qquad \text{Eq. 2-2}$$

where:

- C_j = concentration of radionuclide "j" in some medium (pCi/g or pCi/L);
- IR = ingestion rate (g/year or L/year);
- FOTD = outdoor time fraction (dimensionless); fraction of total year exposed to contaminant while outdoors = (total hours per year exposed outdoors) / (8760 hours);
- FIND = indoor time fraction (dimensionless); fraction of total year exposed to contaminant while indoors = (total hours per year exposed indoors) / (8760 hours);
- ED = exposure duration (years); and
- ETF_j = environmental transport factor radionuclide "j"; could be an area factor, a cover and depth factor, radiological ingrowth and decay, etc.

The ingestion rate (IR) is the average rate projected over the entire year. For example, if the average on-site soil ingestion rate is 50 mg/day the yearly rate is 0.05 g/day × 365 days/year = 18.25 g/year. The rate is calculated independent of the number of days on-site because of the way RESRAD applies the occupancy factor. For example, assume an industrial worker is on-site for 250 days/year and ingests soil at a rate of 50 mg/day. The yearly soil ingestion rate could be incorrectly calculated as 0.05 g/day × 250 days/year = 12.5 g/year. However, RESRAD would interpret this rate as 12.5 g/year ÷ 365 day/year = 0.034 g/day or 34 mg/day (instead of 50 mg/day), and the soil ingestion intake rate (and risk) would be underestimated. The ingestion rate is correctly interpreted as the on-site rate projected over a 24 × 365 = 8760 hour year.

The time fraction terms (FOTD and FIND) are the same as described under the external gamma and inhalation pathways. For the ingestion pathway there is no shielding or dilution factor to adjust for indoor occupancy. Therefore, the ingestion rate in RESRAD is used as it is in standard RAGS equations, with the exception that the ingestion rate is a yearly rate (e.g., 18.25 g/year) and not daily (50 mg/day).

The ETF includes an area factor (FA) that impacts the ingestion pathways. The ingestion pathway is divided into five subcategories including soil/sediment, meat and dairy, fish, water, and homegrown produce (non-soil factors are described under Section 4.4). In general, soil ingestion intake (and risk) are related to area (A) using the following relationship (also see Appendices F of ANL 2001):

$$FA\ (soil) = A/1{,}000 \text{ for } A < 1{,}000\ m^2 \text{ or } 1 \text{ for } A > 1{,}000\ m^2$$

Therefore, FA for soil is linearly dependent on area up 1,000 m^2. Once the area reaches 1,000 m^2 the receptor is assumed to ingest all soil from the contaminated zone.

The soil ingestion rate is also dependent on the somewhat complex relationship between cover and depth factors, erosion rate, the thickness of the contaminated zone, and the mixing layer. As long as the cover depth is thicker than the mixing layer there will be no intake through the soil ingestion pathway. Over time, however, the cover may erode, or no cover may be assumed. The relationship between depth factor and exposure are presented in Appendices F of ANL 2001. Generally, the soil ingestion pathway is complete as long as there is some thickness of contaminant at the surface (i.e., is not covered deeper than the mixing layer and the cover has not eroded away). RESRAD also accounts for leaching, radiological decay, radiological ingrowth, etc. All these variables are included in the ETF term and can significantly impact risk assessment results.

4.4 INGESTION – DRINKING WATER AND FOODSTUFF

As noted in Section 2.1, produce, meat, dairy, and fish ingestion are not automatically included in chemical risk calculations. This is because the uncertainties in the associated environmental transport and bioaccumulation factors (e.g., from soil to cow to milk) are large and can dominate risk estimates. However, the radiological risk/dose estimates often default to include subsistence farming and fishing exposure pathways with little consideration of these uncertainties. The environmental transport and bioaccumulation factors used by RESRAD are interpreted on the same level as cancer slope factors: factors are accepted as approved point estimates in spite of large uncertainties. The RESRAD default scenario (as subsistence farmer/fisherman) is consistent with the paradigms established by the DOE and the NRC for establishing concentration limits for radiological contaminants. Moving away from the subsistence exposure pathways requires special justification under the DOE and NRC paradigms, whereas special circumstances must exist for including meat, milk, produce, and fish in a typical CERCLA risk assessment.

Recalling the basic water and foodstuff ingestion intake equation from Section 2.1, there are three factors of particular interest: IR, FO, and ETF.

$$Intake_{ing}\ (pCi) = C_j \times IR \times FO \times ED \times ETF_j\ , \qquad \text{Eq. 2-3}$$

where:

C_j	=	concentration of radionuclide "j" in some medium (pCi/g or pCi/L);
IR	=	ingestion rate (g/year or L/year);
FO	=	usage factor; fraction originating from a potentially contaminated medium or used by the receptor, e.g., 0.05 if 5% of produce is from an on-site garden (unitless);;
ED	=	exposure duration (years); and
ETF_j	=	environmental transport factor radionuclide "j"; could be an area factor, a cover and depth factor, radiological ingrowth and decay, etc.

The ingestion rate (IR) can be interpreted more than one way, but is most easily interpreted as the average rate of ingestion while on-site. For example, if the average residential homegrown produce ingestion rate is 1 kg/day, the yearly rate is 1 kg/day × 350 days/year = 350 kg/year. The risk assessor may then set the usage factor to 1.0 to estimate total intake. The usage factor (FO) interpreted as the fraction of the on-site potentially contaminated medium used for direct or indirect[4] consumption. If FO = 1.0, then it is assumed that 100% of the ingested medium is impacted by contaminated soil. In the above example, the resident would consume 1.0 × 350 kg of homegrown produce per year. The same result is achieved by setting IR = 1 kg/day × 365 days/year = 365 kg/year and FO = 350/365 = 0.959, although this is a less straightforward approach (other combinations may produce the same result). Note that there are no time fraction terms

[4] An example of indirect consumption is drinking milk from a cow that eats grass growing in contaminated soil.

(FOTD and FIND) for water and foodstuff ingestion. Instead, fractional intakes are modeled exclusively though the usage factor (FO).

For drinking water FO can be broken into two additional factors: the fraction of the drinking water (FDW) from the site and the fraction of water from an on-site well (FD1 – balance of the on-site drinking water comes from a potentially contaminated surface water body). Consider an example industrial worker. This worker drinks 250 L/year from the site, 90% from an on-site well and 10% from an on-site pond, but has an overall average consumption rate of 2 L/day. The worker's on-site intake is calculated by setting IR = 1 L/day × 250 days/year = 250 L/year, FDW = 1.0, and FD1 = 0.9[5]. The same result is achieved by setting IR = 2 L/day × 365 days/year = 730 L/year, FDW = 250/365 = 0.685, and FD1 = 0.9, although this is a less straightforward approach (other combinations may produce the same result). Any fraction of the drinking water originating from an off-site source is assumed to be uncontaminated.

The ETF includes an area factor (FA) that impacts the ingestion pathways. The ingestion pathway is divided into five subcategories including soil/sediment, meat and dairy, fish, water, and homegrown produce (soil/sediment factors are described under Section 4.3). In general, non-soil ingestion intake (and risk) are related to area (A) using the following relationship (also see Appendices D and E of ANL 2001):

> FA (meat and dairy) = A/20,000 for A < 20,000 m^2 or 1 for A > 20,000 m^2;
> FA (plant) = A/2,000 for A < 1,000 m^2 or 0.5 for A > 1,000 m^2;
> FA (water) = 1 and
> No FA for fish.

Therefore, FA for meat, dairy, and plant ingestion is linearly dependent on area up to some maximum value. At the maximum value, the receptor is assumed to ingest all meat and dairy from the contaminated zone, but only half of the produce from the contaminated zone. The drinking water pathway is linearly related to area as defined in Appendix E of ANL 2001. Note that there is no area factor for the fish ingestion pathway.

As with the soil ingestion pathway, the foodstuff ingestion rate is dependent on the cover and depth factors, erosion rate, the thickness of the contaminated zone, and the mixing layer (see below for additional details on drinking water). However, the root depth is now a factor for produce, meat, and dairy ingestion. Plant roots can reach through a clean cover allowing contamination of plants that may be ingested by humans, or may be ingestion by livestock and transferred to humans through meat and dairy products. As long as the cover depth is thicker than the mixing layer and root depth there will be no ingestion intake. Over time, however, the cover may erode, or no cover may be assumed. The relationship between depth factor are also resented in Appendices D of ANL 2001. RESRAD also accounts for leaching, radiological decay, radiological ingrowth, etc. All these variables are included in the ETF term and can significantly impact risk assessment results.

The RESRAD ETF for groundwater and surface water is complex and not discussed in detail in this paper (see Appendix E of ANL 2001). However, there are some components of ETF that are worth describing to give a risk assessor some tools for properly estimating risk from the drinking water pathway. A general description of the groundwater is first provided followed by a description of certain components of the ETF term.

4.4.1 Groundwater – Environmental Transport

RESRAD contains an environmental transport model that may be used to predict radionuclide impacts on groundwater. Risk assessors may chose to use RESRAD to model migration to groundwater or may use one or a combination of other models such as SESOIL, DUST, AT123D, and PATHRAE. Assessors may

[5] FD1 = 0.9 indicates 90% from on-site well and 10% (1 – FD1 = 0.1 or 10%) from surface water.

also chose to use the prescriptive methods described in the SSG (EPA 2000). Most of these models are used to predict when, where, and how contaminants will reach groundwater and are both more complex and more flexible than RESRAD. However, most models do not calculate risk, thus additional risk calculations would be required. Models such as PATHRAE (from Brookhaven National Laboratory), and as described in the SSG, model migration to groundwater and estimates risk but still contains significant differences from the RESRAD model. Whichever model is selected, an experienced geologist and/or hydrogeologist should be consulted when selecting modeling parameters. Of particular importance is the selection of parameters related to the migration of contaminants to the saturated zone. The selection of inappropriate or non-site-specific parameters (e.g., leaving all RESRAD parameters as defaults) could result in gross overestimates or underestimates of risk.

The RESRAD groundwater model generally included the following components:

- The flow of precipitation or irrigation water through the cover, contaminated zone, and uncontaminated zone(s) of soil;

- The time-dependent migration of radionuclides from the unsaturated zone to the saturated zone (water table);

- A well located immediately down-gradient (but outside) of the contaminated zone.

There are numerous factors that impact the ability of radionuclides in the contaminated zone to reach the saturated zone and the drinking water well. Three primary factors are discussed here including the inflow of water, the thickness of the unsaturated zone, and the distribution coefficient.

Inflow rates are estimates by considering what fraction of precipitation and irrigation water infiltrates the soil. The model assumes that one of three things will happen to the water at the surface of the contaminated area: the water will run off, evaporate, or infiltrate. Table 3-1 above and Table E.1 in ANL 2001 present runoff coefficient estimates. If no water seeps into the soil, none will leach through the contaminated zone and no contamination will reach the down-gradient well. However, unless a surface is impervious or otherwise engineered to prevent water infiltration, some water will reach the root zones and beyond. RESRAD sets the default runoff coefficient at 0.2, meaning 20% of all precipitation and irrigation water will infiltrate the surface soil.

From the fraction of water that infiltrates the surface soil, some fraction is assumed to evaporate before reaching the saturated zone. RESRAD uses an evapotranspiration coefficient to estimate the fraction of the water in surface soil that evaporates outright or transpires (transferred from the ground to the atmosphere through plants). RESRAD sets the default evapotranspiration coefficient at 0.5, meaning 50% of the water available in the root zone is available to reach the saturated zone.

Water that could reach the saturated zone may carry with it radionuclides that move from the solid phase into the liquid phase (are soluble). The primary factor describing the transport of radionuclides to groundwater is the distribution coefficient (K_d). The K_d can be defined as the mass of a radionuclide in soil divided by the mass of the radionuclide in water (cm^3/g) and generally represents the ease at which a radionuclides can be flushed from the soil. A high K_d mean the that radionuclides will not easily move into the liquid phase. A low K_d means that a radionuclide is more likely to reach groundwater. RESRAD allows the risk assessor to enter a K_d for each radionuclide and each soil stratum [contaminated zone, uncontaminated unsaturated zone (up to four layers), and the saturated zone] excluding the cover layer. ANL 2001 and ANL 1993 list K_d values by soil type (sandy, loam, clay, etc.) and for a range of radionuclides. Note that K_d values are given by element and not isotope. This is because all isotopes of a given element are assumed to act chemically identical. For example, radium-228 would have the same K_d as radium-226.

Depending on the combination of inflow rates, evaporation, transpiration, K_d, etc., radionuclides may or may not reach groundwater in the near term. However, RESRAD is a dynamic model that not only accounts for radiological decay and ingrowth, but also projects impacts to groundwater over time. The default period of evaluation is 1,000 years. The RESRAD model may show no risk from the groundwater pathway for hundreds of years because the contamination does not reach the water supply, then in later years when the contamination reaches the groundwater it could dominate the total risk estimate. The risk assessor must check risk estimates for each year to assure that the groundwater pathway has been included, as appropriate, in the total risk estimate.

4.4.2 Groundwater – Other Considerations

Drinking water is one of the water dependent pathways. RESRAD also includes ways to use well water for irrigation and for watering livestock. As with the direct ingestion pathway, an intake will not occur until radionuclides reach the saturated zone. That is, although the model includes the use of well water to irrigate plants and water livestock, an intake will not occur until radionuclides leach from the contaminated zone to the saturated zone. It may take many years for this to occur, or may not occur at all. (Note that livestock could be exposed through the ingestion of contaminated plants. This will occur if there is contamination in the root zone, thus the ingestion of contaminated plant is independent of impacts to the groundwater.)

RESRAD allows the user to insert a groundwater concentration as a direct input. This is done under "Soil Concentration" and "Transport" headings within the model and can be a useful tool for estimating short-term risk from radionuclides. However, the user should take caution when using this approach. When a groundwater concentration is entered directly, RESRAD uses the available information to estimate the K_d. This is not necessarily inappropriate, but depending on the accuracy of other input parameters, the risk estimates may have significant uncertainty when projecting future doses. A common mistake is to allow RESRAD to model well into the future assuming the estimated K_d, but not considering the uncertainties associated with the estimated value. RESRAD may calculate the K_d to be very small, thus flushing the radionuclide from soil over a short amount of time. Results may be unrealistic in that risks associated with direct exposure (e.g., external gamma and inhalation) may be grossly underestimated because the radionuclides of interest are flushed too rapidly. As in all cases, the RESRAD model assumptions and results should be carefully evaluated to make sure they make physical sense.

RESRAD also allows the user to estimate the K_d using the soil-to-plant transfer factors. This may be the least site-specific approach, perhaps less reliable than simply using default values. However, the option is there for risk assessors to consider, and may be the best option at some sites.

4.5 RADON

RESRAD includes a diffusion model for estimating radon flow in soil and into habitable structures. Sites that contain radium contamination in soil may also exhibit elevated indoor radon concentrations. However, some factors should be considered before evaluating indoor radon concentrations using the RESRAD code. The general recommendation of this paper is to use RESRAD (or any) radon model only as a last resort. There may not be a need to present quantitative calculations considering that the uncertainties associated with the radon exposure pathway are significant.

Before presenting radon calculations, the risk assessor should evaluate the need to estimate risk from radon. Radon limits and guidelines are based on concentration and not risk. EPA used an indoor concentration limit of 0.02 Working Level (WL), or approximately 4 pCi/L. This limit has been adopted by the NRC and the DOE and is typically categorically excluded for radiological dose calculations under these agencies.

Risks associated with a concentration of 4 pCi/L (assuming residential exposure) is well above the CERCLA target risk range, and even small fractions of the guideline can produce risks on the order of 10^{-4}.

While a qualitative evaluation is preferred, the 0.02 WL guideline does exist and, in some cases, must be evaluated in some detail to satisfy regulators and stakeholders. For example, Title 40 Code of Federal Regulations (CFR) Part 192 specifically limits indoor radon levels to 0.02 WL. Although not a risk limit, the regulatory requirement exist and RESRAD can be used to predict indoor radon levels in both WL and pCi/L concentration. One option is to present a qualitative discussion on the radon guideline and, assuming radium is a contaminant in soil, the need to limit indoor radon concentrations. Perhaps the discussion could be supplemented with actual radon data collected in the area or in a structure of interest.

Indoor radon concentrations based on models (including RESRAD) should generally not be considered at the same level of certainty as other risk-related calculations. RESRAD, specifically, does contain parameters that can be adjusted to specific building design characteristics, but actual radon migration does not necessarily adhere to this model. Indoor radon concentrations are driven by meteorological conditions, indoor heating and air conditioning practices, local geological characteristics, structural air spaces and air flow conduits, seasonal variances, and other factors that are beyond RESRAD programming. Assuming a future receptor is considered (e.g., a future resident on a currently open field), it is also very difficult to predict the physical characteristics of a future structure. As the bottom line, indoor radon concentrations using RESRAD (or another model) may grossly underestimate or overestimate indoor radon concentrations. Without direct measurements, there is no way to determine the accuracy of the model, and if direct measurements are available, there is little reason to use any model. It is strongly recommended use actual radon measurement and only present risks from radon when absolutely required.

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5.0 SOURCE TERM DEVELOPMENT

RESRAD can simultaneously estimate risk from exposure to 74 principle radionuclides (half-lives greater than 6 months) and 53 associated radionuclides (short-lived decay products). Primary radionuclide concentrations are entered in pCi/g units and associated radionuclides are entered automatically by RESRAD. For example, radium-228 is a principle radionuclide with one short-lived decay product (actinium-228). If a risk assessor enters the radium-228 concentration of 10 pCi/g, RESRAD automatically assumes the actinium-228 concentration is 10 pCi/g. If the primary radionuclide is part of a multiple radionuclide series, radionuclides that follow in the series will also be listed, but the concentration indicated as 0.0. For example, after radium-228 is entered at 10 pCi/g, RESRAD will automatically enter thorium-228 at 0.0 pCi/g. The risk assessor can then go back and add the appropriate thorium-228 concentration. Even if no thorium-228 concentration is entered RESRAD will allow for ingrowth over time.

Three series considered at many CERLCA sites and common to FUSRAP sites are the uranium, thorium, and actinium series as presented in Figures 5-1, 5-2, and 5-3, respectively. Consider the uranium series shown in Figure 5-1 and assume a site is contaminated with uranium series radionuclides. The site may show the average uranium-238 concentration is 50 pCi/g, and this value is entered into RESRAD. The code will automatically add uranium-234, thorium-230, radium-226, and lead-210, all at 0.0 pCi/g. The risk assessor should consider the appropriate concentration of each of these radionuclides based on site knowledge or reasonable rules-of-thumb. If site data are available, the appropriate concentrations can be entered. If data are not available for each radionuclide, concentrations should be estimated else risks will be underestimated. The default assumption can be that all radionuclides in a series are present at the same concentration (in equilibrium). This assumption typically would be conservative, but may not be depending on the process history and age of the radiologically contaminated soil. For example, if the contaminant is uranium oxide, it likely contains only trace concentrations of anything besides uranium-234 and uranium-238. These uranium isotopes should be entered into RESRAD at the same concentration and the other radionuclides in the series can be left at 0.0 pCi/g. Even after 1,000 years the relative concentrations of non-uranium radionuclides will not change enough to register in risk calculations.

Consider again a site contaminated with uranium series radionuclides, but now assume that the site contains processed uranium ore. The concentration of each individual long-lived radionuclide should be estimated using site data, because equilibrium assumptions may not accurately predict site conditions. For example, radium-226 may be only 10% of the thorium-230 concentration. Additionally, radium-226 has a half-life that is short enough (1600 years) so that ingrowth and decay will impact risks within the 1,000-year RESRAD default evaluation period. Under this scenario every effort should be used to estimate the concentration of each long-lived radionuclide in the series.

Using Figure 5-2 assume a site is contaminated with thorium series radionuclides. The series contains only thorium-232, radium-228, and thorium-228 as long-lived radionuclides. However, the latter two radionuclides have relatively short half-lives at 5.75 years and 1.91 years, respectively. This means that even if pure thorium-232 is present at time = 0.0 (now), it will only take a few decades for the radium and thorium isotopes to approach equilibrium conditions. The risk assessor should consider this fact when estimating the source term for thorium series concentrations, or concentrations or series radionuclides with relatively short half-lives.

Perhaps the most important thing to consider when developing a source term in RESRAD is that RESRAD will make default assumptions about the relative concentrations of series radionuclides. It is up to the user to change the default assumptions to match site conditions.

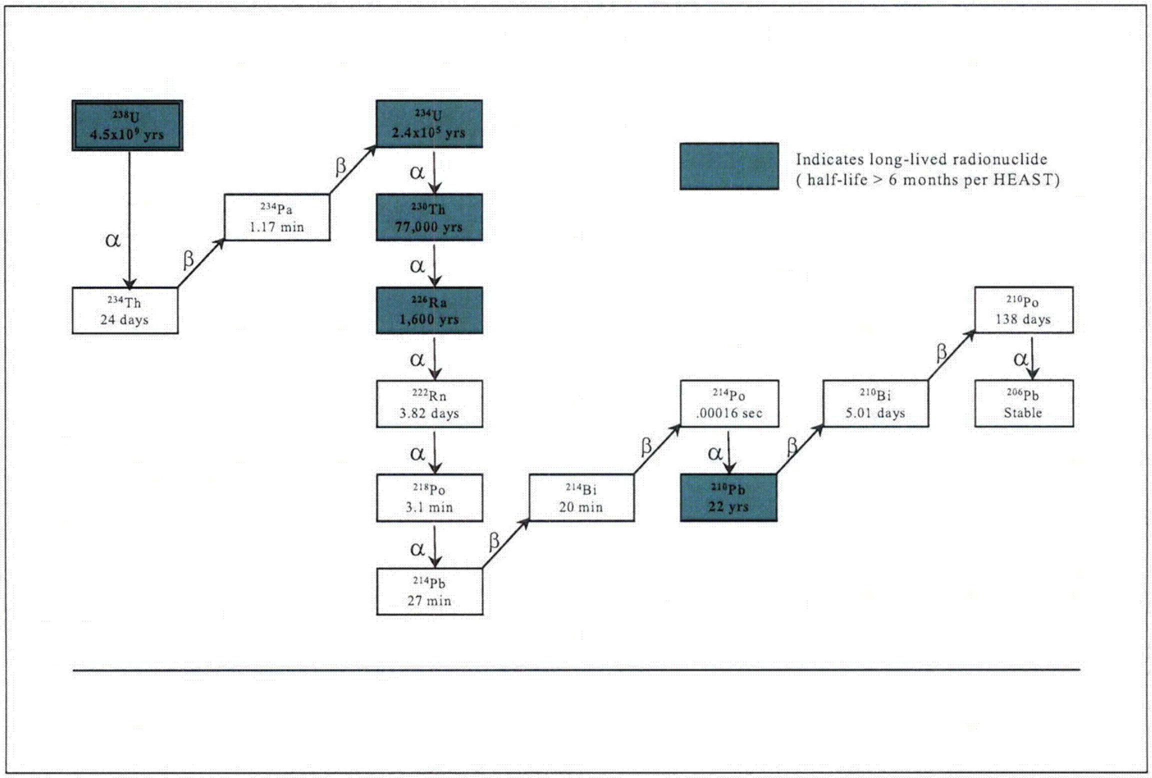

Figure 5-1. Uranium Series

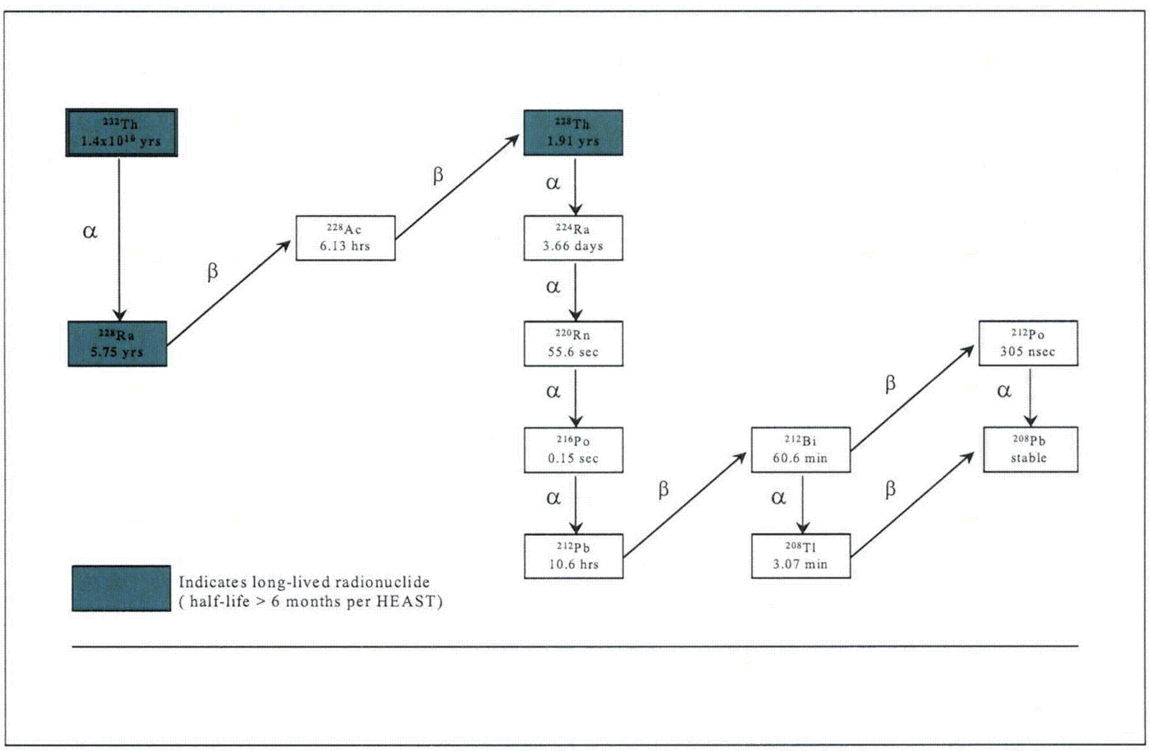

Figure 5-2. Thorium Series

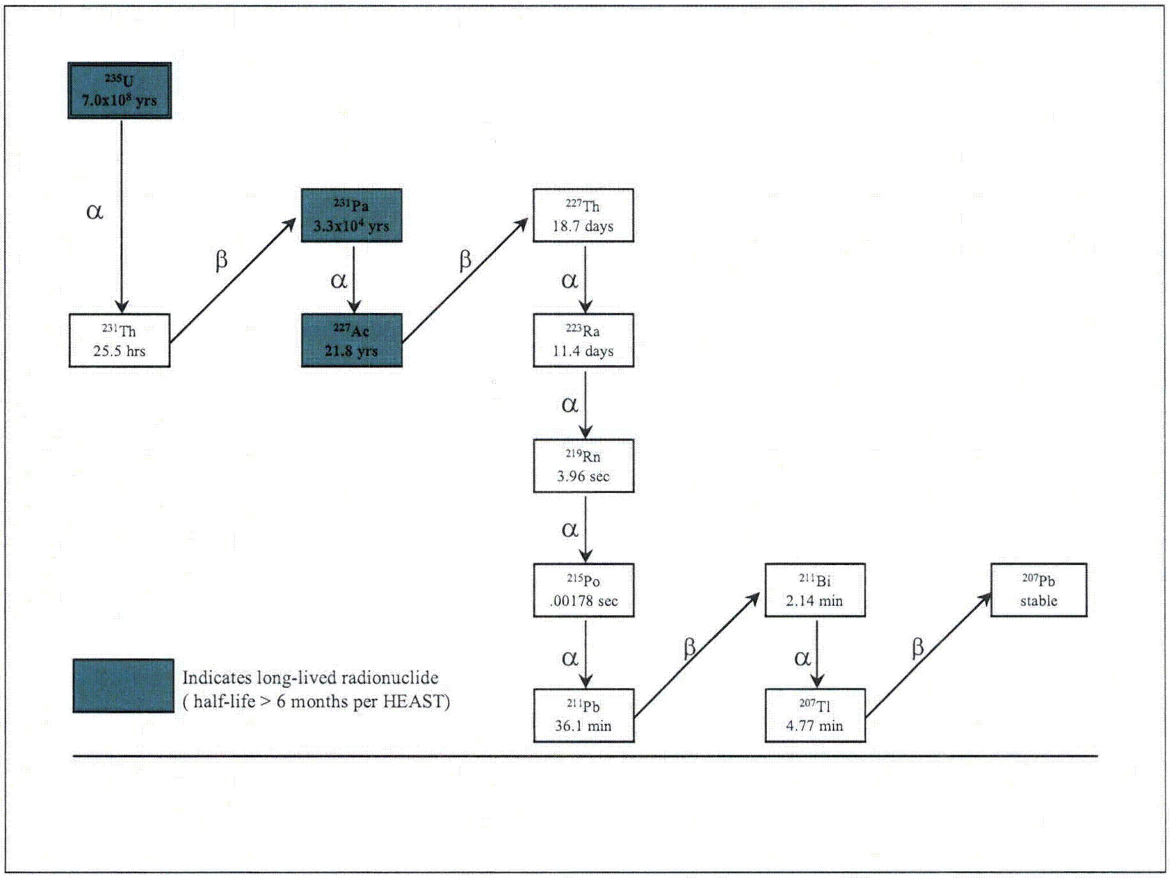

Figure 5-3. Actinium Series

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6.0 OUTPUT INTERPRETATION AND MANIPULATION

6.1 RISK REPORT

RESRAD risk-related output is found in two primary places: the *Summary Report* and the *Health Risk Report*. The *Summary Report* lists input parameter names and values, the radiological dose by year, pathway, and radionuclide, and other information related to radiological dose such as dose-to-source ratios and soil guidelines (concentrations that correspond to a specific dose limit). A risk assessor can use the *Summary Report* to document inputs, to identify the year of maximum exposure (it will be the same year for dose and risk), primary pathways of interest, risk-driving radionuclides, and other information that may be used in a risk assessment. However, the risk results are found in the *Health Risk Report*.

As with the *Summary Report*, the *Health Risk Report* presents results by year. As a default, RESRAD calculates risk beginning with years 0.0 (now), 1, 3, 10, 30, 100, 300, and 1000. This does not mean that a receptor is exposed for as long as 1,000 years, but that future inhabitants may be exposed at later dates to contamination present at the site. The model allows for radionuclide ingrowth, decay, and leaching, allows soil to erode, and otherwise allows the ETFs to run their course. A receptor is placed into the model beginning at the indicated times. Take, for example, a resident with a 30-year exposure duration. RESRAD exposes the receptor to the modeled conditions from years 0-30, 1-31, 3-33, 10-40, 30-60, 100-130, 300-330, and 1000-1030.[6]

The *Health Risk Report* is broken into three main sections. The first section lists the cancer slope factors (CSFs) used in risk calculations. Slope factors are from HEAST, are listed in alphabetical order by radionuclide and by pathway, and are listed with a "+D" when including short-lived decay products. For example, radium-228 is listed as "Ra-228+D" because actinium-228 is included in the radium-228+D slope factors. The first section of the *Health Risk Report* can be used as toxicity tables of a toxicity assessment, if desired. The second section of the *Health Risk Report* lists intake and risk estimates by specific year starting with year 0.0.

Intake estimates are broken into two tables: all pathway excluding radon, and radon. Of course, the radon table will only be present if radium is a contaminant and should be ignored under most circumstances based upon the uncertainties described previously. Non-radon intakes are listed by radionuclide in pCi/yr units including a total intake across all pathways. External gamma exposure (listed as ground in RESRAD) technically is not an intake and is not listed in the intake table of the *Health Risk Report*. This is likely because the "intake" for the external gamma pathway is the soil concentration itself. For example, the inhalation risk is calculated as follows:

$$Risk_{inh} = \text{Intake (pCi/year)} \times \text{ED (years)} \times CSF_{inh} \text{ (risk/pCi)},$$

while the risk from external gamma calculated as follows:

$$Risk_{ext} = \text{Soil Concentration (pCi/g)} \times \text{ED (years)} \times CSF_{ext} \text{ (risk/year per pCi/g)}.$$

The subscript "inh" represents the inhalation pathway and the subscript "ext" represents the external gamma pathway.

The next two sets of tables in the *Health Risk Report* present the pathway specific risks for each radionuclide. Tables are broken into water independent and water dependent pathways and include a total

[6] Risks are still averaged over a lifetime even though the exposure duration is limited (e.g., to 30 years).

risk across all pathways. However, risk assessors should use caution when selecting the appropriate table to extract risk estimates. The first set of tables are titled (abbreviated) "Excess Cancer Risks for Individual Radionuclides" (ECRIR) and the second set of tables are titled (abbreviated) "Total Excess Risk for Initially Existent Radionuclides" (TERIER). The interpretation of each table's contents is explained using the following example.

Assume a site contains thorium series contaminants with long-lived radionuclides thorium-232, radium-228, and thorium-228. The risk assessor enters a concentration for each radionuclide, runs the code, and then must extract the appropriate risk results from the *Health Risk Report*. Before selecting the appropriate tables, the risk assessor notes that RESRAD automatically considers decay products differently depending on whether the ECRIR tables or TERIER tables are selected. The risk assessor creates Table 6-1 as a composite of the different risk tables. It is noted that RESRAD estimates risk for radium-228 either because it was entered directly as part of the source term or because it is the decay product of thorium-232. Likewise, RESRAD estimates risk for thorium-228 either because it was entered directly as part of the source term or because it is the decay product of both thorium-232 and radium-228.

The ECRIR results in Table 6-1 represent the risks across rows and are associated with individual radionuclides whether directly entered as part of the source term or as a decay product of another radionuclide. These results are likely of no use to the risk assessor because they can not be used as estimates of risk per unit initial concentration.

The TERIER results in Table 6-1 represent the risks down columns and are associated with individual radionuclides directly entered as part of the source term. These results are of most use to risk assessors because they represent estimates of risk per unit initial concentration.

It is recommended that the risk assessors extract risk estimates from the TERIER tables. The risk estimates in these tables represent the pathway-specific risks associated with the concentrations entered as part of the source term. These results can be interpreted as risk per X pCi/g, where X represents the concentration entered into the code. From the example, if the risk assessor enters 5 pCi/g for radium-228 and the total risk estimate is 4.38E-5 (as in Table 6-1), then the result can be interpreted as 4.38E-5 per 5 pCi/g of the initially existing radium-228 plus decay products. This interpretation applies to total risk and to pathways-specific risk estimates.

Table 6-1. Health Risk Report Risk Estimates

User Enters **Calculated**	**Risk Estimate**	**User Enters** **Calculated**	**Risk Estimate**	**User Enters** ***Calculated***	**Risk Estimate**	**ECRIR***
Thorium-232		Radium-228+D		Thorium-228+D		
Thorium-232	1.10E-7					1.10E-7
Radium-228+D	1.50E-6	*Radium-228+D*	3.60E-5			3.75E-5
Thorium-228+D	9.00E-6	*Thorium-228+D*	7.80E-6	*Thorium-228+D*	1.70E-5	1.85E-5
TERIER **	1.06E-5		4.38E-5		1.70E-5	

* Less useful to risk assessors; sum across rows as per "**E**xcess **C**ancer **R**isk for **I**ndividual **R**adionuclides" tables.

** More useful risk results because can be interpreted as risk per initial concentration; sum down columns as per "**T**otal **E**xcess **R**isk for **I**nitially **E**xistent **R**adionuclides" tables.

6.2 RADIONUCLIDE-SPECIFIC RESULTS

Risk assessments using RESRAD often includes multiple runs and the transfer of results to a risk assessment report. The risk assessor may wish to summarize pathway-specific risk results and may wish to find a more efficient way to manipulate RESRAD output. Recall that risk results may be interpreted as

risk per X pCi/g. If the original concentration is 1 pCi/g, the results can be used as a risk-to-source ratio (RSR). This is important because any concentration multiplied by the RSR is risk, whether the total or pathway-specific risk. The RSRs in the *Health Risk Report* can, therefore, be interpreted as scenario and site-specific cancer slope factors and used in spreadsheets, thus avoiding a run for each exposure unit. The spreadsheet would simply contain the RSR values, the source term and the products. Table 6-2 presents an example risk assessment calculation using RSRs. The same set of RSRs can be used with any source term as long as only the concentration values are allowed to vary (i.e., source geometry, ETFs, and receptor-specific parameters are held constant). That is, RSRs are scenario-specific and a new set of RSRs are required for residential versus industrial workers and so on. Notice that RSRs are specific to a given year. A risk assessor can consider a matrix of time-dependent RSR values or can simply evaluate the radionuclides in the source term to determine the year or years of particular interest.

Table 6-2. Example Risk Calculation Using Risk-to-Source Ratios

Location	Year	Parameter	Concentration (pCi/g)	RSR (pCi/g^{-1})	Risk Estimate*
Unit 1	0	Radium-226	4.2	2.05E-04	8.61E-04
Unit 1	0	Thorium-230	3.5	1.44E-06	5.04E-06
Unit 1	0	Uranium-234	3.2	5.95E-07	1.90E-06
Unit 1	0	Uranium-238	3.1	2.19E-06	6.79E-06

* Risk = Concentration × RSR

The time dependence of RESRAD output is useful but can introduce complications not encountered while using standard RAGS equations. The code accounts for contaminant loss through decay and environmental transport and accounts for decay product ingrowth. Losses and ingrowth should be considered when using RSRs or when considering the risk from individual radionuclides. For example, a risk assessor may wish to calculate cleanup goals for a set of contaminants of concern and intends to find the year of maximum risk for each individual radionuclide. When considering this task, the risk assessor should understand that RESRAD accounts for radiological decay and ingrowth and the maximum risk may occur at any time within the evaluation period (e.g., the default evaluation period is 1,000 years). Consider again the example of a thorium-series, contaminated site and the example output in Table 6-3, Table 6-4, and Figure 6-1.

The risk assessor could erroneously select from Table 6-3 the year 0 risk for radium-228 and thorium-228 and the year 100 risk for thorium-232. These values represent the maximum risk estimates by individual radionuclide covering a 100-year period. A receptor would not be exposed to maximum concentrations both at year 0 and year 100, and risks would be overestimated. However, RESRAD accounts for ingrowth and decay as is demonstrated through the decline in radium-228 and thorium-228 risk over time and the increase of thorium-232 risk over time (see Table 6-4 and Figure 6-1). The decline is caused by decay (plus loss through environmental transport) given that radium-228 has a half-life of 5.75 years and thorium-228 has a half-life of 1.91 years. By year 100, when thorium-232 reaches maximum risk, almost all of the original radium-228 and original thorium-228 has decayed away contributing negligibly to the total risk. Thorium-232 reaches a maximum after year 30 (at year 100 according to RESRAD output) because of the ingrowth of radium-228 and thorium-228. Therefore, radium-228 and thorium-228 have reached equilibrium (same concentration) with thorium-232 by year 100 and the combination of all three radionuclides produces the maximum risk. Past year 100, decay and losses from environmental transport cause the risk from thorium-232 and decay products to decline.

If the risk assessor selects the maximum values for individual radionuclide, risks are overestimated because some radionuclides are counted more than once. The maximum risk from radium-228 includes some contribution from thorium-228 and the maximum risk from thorium-232 includes radium-228 and thorium-228 at equilibrium concentrations. Thus, risk contributions from thorium-228 could be counted as many as three times and risks contributions from radium-228 could be counted twice. In fact, the sum

Table 6-3. Example Risk Calculations by Year

COC	Year 0	Year 1	Year 3	Year 10	Year 30	Year 100	Year 300
Radium-228	**9.79E-05**	9.01E-05	7.43E-05	3.36E-05	2.92E-06	5.35E-10	1.13E-20
Thorium-228	**1.24E-05**	8.60E-06	4.17E-06	3.30E-07	2.35E-10	2.27E-21	0.00E+00
Thorium-232	2.56E-04	2.68E-04	2.88E-04	3.31E-04	3.62E-04	3.64E-04	3.62E-04
Total*	**3.67E-04**	3.66E-04	3.66E-04	3.65E-04	3.65E-04	3.64E-04	3.62E-04

* Total = sum down column. The sum of the maximums from individual radionuclides is inappropriate when occurring in different years. Risk assessor should use the total maximum value.
Maximum risks are presented in **bold**.
COC = contaminant of concern

Table 6-4. Thorium Series Example Ingrowth and Decay

	Initial Thorium-232+D			Initial Radium-228+D		Initial Thorium-228
Year	Thorium-232	Radium-228	Thorium-228	Radium-228	Thorium-228	Thorium-228
0	1.0	0.0	0.0	1.0	0.0	1.0
1	1.000	0.114	0.035	0.8862	0.2695	0.6959
3	0.999	0.305	0.202	0.6960	0.4614	0.3370
10	0.997	0.701	0.683	0.2987	0.2908	0.0266
30	0.991	0.965	0.965	0.0267	0.0267	0.0000
100	0.970	0.970	0.970	0.0000	0.0000	0.0000
300	0.914	0.914	0.914	0.0000	0.0000	0.0000

All concentrations in pCi/g; unit concentrations assumed for initially existing radionuclides at time = 0

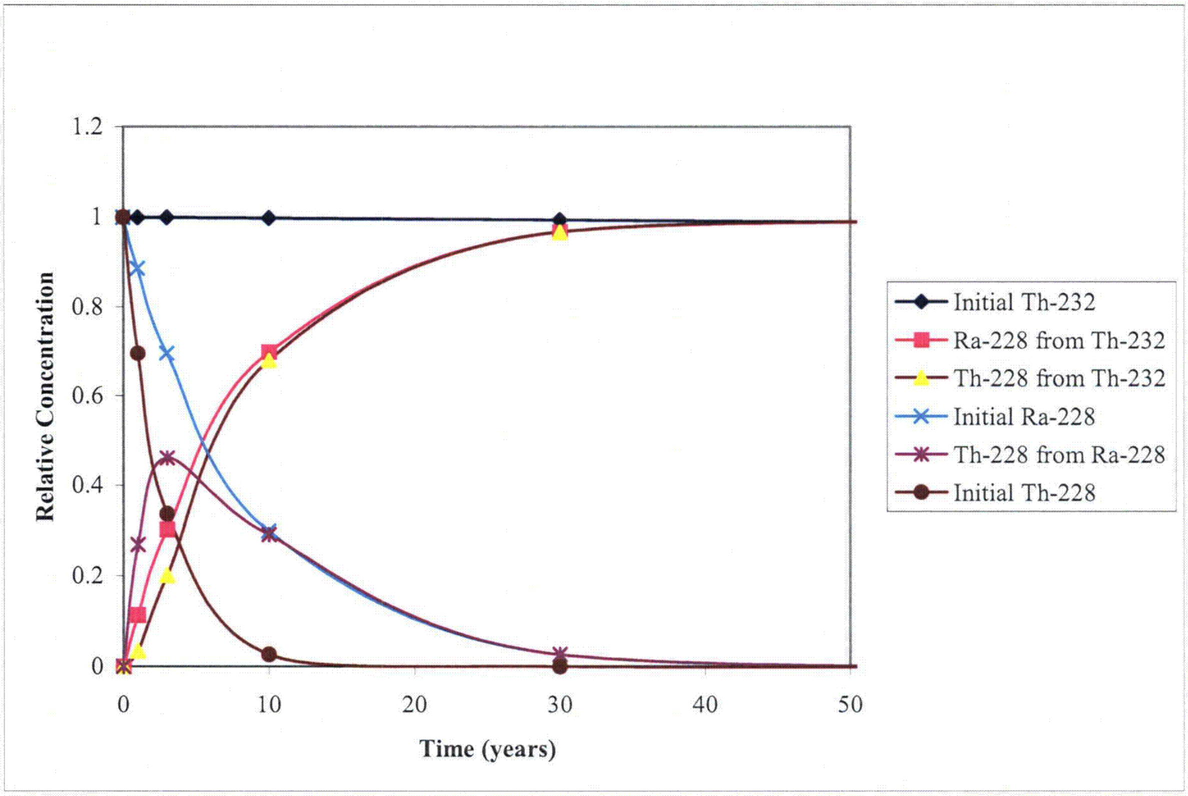

Figure 6-1. Thorium Series Example Ingrowth and Decay Model

of the maximum radionuclide-specific risk estimates is equal to 4.74E-04 while the maximum risk for any one year is 3.67E-04. It is more accurate to assume that the sum of the risks from year 0 represents the risk for the entire series. Using the 0 year estimate RESRAD would account for ingrowth and decay on equal terms and risks from certain radionuclides would not be counted more than once.

The example demonstrated in Table 6-3, Table 6-4, and Figure 6-1 can be used consistently when groundwater is not a concern. When groundwater is a concern, risks tend to reach maximums at odd years (e.g., 232.5 years) that represent groundwater breakthrough times. When this is the case the risk estimates and RSR values may need to be extracted from the maximum years as dictated by the groundwater pathway. There are many factors to consider in any risk assessment, and a simple rule will likely not apply to all or even most sites. Therefore, it is suggested that risk assessors consider the relative contributions of each radionuclide with the relationships between decay and ingrowth before tabulating risks or selecting RSRs for external risk calculations.

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7.0 SENSITIVITY ANALYSIS AND UNCERTAINTIES

7.1 SENSITIVITY ANALYSIS

The purpose of this section is to briefly address parameters subject to the RESRAD sensitivity analysis tool. This tool allows the user to evaluate the sensitivity of specific inputs as they are related to risk. For example, risk is linearly related to the soil ingestion rate but risk is relatively insensitive to soil density. A risk assessor may also input multiple site-specific parameters related to the hydrogeology of a site (conductivity, porosity, etc.). While these inputs may produce the appearance of a "site-specific risk assessment," they will have a negligible, if any, impact on the final risk unless the drinking water pathway is evaluated.

Table 7-1 presents select pathway-specific parameters that could be considered with RESRAD sensitivity analysis tool. While other parameters may also be considered, those presented in Table 7-1 are the more sensitive to the ingestion, inhalation, and external gamma pathways. Table 7-1 includes the parameter name as presented in RESRAD output (and Table 3-1), the relative sensitivity, and comments, as appropriate.

Table 3-1 also lists sensitivity indicators as presented in NUREG/CR-6697 (see the Table 3-1 column titled "Risk Variability"). The indicators listed in Table 3-1 are ranked relative to the subsistence farming scenario, thus ranks may not be appropriate for residential, industrial, and other scenarios. The comparison between the "Sensitivity" column in Table 7-1 and the "Risk Variability" column in Table 3-1 show that risk assessors should evaluate parameter sensitivity on a site-specific and scenario-specific basis.

Consider an example calculation where both RME and central tendency exposures are considered. The RME exposure duration is assumed to be 30 years and the central tendency exposure duration is assumed to be 9 years. Assuming all other parameter values are held constant, the risk to the central tendency receptor would be 9/30-times less than the RME resident, thus the sensitivity to exposure duration is high (linear). Now consider parameters such as cover depth and mixing layer (also refer to the discussion in Section 4). If the cover depth is much less than the mixing layer, risk results are likely only marginally sensitive to these parameters. However, the relationship between cover depth and mixing layer is also dependent on the erosion rates (thus is time-dependent), the thickness of the contaminated zone, and the radionuclides in the contaminated medium. Risk assessors must consider these and all parameters with an understanding of the overall sensitivity to risk estimates. Again, sensitivity evaluations are site-specific and receptor-specific.

RESRAD does provide tools for evaluating the sensitivity of individual parameters and for evaluating correlations between related parameters. These analyses can be complex and are considered to be beyond the scope of this white paper. NUREG/CR-6697 may be consulted if the probabilistic (uncertainty) evaluations are warranted, but the use and interpretation of probabilistic data is less than intuitive and is not designed for risk calculations [only results for dose (i.e., in mrem/yr) are presented]. The sensitivity analysis tools is more straightforward, but is also limited in application. In the end it is up to the risk assessor to understand and justify each parameter value selection and the its impact on risk estimates.

7.2 UNCERTAINTIES

RESRAD-related uncertainties are in many ways similar to uncertainties associated with standard risk calculations. For example, uncertainties associated with the RESRAD groundwater model can be similar

Table 7-1. Sensitivity Relative to Risk for Select RESRAD Input Parameters

Parameter	Sensitivity	Comment
Area of contaminated zone	Varies	Low sensitivity for areas > 1000 m^2; can be high for smaller areas especially when combining multiple pathways.
Thickness of contaminated zone	Varies	Low sensitivity for thickness > 1 m; dependent on cover depth, erosion rate, and mixing layer.
Cover depth erosion rate	Varies	Dependent on cover depth and mixing layer.
Contaminated zone erosion rate	Varies	Dependent on cover variables and mixing layer.
Evapotranspiration coefficient	Low	For groundwater pathway only; only reduces fraction of water that infiltrates the root zone.
Runoff coefficient	Varies	For groundwater pathway only; can be used to eliminate most groundwater infiltration.
Distribution coefficients	High	High values will keep radionuclides in surface soil where exposures occur; low values can produce high risks from groundwater pathway.
Inhalation rate	Moderate/High	Linear for all exposures; dependent on dust shielding factor for indoor exposures; directly proportional for outdoor exposures; more significant for alpha-emitting radionuclides.
Mass loading for inhalation	Moderate/High	Linear for inhalation pathway only; dependent on dust shielding factor for indoor exposures; directly proportional for outdoor exposures; more significant for alpha-emitting radionuclides.
Exposure duration	High	Directly proportional for all pathways.
Shielding factor, inhalation	Varies	Directly proportional for indoor exposures and the inhalation pathway; no impact on outdoor exposures; more significant for alpha-emitting radionuclides.
Shielding factor, external gamma	Varies	Directly proportional for indoor exposures and the external gamma pathway; no impact on outdoor exposures.
Fraction of time spent indoors	Varies	Directly proportional for all indoor exposures (high sensitivity); no impact on outdoor exposures.
Fraction of time spent outdoors (on site)	Varies	Directly proportional for all outdoor exposures (high sensitivity); no impact on indoor exposures.
Fruits, vegetables and grain consumption	High	Directly proportional for produce ingestion pathway; dependent on K_d and other groundwater-dependent variables (for irrigation).
Leafy vegetable consumption	High	Directly proportional for produce ingestion pathway; dependent on K_d and other groundwater-dependent variables (for irrigation).
Milk consumption	Moderate	Radionuclide-specific; dependent on groundwater-dependent variables.
Meat and poultry consumption	Moderate	Radionuclide-specific; dependent on groundwater-dependent variables.
Fish consumption	Low	Radionuclides have to reach surface water and bioaccumulate in fish tissue.
Soil ingestion rate	High	Directly proportional for soil ingestion pathways.
Drinking water intake	High	Directly proportional for drinking water pathways assuming RESRAD models breakthrough during the evaluation period.
Depth of soil mixing layer	Varies	Dependent on erosion rates, thickness of contamination zone, and cover depth.

to those from other models integrated into RAGS/SSG calculations. However, there are some specific uncertainties that risk assessors should consider when using RESRAD to estimate receptor risks:

- RESRAD results are time-dependent, typically with projections over 1,000 years. Any prospective calculation is inherently uncertain, but every input parameter could be significantly different if selected 1,000 years from now, thus increasing uncertainty.

- RESRAD results are dependent on the surface area and depth of the contaminated zone. This is an uncertainty typically not associated with standard RAGS/SSG calculations which generally consider a semi-infinite plane of contamination. The methods used by RESRAD to account for finite contaminant area and depth can increase the uncertainty in results if not properly utilized.

- RESRAD default values are typically used for a large number of parameters, especially when considering farming and groundwater scenarios. These values likely have little or no site tie-in, but are used when site-specific data are unavailable. Use of default parameter values increases the uncertainty in risk estimates.

- If used, the RESRAD radon migration calculations is based on a diffusion model. There is significant uncertainty associated with this model that does not account for radon migration through inhomogeneous (e.g., karst) strata, pressure-driven flow, or building characteristics that could inhibit or increase radon infiltration.

In general, risk assessment results or only a good as the input parameters. Consulting geologists, hydrologist, health physicists, and other qualified project personnel will likely increase the accuracy of risk calculations and decrease uncertainty.

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8.0 REFERENCES

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