

**FEDERAL RADIOLOGICAL  
MONITORING AND ASSESSMENT CENTER**

**FRMAC ASSESSMENT MANUAL**

**VOLUME 1**

**OVERVIEW AND METHODS**



**The Federal Manual for Assessing Environmental  
Data During a Radiological Emergency**

**June 2012**

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FRMAC Assessment Manual

**Overview and Methods**

**Volume 1**



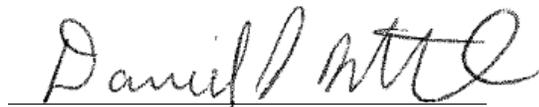
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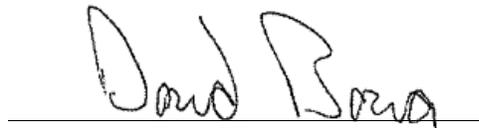
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FRMAC is an acronym for Federal Radiological Monitoring and Assessment Center.

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## PREFACE

This Federal Radiological Monitoring and Assessment Center (FRMAC) Assessment Manual has been prepared by representatives of those Federal and State agencies that can be expected to play the major roles during a radiological emergency. Federal Agencies include: the National Nuclear Security Administration (NNSA), the Nuclear Regulatory Commission (NRC), the Environmental Protection Agency (EPA), the Department of Agriculture (USDA), the Food and Drug Administration (FDA), and the Centers for Disease Control (CDC). This final manual was reviewed by experts from across the community and their input has been incorporated.

To ensure consistency, completeness, and the highest quality of assessed data produced by the FRMAC, an attempt was made to compile the most appropriate assessment methods and values available in this manual. The criteria were (1) scientifically defensible, (2) simple, (3) applicable to a FRMAC deployment, and (4) likelihood of being adopted by others.

The primary purposes of this volume are:

- To define the technical methods for performing radiological assessment.
- To serve as the scientific basis for the Turbo FRMAC<sup>®</sup> software.

Future revisions of the manual will be made to update current methods and to add new methods as the science is developed and the methods are approved by the FRMAC Assessment Working Group (AWG). It is dependent upon the user to ensure that they are using the correct version of this Assessment Manual.

It is the responsibility of the user to update uncontrolled copies of this manual. The most current version is available on the Consequence Management web site at:

<http://www.nv.doe.gov/nationalsecurity/homelandsecurity/frmac/manuals.aspx>

Users are urged to update their manual as appropriate.

The National Nuclear Security Administration Nevada Site Office (NNSA/NSO) has the overall responsibility for maintaining the master of all FRMAC manuals. Please provide comments on this manual to:

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Acknowledgment is given to those who participated in development of previous version of the manual because this revision was built upon those efforts.

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## ACRONYMS AND ABBREVIATIONS

<b>AMAD</b>	Activity Median Aerodynamic Diameter
<b>ANL</b>	Argonne National Laboratory
<b>APF</b>	Assigned Protection Factor
<b>AWG</b>	Assessment Working Group
<b>BNL</b>	Brookhaven National Laboratory
<b>CDC</b>	Centers for Disease Control and Prevention
<b>CED</b>	Committed Effective Dose
<b>DCFPK</b>	Dose Coefficient Package
<b>DHS</b>	US Department of Homeland Security
<b>DIL</b>	Derived Intervention Level
<b>DOE</b>	US Department of Energy
<b>DRL</b>	Derived Response Level
<b>EPA</b>	US Environmental Protection Agency
<b>FDA</b>	US Food and Drug Administration
<b>FRMAC</b>	Federal Radiological Monitoring and Assessment Center
<b>ICRP</b>	International Commission on Radiological Protection
<b>KIPF</b>	Potassium Iodide Protection Factor
<b>LANL</b>	Los Alamos National Laboratory
<b>LLNL</b>	Lawrence Livermore National Laboratory
<b>MDA</b>	Minimum Detectable Activity
<b>NCRP</b>	National Council on Radiation Protection and Measurements
<b>NNSA</b>	National Nuclear Security Administration
<b>NRC</b>	US Nuclear Regulatory Commission
<b>ORNL</b>	Oak Ridge National Laboratory
<b>PAG</b>	Protective Action Guide
<b>PAR</b>	Protective Action Recommendations
<b>PNNL</b>	Pacific Northwest National Laboratory
<b>PPD</b>	Projected Public Dose
<b>PPE</b>	Personal Protective Equipment
<b>RAP</b>	Radiological Assistance Program
<b>RBE</b>	Relative Biological Effectiveness
<b>RF</b>	Respirable fraction
<b>RSL</b>	Remote Sensing Laboratory
<b>SNL</b>	Sandia National Laboratories
<b>SNM</b>	Special Nuclear Material
<b>SRNL</b>	Savannah River National Laboratory
<b>SRD</b>	Self Reading Dosimeter
<b>ST</b>	Stay Time

<b>TBL</b>	Turn Back Limit
<b>TED</b>	Total Effective Dose
<b>TF</b>	Transfer Factor
<b>USAF</b>	US Air Force
<b>USDA</b>	US Department of Agriculture

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## Introduction

The Federal Radiological Monitoring and Assessment Center (FRMAC) Assessment Manual is the tool used to organize and guide activities of the FRMAC Assessment Division. In a radiological emergency, it is necessary to quickly interpret radiological measurements, predict worker and public doses, and make recommendations in accordance with Protection Action Guides (PAGs) issued by government agencies. This manual integrates many health physics tools and techniques used to make these assessments.

This manual:

- 1) Is intended for use by trained FRMAC Assessment Scientists. It is the basis for training FRMAC Assessment Scientists in standard FRMAC technical methods, and defines the standard technical methods used when responding to radiological incidents.
- 2) Represents the technical consensus of multiple federal agencies with expertise in and authority over aspects of radiological emergency response.
- 3) Defines Methods to make many different radiological assessment calculations based on default assumptions agreed upon by the interagency FRMAC Assessment Working Group as being most applicable to a wide variety of conditions. These default assumptions may or may not be appropriate for a specific incident.
- 4) Frequently uses the word “would” to define the result of the calculation, and it is important to be aware that this result is based on the established default assumptions. Should circumstances of the specific incident be different than the default assumptions, the predicted results may not reflect actual conditions. It is recommended that assessors obtain real-world data as soon as possible to validate the predictions made by the Methods in this Manual.
- 5) Is only intended to address the early and intermediate phases of a radiological incident. It does not address recovery phase issues such as remediation.
- 6) Defaults to the International Commission on Radiological Protection (ICRP) 60+ dosimetry model based on agreement with the EPA. ICRP 60+ refers to ICRP 60 (ICRP90) and the collection of ICRP documents relating to the ICRP 60 dosimetry model published subsequently. ICRP 60+ terminology is used throughout the manual.
- 7) Is not prescriptive. Situations may arise when the methods described in the Assessment Manual will not be sufficient, so the user may employ alternative methods or assumptions. Assessment Scientists must be sufficiently skilled in health physics to recognize when, which, and how alternative methods or assumptions may be employed. Possible alternatives may include dosimetry models, weathering factor, and resuspension factor.

Volume 1 contains the scientific bases and computational methods for assessment calculations. These calculations are broken up into sections:

Section 1 – Public Protection;

Section 2 – Emergency Worker Protection;  
Section 3 – Ingestion Pathway Analysis; and  
Section 4 – Supplemental Methods.

All variables used in these calculations are listed and defined in Appendix B.

Key data used in these calculations are provided in Appendix C.

Volume 2 provides analyses for preassessed scenarios. These default scenarios include:

- A nuclear power plant accident,
- A nuclear weapon accident,
- An aged fission product accident,
- A nuclear fuel accident,
- A radionuclide thermoelectric generator (RTG) accident,
- A domestic nuclear explosion (RESERVED), and
- A radiological dispersal device (RDD, a.k.a. “dirty bomb”).

Volume 3 addresses FRMAC administrative information and processes relevant to assessment activities.

## Overview of Assessment

The FRMAC Assessment Division supports the technical needs of government response organizations and augments their technical capabilities. It serves as the integrating point for all radiological data collected by responders. It also facilitates a uniform and consistent analysis of that data. As such, it is intended to be the single point for dissemination of data and analyses for the Federal response.

FRMAC's broad-based staff is the key to achieving Assessment's objectives. The staff is drawn from multiple agencies and has a variety of skills. The staff includes health physicists, data analysts, cartographers, modelers, meteorologists, and computer scientists. These professionals facilitate the analysis, interpretation, presentation and preservation of incident specific radiological data.

These individuals are primarily drawn from the NNSA and the EPA. However, staff also includes members from the NRC, USDA, FDA, CDC, and other Federal agencies. State, Local and Tribal scientific specialists are also invited to participate.

### Assessment Objectives

The objective of FRMAC Assessment is to interpret radiological conditions and provide guidance to responsible government authorities. All radiological predictions and measurements are evaluated in terms of the PAGs, which are the criteria for making decisions such as evacuation, sheltering, relocation and food embargo. Generally, PAGs are used to control health risks by placing restrictions on the radiological dose received via the principal pathways.

FRMAC Assessment works closely with the responsible government authorities to tailor Assessment data products for the incident. The Assessment Division also works closely with the Federal Advisory Team for Environment, Food, and Health. The Advisory Team includes representatives from those Federal agencies that have specific statutory responsibilities for public health. The Advisory Team may provide incident specific guidance including adjustments to Assessment Division assumptions, parameters and methodology. The Advisory Team uses FRMAC Assessment interpretations to develop their advice and reviews the application of PAGs.

FRMAC Assessment does not make Protective Action Recommendations (PARs). State, Local, and/or Tribal response organizations are responsible for developing and implementing PARs. The Coordinating Agency, the utility (if applicable), and the Advisory Team support the development of PARs.

FRMAC Assessment remains a key function during all phases of an incident. The Assessment Division will continue to support incident response when the management of FRMAC transfers to EPA during the intermediate/recovery phase.

## Manual Objectives

The objectives of the FRMAC Assessment Manual are:

- Provide technical basis for assessments

The manual describes each assessment method in detail, provides references to scientific publications and guidance documents, and specifies the assumptions used.
- Provide technical basis for the Turbo FRMAC<sup>®</sup> Software Package

The Turbo FRMAC<sup>®</sup> Software Package, which was developed under the NA-42 Technology Integration Program, automates the calculations in the assessment manual allowing for rapid computation of important dose assessment data. Turbo FRMAC<sup>®</sup> uses the default input values established by the FRMAC Assessment Working Group. Assessment Scientists can modify some of these input values to accommodate incident-specific conditions.
- Document the assessment process

The manual defines the Assessment Division's operations and provides descriptions of organization, functions, and objectives.
- Function as an orientation and training guide for Assessment Division members

The manual is used to train health physicists to use FRMAC Assessment Methods to evaluate environmental radiological conditions. It also describes the conduct of operations employed by FRMAC.
- Provide Federal family consensus

The manual is based on the guidance issued by the NRC, EPA and FDA and on consensus standards, such as the ICRP and NCRP. It was developed by the FRMAC AWG, and has had broad review from multiple Federal agencies (NNSA, NRC, EPA, FDA, USDA, and CDC), State Agencies, and other participants.

## Utilization

### Using this Manual

This manual defines the FRMAC process for performing radiological assessment calculations for:

- the Early Phase,
- the Intermediate Phase,
- the ingestion pathway, and
- emergency worker protection.

This manual does not address the Recovery Phase of an incident.

Default Time Phases, PARs and PAGs are defined in the EPA's Manual of Protective Action Guides and Protective Actions for Nuclear Incidents (EPA PAG Manual) (EPA92).

Volume 1, "Overview and Methods," provides an overview of Assessment and detailed descriptions of generalized assessment methods. These methods are NOT prescriptive. If a method is inappropriate for the incident, the Assessment Scientists should use their best judgment and implement a more appropriate method. Volume 1 also includes supporting information (e.g., default values for variables used in the methods) for performing the methods under certain conditions and assumptions.

Volume 2, "Pre-assessed Default Scenarios," provides default assessment guidance for different types of accidents. A section is devoted to each generic scenario, that describes default Derived Response Levels (DRLs) and Derived Intervention Levels (DILs) and methodologies. Default accident scenario cases are not necessarily worst possible cases, but are those more likely to exist.

Volume 3, "Assessment Operations Overview and Procedures," offers guidance and procedures for internal FRMAC Assessment conduct of operations.

### Using Data Products

Assessment prepares a variety of data products, each designed for a particular audience and application. The products may be interpretations, analyses, and assessed data sets or reference information. Most data products are presented as maps.

PAG Zone Maps and Monitoring/Sampling Status Maps are the primary data products generated for release and communication to local decision makers. FRMAC emphasizes production, approval, and release of these products to summarize Assessment's appraisal of the radiological incident.

- The **PAG Zone Maps** indicate where particular PAGs might be exceeded. Initially, the PAG Zone Maps are based only on modeling predictions. The maps are updated as monitoring and sampling measurements become available.

- The **Monitoring/Sampling Status Maps** summarize the location and type of both monitoring and sampling data collected up to the current time. The purpose of these maps is to portray the progress of the monitoring effort and to indicate the confidence level of the PAG Zone Map.

The following data products are intended for internal Assessment use by health physics professionals performing independent interpretations or analyses. These data products may be made available outside the FRMAC; however they are not produced on a regular schedule.

- Predictive Model Maps – exposure/dose rate, areal deposition or integrated exposure/dose
- Monitoring/Sampling Maps - measurements of exposure/dose rate, areal deposition or integrated exposure/dose estimations
- Assessed Data - field measurements and/or sample analysis results
- Calculation Analyses - DRLs/DILs, estimated doses, radionuclide mix, resuspension factor, etc.

Other data products may be developed to meet specific needs as the incident progresses. All of the above data products, and others, are created as drafts or preliminary results during the Assessment process and usually precede approved products by a significant period of time. These are not available for release outside of the FRMAC because their quality cannot be assured. Representatives of other FRMAC Divisions, Federal Agencies, the Advisory Team or local governmental authorities may have access to the draft or preliminary products within the FRMAC. This information may be used to relay progress of monitoring and sampling or developing trends to counterparts.

Data products that have not been approved by the FRMAC Director should NEVER be released and MUST NOT be used for determining PARs.

### **Differences between FRMAC approach and other published guidance**

The FRMAC Assessment Working Group (AWG) approves the methods used in this manual. The AWG includes knowledgeable subject matter experts from diverse government entities. The goal of the AWG is to craft a set of methods that represent a unified federal consensus and are implemented by member agencies.

The FRMAC intends that this manual will be responsive to new technical developments. The AWG reviews technical developments as they become available and evaluates them for inclusion in this manual. Therefore, this manual may vary from individual guidance documents as new developments are incorporated.

The FRMAC Assessment Division implements the best health physics practices to perform radiological assessments. These practices may differ from those in other agencies' publications due to a difference in publication date or based upon alternate assumptions.

## SECTION 1. PUBLIC PROTECTION METHODS

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## Introduction to Public Protection Methods

This section defines radiological assessment methods to evaluate the radiological impacts to members of the public from exposure to radioactive material. Methods in this section have been developed to address hazards from exposure to the passage of a plume of radioactive material and the resulting ground deposition. Methods include developing Derived Response Levels (DRLs) and projecting doses by relating modeling projections or field monitoring results to established Protective Action Guides (PAGs). (See Appendix C, Table 2-2 for PAG values.)

DRLs are levels of radioactivity in an environmental medium (i.e., the ground) that would be expected to produce a dose equal to the corresponding PAG (EPA92). DRLs are values which can be measured (e.g.,  $\mu\text{Ci}/\text{m}^2$  or  $\text{mrem}/\text{hr}$ ) with monitoring instrumentation.

An airborne release of radioactive material creates multiple pathways for radiation exposures. The primary exposure pathways while the material is airborne are inhalation and external exposure (plume submersion). The primary exposure pathways from ground-deposited radioactive material are external exposure (groundshine) and inhalation of resuspended material.

Methods in this section may be performed in two ways.

- 1) Four-Pathway Assessment (4Path) includes the dose from all of the pathways described above.
- 2) Two-Pathway Assessment (2Path) includes only the dose from the ground-deposited radioactive material.

The process of airborne material being deposited on the ground is complex and depends upon many variables including: meteorological conditions (e.g., wind speed, rainout, washout, snowout) and physical properties (e.g., particle size, gas, vapor, and aerosol). Although rainout, washout and snowout are distinct processes they are all wet deposition processes, and for convenience are referred to collectively as washout.

Washout can have a significant effect on ground deposition; but it is not considered in this section because:

- 1) washout is likely to affect only part of the area impacted by the incident (i.e., only where it rains or snows during plume passage) and
- 2) washout effects are highly dependent on variables for which FRMAC is unlikely to have data (e.g., particle size, raindrop size).

Therefore, the following methods are limited to dry deposition. Future revisions of this section may include the effects of washout and wet deposition.

## Default Assumptions

FRMAC radiological assessment calculations utilize the default assumptions established by the FRMAC Assessment Working Group. Users are urged to use the default assumptions until site-specific values become available and Decision Makers endorse their use.

The following default assumptions are used in the methods in this section:

- 1) The dose projections from this section may include contributions from either two or four exposure pathways:
  - a. Two-Pathway (2Path) Assessment includes:
    - i. external exposure (groundshine) to material deposited by the release, and
    - ii. inhalation of resuspended material deposited by the release.
  - b. Four-Pathway (4Path) Assessment includes:
    - i. the pathways from Two-Pathway Assessment above, plus
    - ii. external exposure (plume submersion) during plume passage, and
    - iii. direct inhalation of radioactive material during plume passage.

**NOTE: Because the 2<sup>nd</sup> year Time Phase does not include the effects of plume passage, only 2Path Assessment is applicable for calculating values for the 2<sup>nd</sup> year.**

- 2) The plume is assumed to be in contact with the ground, so that the receptor is in the plume.
- 3) Because the temporal deposition of plume-borne radioactive material cannot be inferred from air sample data, any material deposited by plume passage is assumed to be immediately and completely deposited at the beginning of the passage of the plume.
- 4) Airborne noble gases are **not** deposited on the ground. These radionuclides **are not** included in assessment calculations.

**NOTE:** Noble gases that are daughters of deposited radionuclides **are** included in assessments.

- 5) The effects of radioactive decay, weathering and resuspension are included in the calculations.
- 6) All deposition is assumed to be dry particulates. Wet deposition (increases caused by rain or snow) is not included in these methods. (See Method 4.5 for discussion of deposition velocity.)
- 7) Ingestion is not included in these methods. If ingestion is a significant dose pathway (i.e., >10% of the total dose), it should be addressed separately and included in protective action decisions. (See Section 3 – Ingestion Methods.)
- 8) Default calculations assume:

- a. the receptor is outside in the contaminated area continuously during the time phase under consideration without any protective measures (e.g., shielding, respiratory protection);
  - b. adult receptor;
  - c. inhalation of 1-micron Activity Median Aerodynamic Diameter (AMAD) particles in the lung clearance class which provides the maximum dose.
- 9) The Bateman Equations (Ba1910) are used to model the decay and in-growth of all radionuclides. See Appendix F, Supplement 1 for details.
- 10) FRMAC's public protection methods generally assume that the organ of interest is the whole body (Total Effective Dose). However, other organs may be evaluated against PAGs by utilizing the organ-specific Dose Coefficients and PAGs. (See Method 1.1 Example 1, Section E1.8.)

## Default Inputs

The following information is required for the methods described in this section:

- 1) Data – This information may come from predictive analysis (models) or field data (monitoring and/or samples):
  - Composition of the plume and of the deposited radionuclide mixture (radionuclides and volumetric or areal activity, concentration, activity ratio or mass ratio); and/or
  - External dose (or exposure) rates.
- 2) Other Factors:
  - Plume Deposition Velocity;
  - Ground roughness;
  - Weathering;
  - Resuspension; and
  - Decay of radionuclides during the time period under consideration.
- 3) Constants:
  - Breathing rate (defaults: Activity-Averaged Breathing Rate of 0.92 m<sup>3</sup>/hr for inhalation of resuspended material and Light-Exercise Breathing Rate of 1.5 m<sup>3</sup>/hr for in-plume inhalation based on the ICRP 60+ lung model);
  - Inhalation dose coefficient (defaults from ICRP 60+ dosimetry model);
  - External dose coefficient (defaults from ICRP 60+ dosimetry model);
  - Dose limits (e.g., PAGs – defaults from EPA/DHS guidance); and
  - Exposure to Dose conversion factor (default of 1.0 mrem/mR).
- 4) Time Phase:
  - Release Time ( $t_0$ ) – The time the release begins. This time is usually assumed to correspond to the “Time of Deposition”.
  - Start Time ( $t_1$ ) – The start of the Time Phase (integration period) under consideration.

- End Time ( $t_2$ ) – The end of the Time Phase (integration period) under consideration.
- Evaluation Time ( $t_n$ ) – The point in time, relative to the start of the release, for which the calculation is being performed.

The EPA and DHS have established certain default time phases (early, intermediate, etc.) with specified durations, but the time phase may be set to any period chosen by Decision Makers for a specific incident. The start of the time phase may be set to a time other than the time of the initial release to not include the unavoidable dose received before protective actions may be initiated.

The calculations presented in these methods are applicable to any time phase. To accommodate calculations for varying time phases, adjust the start ( $t_1$ ) and end ( $t_2$ ) of the integration period to the desired values. For example:

- To calculate a value for the first year, set  $t_1$  and  $t_2$  to 0 (beginning of day 1) and 365 (end of day 365) days, respectively, and
- To calculate a value for the second year, set  $t_1$  and  $t_2$  to 365 (beginning of day 366) and 730 (end of day 730) days, respectively.

**NOTE:** Many of the terms in the methods are dependent on variables (e.g., time phase, target organ, PAG, etc.). When critical, these dependencies are shown as subscripts to the appropriate terms. (See Appendix B for the variable list.)

## METHOD 1.1 INTEGRATED-AIR AND DEPOSITION DERIVED RESPONSE LEVELS

### Application

This method has been developed to calculate Integrated-Air and Deposition Derived Response Levels (DRLs) for radioactive material that has been released into the environment. DRLs can be based upon either integrated air activity ( $4\text{Path\_DRL}_{\tilde{A}}$  or  $2\text{Path\_DRL}_{\tilde{A}}$ ) or areal activity ( $4\text{Path\_DRL}_{Dp}$  or  $2\text{Path\_DRL}_{Dp}$ ).

The  $4\text{Path\_DRL}_{\tilde{A}}$  and  $2\text{Path\_DRL}_{\tilde{A}}$ :

Represent the integrated air activity ( $\tilde{A}$ ) ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ ), of radionuclide  $i$  at which the total dose from *all radionuclides* in a release would equal the Protective Action Guide (PAG) over the time phase under consideration.

The  $4\text{Path\_DRL}_{Dp}$  and  $2\text{Path\_DRL}_{Dp}$ :

Represent the areal activity ( $\mu\text{Ci}/\text{m}^2$ ), at a specific Evaluation Time ( $t_n$ ), of radionuclide  $i$  at which the total dose from *all radionuclides* in a release would equal the Protective Action Guide (PAG) over the time phase under consideration.

All DRLs developed in this Method are:

- 1) Derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA92) or the Department of Homeland Security (DHS) (DHS08). A projected or measured value greater than the DRL indicates the potential to exceed the PAG.
- 2) Used to create data products and define activity levels for a radionuclide to help Decision Makers determine where protective actions (e.g., sheltering, evacuation, relocation) may be warranted.

### Discussion

The  $4\text{Path\_DRL}_{\tilde{A}}$ :

- 1) Represents the integrated air activity ( $\tilde{A}$ ) of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.
- 2) Considers the integrated air activity of each radionuclide present in a release, projects the inhalation and external dose received over the time phase under consideration

from plume-borne materials and from material deposited on the ground and relates the combined dose to the PAG.

- 3) Is based on the ratio of activities of each radionuclide in a release, not the individual activity values of those radionuclides.

The 4Path\_DRL<sub>Dp</sub>:

- 1) Represents the areal activity, at time  $t_n$ , of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.
- 2) Considers the areal activity of each radionuclide present in a release, projects the inhalation and external dose received over the time phase under consideration from plume-borne materials and from material deposited on the ground and relates the combined dose to the PAG.
- 3) Is based on the ratio of activities of each radionuclide in a mixture, not the individual activity values of those radionuclides.

The 2Path\_DRL <sub>$\tilde{A}$</sub> :

- 1) Represents the integrated air activity ( $\tilde{A}$ ) of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.
- 2) Considers the integrated air activity of each radionuclide present in a release, projects the inhalation and external dose received over the time phase under consideration from material deposited on the ground and relates the combined dose to the PAG.
- 3) Is based on the ratio of activities of each radionuclide in a release, not the individual activity values of those radionuclides.

The 2Path\_DRL<sub>Dp</sub>:

- 1) Represents the areal activity, at time  $t_n$ , of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.
- 2) Considers the areal activity of each radionuclide present in a release, projects the inhalation and external dose received over the time phase under consideration from material deposited on the ground and relates the combined dose to the PAG.
- 3) Is based on the ratio of activities of each radionuclide in a mixture, not the individual activity values of those radionuclides.

Once a relative ratio of the amount of each radionuclide present is known, these values can be calculated for any radionuclide in the mixture to represent the hazard of the entire mixture. The DRLs must be recalculated for areas with differing relative ratios.

FRMAC recommends that values be calculated for a single radionuclide, chosen for ease of detection with available instrumentation, to eliminate the need to separately measure the concentration of every radionuclide in the mixture in the environmental medium.

For example: If the mixture includes Co-60, Sr-90, and Am-241, it would generally be most appropriate to calculate DRLs for Co-60 because it can be more easily detected in the field than the other radionuclides.

**NOTE:** These DRLs may be calculated for Stochastic (Chronic) or Deterministic (Acute) doses by using either Acute or Chronic Dose Coefficients.

## Assumptions

There are no additional assumptions beyond the Default Assumptions above.

## Inputs

There are no additional inputs beyond the Default Inputs above.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available and Decision Makers endorse their use.

## Outputs

### Final

The final output of this method is the DRL value for a radionuclide from a release of radioactive material.

$4\text{Path\_DRL}_{\tilde{A}}$  = Four-Pathway Air Derived Response Level, the integrated air activity ( $\tilde{A}$ ) of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration, ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ ).

$4\text{Path\_DRL}_{\text{Dp}}$  = Four-Pathway Deposition Derived Response Level, the areal activity, at time  $t_n$ , of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration, ( $\mu\text{Ci}/\text{m}^2$ ).

$2\text{Path\_DRL}_{\tilde{A}}$  = Two-Pathway Air Derived Response Level, the integrated air activity ( $\tilde{A}$ ) of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration, ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ ).

$2\text{Path\_DRL}_{\text{Dp}}$  = Two-Pathway Deposition Derived Response Level, the areal activity, at time  $t_n$ , of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering only ground dose pathways)

would equal the PAG over the time phase under consideration, ( $\mu\text{Ci}/\text{m}^2$ ).

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

- 2Path\_MTDP = Two-Pathway Mixture Total Dose Parameter for all radionuclides (mrem)
- 4Path\_MTDP = Four-Pathway Mixture Total Dose Parameter for all radionuclides (mrem)
- Dp\_ExDP = Deposition External Dose Parameter for each radionuclide (mrem)
- Dp\_InhDP = Deposition Inhalation Dose Parameter for each radionuclide (mrem)
- Dp\_TDP = Deposition Total Dose Parameter for each radionuclide (mrem)
- Pl\_ExDP = Plume External Dose Parameter for each radionuclide (mrem)
- Pl\_InhDP = Plume Inhalation Dose Parameter for each radionuclide (mrem)
- Pl\_TDP = Plume Total Dose Parameter for each radionuclide (mrem)

### Calculation

Calculation of the DRLs can be challenging, especially when considering complex radionuclide mixtures or a single radionuclide with multiple progeny in equilibrium. Therefore the user is urged to use a computer code, such as Turbo FRMAC<sup>®</sup>, to complete these calculations.

#### 1) Four-Pathway Air Derived Response Level

Equation 1.1-1 shows the final form of the  $4\text{Path\_DRL}_{\tilde{A}_i, TP}$  calculation:

$$4\text{Path\_DRL}_{\tilde{A}_i, TP} = \frac{PAG_{TP} * \tilde{A}_i}{4\text{Path\_MTDP}_{TP}} \quad (\text{Eq. 1.1-1})$$

$$\frac{\mu\text{Ci} \cdot \text{s}}{\text{m}^3} = \frac{\text{mrem} * \frac{\mu\text{Ci} \cdot \text{s}}{\text{m}^3}}{\text{mrem}}$$

where:

- $4\text{Path\_DRL}_{\tilde{A}_i, TP}$  = Four-Pathway Air Derived Response Level, the integrated air activity ( $\tilde{A}$ ) of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ),  $\mu\text{Ci} \cdot \text{s}/\text{m}^3$ ;
- $PAG_{TP}$  = Protective Action Guide for total dose, as specified by the EPA, DHS or other Decision Makers, over the time phase under consideration ( $TP$ ), mrem;

$\tilde{A}_i$  = Integrated air activity of radionuclide  $i$  in a release,  $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ ; and  
 $4Path\_MTDP_{TP}$  = Four-Pathway Mixture Total Dose Parameter, the sum of the external dose from submersion and groundshine and the committed dose from inhalation of plume-borne and resuspended material, over the time phase under consideration ( $TP$ ), from the radionuclide mixture, mrem.

## 2) Four-Pathway Deposition Derived Response Level

Equation 1.1-2 shows the final form of the  $4Path\_DRL_{Dp}$  calculation:

$$4Path\_DRL_{Dp,i,t_n,TP} = \frac{PAG_{TP} * Dp_{i,t_n} * WF_{t_n}}{4Path\_MTDP_{TP}} \quad (\text{Eq. 1.1-2})$$

$$\frac{\mu\text{Ci}}{\text{m}^2} = \frac{\text{mrem} * \frac{\mu\text{Ci}}{\text{m}^2} * \text{unitless}}{\text{mrem}}$$

where:

$4Path\_DRL_{Dp,i,t_n,TP}$  = Four-Pathway Deposition Derived Response Level, the areal activity, at time  $t_n$ , of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ), ( $\mu\text{Ci}/\text{m}^2$ );

$PAG_{TP}$  = Protective Action Guide for total dose, as specified by the EPA, DHS or other Decision Makers, over the time phase under consideration ( $TP$ ), mrem;

$Dp_{i,t_n}$  = Deposition, the areal activity of radionuclide  $i$  at time  $t_n$ ,  $\mu\text{Ci}/\text{m}^2$ ;  
**NOTE:** See Appendix F, Supplement 1 for details on decay and in-growth calculations to estimate the activity at  $t_n$ .

$WF_{t_n}$  = Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind) from  $t_0$  (deposition) to  $t_n$  (evaluation time), unitless; and

**NOTE:** See Appendix F, Supplement 2 for details on calculating WF.

$4Path\_MTDP_{TP}$  = Four-Pathway Mixture Total Dose Parameter, the sum of the external dose from submersion and groundshine and the committed dose from inhalation of plume-borne and resuspended material, over the time phase under consideration ( $TP$ ), from the radionuclide mixture, mrem.

## 3) Two-Pathway Air Derived Response Level

Equation 1.1-3 shows the final form of the  $2Path\_DRL_{\tilde{A}}$  calculation:

$$2Path\_DRL_{\tilde{A}_{i,TP}} = \frac{PAG_{TP} * \tilde{A}_i}{2Path\_MTDP_{TP}} \quad (\text{Eq. 1.1-3})$$

$$\frac{\mu\text{Ci} \cdot \text{s}}{\text{m}^3} = \frac{\text{mrem} * \frac{\mu\text{Ci} \cdot \text{s}}{\text{m}^3}}{\text{mrem}}$$

where:

$2Path\_DRL_{\tilde{A}_{i,TP}}$  = Two-Pathway Air Derived Response Level, the integrated air activity ( $\tilde{A}$ ) of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ),  $\mu\text{Ci} \cdot \text{s}/\text{m}^3$ ;

$PAG_{TP}$  = Protective Action Guide for total dose, as specified by the EPA, DHS or other Decision Makers, over the time phase under consideration ( $TP$ ), mrem;

$\tilde{A}_i$  = Integrated air activity of radionuclide  $i$  in a release,  $\mu\text{Ci} \cdot \text{s}/\text{m}^3$ ; and

$2Path\_MTDP_{TP}$  = Two-Pathway Mixture Total Dose Parameter, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration ( $TP$ ), from the radionuclide mixture, mrem.

#### 4) Two-Pathway Deposition Derived Response Level

Equation 1.1-4 shows the final form of the  $2Path\_DRL_{Dp}$  calculation:

$$2Path\_DRL_{Dp,i,t_n,TP} = \frac{PAG_{TP} * Dp_{i,t_n} * WF_{t_n}}{2Path\_MTDP_{TP}} \quad (\text{Eq. 1.1-4})$$

$$\frac{\mu\text{Ci}}{\text{m}^2} = \frac{\text{mrem} * \frac{\mu\text{Ci}}{\text{m}^2} * \text{unitless}}{\text{mrem}}$$

where:

$2Path\_DRL_{Dp,i,m,TP}$  = Two-Pathway Deposition Derived Response Level, the areal activity, at time  $t_n$ , of radionuclide  $i$  at which the total dose from all radionuclides in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ), ( $\mu\text{Ci}/\text{m}^2$ );

$PAG_{TP}$  = Protective Action Guide for total dose, as specified by the EPA, DHS or other Decision Makers, over the time phase under consideration ( $TP$ ), mrem;

$Dp_{i,m}$  = Deposition, the areal activity of radionuclide  $i$  at time  $t_n$ ,  $\mu\text{Ci}/\text{m}^2$ ;

**NOTE:** See Appendix F, Supplement 1 for details on decay and in-growth calculations to estimate the activity at  $t_n$ .

$WF_m$  = Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind) from  $t_0$  (deposition) to  $t_n$  (evaluation time), unitless; and

**NOTE:** See Appendix F, Supplement 2 for details on calculating WF.

$2Path\_MTDP_{TP}$  = Two-Pathway Mixture Total Dose Parameter, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration ( $TP$ ), from the radionuclide mixture, mrem.

The following sections provide step-by-step instructions to calculate these DRLs, beginning with determining the Total Dose Parameters for each radionuclide, then finding a Mixture Total Dose Parameter for the release, and finally calculating the DRLs for the chosen radionuclide present in the mixture.

## 1.1 Calculating the Total Dose Parameters for each Radionuclide in a Release

The critical factors in determining the DRLs are the Plume Total Dose Parameter ( $Pl\_TDP$ ) and Deposition Total Dose Parameter ( $Dp\_TDP$ ) for each radionuclide in a release.

The Plume Total Dose Parameter ( $Pl\_TDP$ ) represents the dose from the two plume pathways (inhalation and submersion) and is obtained by adding:

- the Plume Inhalation Dose Parameter ( $Pl\_InhDP$ ) and
- the Plume External Dose Parameter ( $Pl\_ExDP$ ).

The Deposition Total Dose Parameter ( $Dp\_TDP$ ) represents the dose from the two deposition pathways (resuspension inhalation and groundshine) and is obtained by adding:

- the Deposition Inhalation Dose Parameter ( $Dp\_InhDP$ ) and
- the Deposition External Dose Parameter ( $Dp\_ExDP$ ).

### 1.1.1 Calculating the Plume Total Dose Parameter

The  $Pl\_TDP$  is calculated using Equation 1.1-5.

$$Pl\_TDP_{i,TP} = Pl\_InhDP_{i,TP} + Pl\_ExDP_{i,TP} \quad (\text{Eq. 1.1-5})$$

$$\text{mrem} = \text{mrem} + \text{mrem}$$

where:

$Pl\_TDP_{i,TP}$  = Plume Total Dose Parameter, the sum of the external dose from submersion in, and the committed dose from inhalation of, plume-borne radionuclide  $i$  over the time phase under consideration ( $TP$ ), mrem;

$Pl\_InhDP_{i, TP}$  = Plume Inhalation Dose Parameter, the committed dose from the inhalation of plume-borne radionuclide  $i$  over the time phase under consideration ( $TP$ ), mrem; and

$Pl\_ExDP_{i, TP}$  = Plume External Dose Parameter, the external dose from submersion from plume-borne radionuclide  $i$  over the time phase under consideration ( $TP$ ), mrem.

The following sections show how to calculate the components of the  $Pl\_TDP$ .

### 1.1.1.1 Calculating the Plume Inhalation Dose Parameter

#### (Plume Inhalation Pathway)

The Plume Inhalation Dose Parameter ( $Pl\_InhDP$ ) is calculated by multiplying the Inhalation Dose Coefficient ( $InhDC$ ) by the Integrated Air activity of the radionuclide and the receptor's light exercise breathing rate ( $BR_{LE}$ ) to calculate the committed effective dose component from inhaling each of the plume-borne radionuclides.

$$Pl\_InhDP_{i, TP} = InhDC_i * \tilde{A}_i * BR_{LE} \quad (\text{Eq. 1.1-6})$$

$$\text{mrem} = \frac{\text{mrem}}{\mu\text{Ci}} * \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * \frac{\text{m}^3}{\text{s}}$$

where:

$Pl\_InhDP_{i, TP}$  = Plume Inhalation Dose Parameter, the committed dose from the inhalation of plume-borne radionuclide  $i$  over the time phase under consideration ( $TP$ ), mrem;

$InhDC_i$  = Inhalation Dose Coefficient, the committed dose coefficient for radionuclide  $i$ , mrem/ $\mu\text{Ci}$ ;

$\tilde{A}_i$  = Integrated air activity of radionuclide  $i$  in a release,  $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ ; and  
**NOTE:** If integrated air activity data is unavailable, this value may be estimated from the deposition of each radionuclide ( $Dp_i$ ). See Method 4.5.

$BR_{LE}$  = Light Exercise Breathing Rate, the volume of air breathed per unit time by an adult male during light exercise (ICRP, 1994, Table 6),  $4.17\text{E-}04 \text{ m}^3/\text{s}$ .

**NOTE:** This calculation uses the Light Exercise Breathing Rate rather than the Activity Averaged Breathing Rate ( $BR_{AA}$ ) because it is assumed that the individual will be actively seeking to exit the plume.

### 1.1.1.2 Calculating the Plume External Dose Parameter

#### (Submersion Exposure Pathway)

The Plume External Dose Parameter (Pl\_ExDP) is the External Dose Coefficient for submersion in a plume multiplied by the integrated-air activity of each radionuclide.

$$Pl\_ExDP_{i,TP} = Pl\_ExDC_i * \tilde{A}_i \quad (\text{Eq. 1.1-7})$$

$$\text{mrem} = \frac{\text{mrem} \cdot \text{m}^3}{\mu\text{Ci} \cdot \text{s}} * \frac{\mu\text{Ci} \cdot \text{s}}{\text{m}^3}$$

where:

$Pl\_ExDP_{i,TP}$  = Plume External Dose Parameter, the external dose from submersion from plume-borne radionuclide  $i$  over the time phase under consideration ( $TP$ ), mrem;

$Pl\_ExDC_i$  = Plume External Dose Coefficient, the external dose rate from submersion in radionuclide  $i$  in the plume,  $\text{mrem} \cdot \text{m}^3 / \mu\text{Ci} \cdot \text{s}$ ; and

$\tilde{A}_i$  = Integrated air activity of radionuclide  $i$  in a release,  $\mu\text{Ci} \cdot \text{s} / \text{m}^3$ .

**NOTE:** If integrated air activity data is unavailable, this value may be estimated from the deposition of each radionuclide ( $Dp_i$ ). See Method 4.5.

### 1.1.2 Calculating the Deposition Total Dose Parameter

The  $Dp\_TDP$  is calculating using Equation 1.1-8.

$$Dp\_TDP_{i,TP} = Dp\_InhDP_{i,TP} + Dp\_ExDP_{i,TP} \quad (\text{Eq. 1.1-8})$$

$$\text{mrem} = \text{mrem} + \text{mrem}$$

where:

$Dp\_TDP_{i,TP}$  = Deposition Total Dose Parameter, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration ( $TP$ ), from the deposition of radionuclide  $i$ , mrem;

$Dp\_InhDP_{i,TP}$  = Deposition Inhalation Dose Parameter, the committed dose from radionuclide  $i$  deposited on the ground from the inhalation of the resuspended fraction of the radionuclide over the time phase under consideration ( $TP$ ), mrem; and

$Dp\_ExDP_{i,TP}$  = Deposition External Dose Parameter, the external dose from groundshine from radionuclide  $i$  over the time phase under consideration ( $TP$ ), mrem.

The following sections show how to calculate the components of the  $Dp\_TDP$ .

### 1.1.2.1 Calculating the Deposition Inhalation Dose Parameter

#### (Resuspension Inhalation Pathway)

The Deposition Inhalation Dose Parameter ( $Dp\_InhDP$ ) is calculated by multiplying the Inhalation Dose Coefficient ( $InhDC$ ) by the Resuspension Parameter ( $KP$ ) and by the receptor's activity-averaged breathing rate to calculate the committed effective dose component from inhaling resuspended radioactivity over the time phase under consideration.

$$Dp\_InhDP_{i,TP} = InhDC_i * KP_{i,TP} * BR_{AA} \quad (\text{Eq. 1.1-9})$$

$$\text{mrem} = \frac{\text{mrem}}{\mu\text{Ci}} * \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * \frac{\text{m}^3}{\text{s}}$$

where:

$Dp\_InhDP_{i,TP}$  = Deposition Inhalation Dose Parameter, the committed dose from radionuclide  $i$  deposited on the ground from the inhalation of the resuspended fraction of the radionuclide over the time phase under consideration ( $TP$ ), mrem;

$InhDC_i$  = Inhalation Dose Coefficient, the committed dose coefficient for radionuclide  $i$ , mrem/ $\mu\text{Ci}$ ;

$KP_{i,TP}$  = Resuspension Parameter, value that adjusts the airborne radioactivity level of radionuclide  $i$  over the time phase under consideration ( $TP$ ) for radioactive decay and in-growth and the time-dependent resuspension factor ( $K_t$ ),  $\mu\text{C}\cdot\text{s}/\text{m}^3$ ; and

**NOTE:** See Appendix F, Supplement 2 for details on calculating  $KP$ .

$BR_{AA}$  = Activity-Averaged Breathing Rate, the activity-weighted average volume of air breathed per unit time by an adult male (ICRP, 1994, Table B.16B),  $2.56\text{E-}04 \text{ m}^3/\text{s}$ .

### 1.1.2.2 Calculating the Deposition External Dose Parameter

#### (Groundshine Exposure Pathway)

The Deposition External Dose Parameter ( $Dp\_ExDP$ ) is calculated by multiplying the External Dose Coefficient ( $Dp\_ExDC$ ) by a ground roughness factor ( $GRF$ ) and the Weathering Parameter ( $WP$ ) to calculate the effective dose from groundshine per unit activity deposited on the ground over the time period under consideration.

$$Dp\_ExDP_{i,TP} = Dp\_ExDC_i * GRF * WP_{i,TP} \quad (\text{Eq. 1.1-10})$$

$$\text{mrem} = \frac{\text{mrem} \cdot \text{m}^2}{\mu\text{Ci} \cdot \text{s}} * \text{unitless} * \frac{\mu\text{Ci} \cdot \text{s}}{\text{m}^2}$$

where:

$Dp\_ExDP_{i, TP}$  = Deposition External Dose Parameter, the external dose from groundshine from radionuclide  $i$  over the time phase under consideration ( $TP$ ), mrem;

$Dp\_ExDC_i$  = Deposition External Dose Coefficient, the external dose rate from radionuclide  $i$  per unit activity deposited on the ground,  $\text{mrem} \cdot \text{m}^2 / \mu\text{Ci} \cdot \text{s}$ ;

$GRF$  = Ground Roughness Factor, a constant (0.82) that compensates for the fact that the external exposure is not coming from an infinite flat plane ( $An02$ ), unitless; and

$WP_{i, TP}$  = Weathering Parameter, the adjustment for radioactive decay and in-growth and the time-dependent weathering effects that change the amount of a radionuclide available to cause direct exposure or to be ingested over the time phase under consideration ( $TP$ ),  $\mu\text{Ci} \cdot \text{s} / \text{m}^2$ .

**NOTE:** See Appendix F, Supplement 2 for details on calculating WP.

## 1.2 Calculating the Mixture Total Dose Parameters

### 1.2.1 Calculating the Four-Pathway Mixture Total Dose Parameter

The Four-Pathway Mixture Total Dose Parameter ( $4Path\_MTDP$ ) includes the dose contributions from the plume-borne and ground-deposited radionuclide mixture, and is calculated by adding the  $Pl\_TDPs$  and  $Dp\_TDPs$  for each radionuclide in the mixture.

$$4Path\_MTDP_{TP} = \sum_i (Pl\_TDP_{i, TP} + Dp\_TDP_{i, TP})$$

$$\text{mrem} = \text{mrem} + \text{mrem} \quad (\text{Eq. 1.1-11})$$

where:

$4Path\_MTDP_{TP}$  = Four-Pathway Mixture Total Dose Parameter, the sum of the external dose from submersion and groundshine and the committed dose from inhalation of plume-borne and resuspended material, over the time phase under consideration ( $TP$ ), from the radionuclide mixture, mrem;

$Pl\_TDP_{i, TP}$  = Plume Total Dose Parameter, , the sum of the external dose from submersion in, and the committed dose from inhalation of, plume-borne radionuclide  $i$  over the time phase under consideration ( $TP$ ), mrem; and

$Dp\_TDP_{i, TP}$  = Deposition Total Dose Parameter, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration ( $TP$ ), from the deposition of radionuclide  $i$ , mrem.

### 1.2.2 Calculating the Two-Pathway Mixture Total Dose Parameter

The Two-Pathway Mixture Total Dose Parameter (2Path\_MTDP) includes the dose contributions from the ground-deposited radionuclide mixture, and is calculated by summing the  $Dp\_TDPs$  for each radionuclide in the mixture.

$$2Path\_MTDP_{TP} = \sum_i Dp\_TDP_{i,TP} \quad (\text{Eq. 1.1-12})$$

$$\text{mrem} = \text{mrem}$$

where:

$2Path\_MTDP_{TP}$  = Two-Pathway Mixture Total Dose Parameter, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration ( $TP$ ), from the radionuclide mixture, mrem; and

$Dp\_TDP_{i,TP}$  = Deposition Total Dose Parameter, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration ( $TP$ ), from the deposition of radionuclide  $i$ , mrem.

## 1.3 Comparing the MTDP to the PAG to Calculate DRLs

Once the relevant MTDP has been calculated, it is used to determine the DRLs by comparing it to the PAG using the following equations.

### 1.3.1 Four-Pathway Air Derived Response Level (4Path\_DRL $\tilde{A}$ )

$$4Path\_DRL_{\tilde{A}_{i,TP}} = \frac{PAG_{TP} * \tilde{A}_i}{4Path\_MTDP_{TP}} \quad (\text{Eq. 1.1-1})$$

$$\frac{\mu\text{Ci} \cdot \text{s}}{\text{m}^3} = \frac{\text{mrem} * \frac{\mu\text{Ci} \cdot \text{s}}{\text{m}^3}}{\text{mrem}}$$

where:

$4Path\_DRL_{\tilde{A}_{i,TP}}$  = Four-Pathway Air Derived Response Level, the integrated air activity ( $\tilde{A}$ ) of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ),  $\mu\text{Ci} \cdot \text{s}/\text{m}^3$ ;

$PAG_{TP}$  = Protective Action Guide for total dose, as specified by the EPA, DHS or other Decision Makers, over the time phase under consideration ( $TP$ ), mrem;

$\tilde{A}_i$  = Integrated air activity of radionuclide  $i$  in a release,  $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ ; and  
 $4Path\_MTDP_{TP}$  = Four-Pathway Mixture Total Dose Parameter, the sum of the external dose from submersion and groundshine and the committed dose from inhalation of plume-borne and resuspended material, over the time phase under consideration ( $TP$ ), from the radionuclide mixture, mrem.

Because this method uses a time integrated air activity, there is no need to account for decay that occurs during sample collection.

### 1.3.2 Four-Pathway Deposition Derived Response Level ( $4Path\_DRL_{DP}$ )

$$4Path\_DRL_{DP,i,t_n,TP} = \frac{PAG_{TP} * DP_{i,t_n} * WF_{t_n}}{4Path\_MTDP_{TP}} \quad (\text{Eq. 1.1-2})$$

$$\frac{\mu\text{Ci}}{\text{m}^2} = \frac{\text{mrem} * \frac{\mu\text{Ci}}{\text{m}^2} * \text{unitless}}{\text{mrem}}$$

where:

$4Path\_DRL_{DP,i,m,TP}$  = Four-Pathway Deposition Derived Response Level, the areal activity, at time  $t_n$ , of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ), ( $\mu\text{Ci}/\text{m}^2$ );

$PAG_{TP}$  = Protective Action Guide for total dose, as specified by the EPA, DHS or other Decision Makers, over the time phase under consideration ( $TP$ ), mrem;

$DP_{i,m}$  = Deposition, the areal activity of radionuclide  $i$  at time  $t_n$ ,  $\mu\text{Ci}/\text{m}^2$ ;  
**NOTE:** See Appendix F, Supplement 1 for details on decay and in-growth calculations to estimate the activity at  $t_n$ .

$WF_m$  = Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind) from  $t_0$  (deposition) to  $t_n$  (evaluation time), unitless; and

**NOTE:** See Appendix F, Supplement 2 for details on calculating WF.

$4Path\_MTDP_{TP}$  = Four-Pathway Mixture Total Dose Parameter, the sum of the external dose from submersion and groundshine and the committed dose from inhalation of plume-borne and resuspended material, over the time phase under consideration ( $TP$ ), from the radionuclide mixture, mrem.

### 1.3.3 Two-Pathway Air Derived Response Level (2Path\_DRL $\tilde{A}$ )

$$2Path\_DRL_{\tilde{A},i,TP} = \frac{PAG_{TP} * \tilde{A}_i}{2Path\_MTDP_{TP}} \quad (\text{Eq. 1.1-3})$$

$$\frac{\mu\text{Ci} \cdot \text{s}}{\text{m}^3} = \frac{\text{mrem} * \frac{\mu\text{Ci} \cdot \text{s}}{\text{m}^3}}{\text{mrem}}$$

where:

$2Path\_DRL_{\tilde{A},i,TP}$  = Two-Pathway Air Derived Response Level, the integrated air activity ( $\tilde{A}$ ) of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ),  $\mu\text{Ci} \cdot \text{s}/\text{m}^3$ ;

$PAG_{TP}$  = Protective Action Guide for total dose, as specified by the EPA, DHS or other Decision Makers, over the time phase under consideration ( $TP$ ), mrem;

$\tilde{A}_i$  = Integrated air activity of radionuclide  $i$  in a release,  $\mu\text{Ci} \cdot \text{s}/\text{m}^3$ ; and

$2Path\_MTDP_{TP}$  = Two-Pathway Mixture Total Dose Parameter, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration ( $TP$ ), from the radionuclide mixture, mrem.

Because this method uses a time integrated air activity, there is no need to account for decay that occurs during sample collection.

### 1.3.4 Two-Pathway Deposition Derived Response Level (2Path\_DRL $D_p$ )

$$2Path\_DRL_{D_p,i,t_n,TP} = \frac{PAG_{TP} * D_{p,i,t_n} * WF_{t_n}}{2Path\_MTDP_{TP}} \quad (\text{Eq. 1.1-4})$$

$$\frac{\mu\text{Ci}}{\text{m}^2} = \frac{\text{mrem} * \frac{\mu\text{Ci}}{\text{m}^2} * \text{unitless}}{\text{mrem}}$$

where:

$2Path\_DRL_{D_p,i,t_n,TP}$  = Two-Pathway Deposition Derived Response Level, the areal activity, at time  $t_n$ , of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ), ( $\mu\text{Ci}/\text{m}^2$ );

$PAG_{TP}$  = Protective Action Guide for total dose, as specified by the EPA, DHS or other Decision Makers, over the time phase under consideration ( $TP$ ), mrem;

$Dp_{i,t_n}$  = Deposition, the areal activity of radionuclide  $i$  at time  $t_n$ ,  $\mu\text{Ci}/\text{m}^2$ ;

**NOTE:** See Appendix F, Supplement 1 for details on decay and in-growth calculations to estimate the activity at  $t_n$ .

$WF_{t_n}$  = Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind) from  $t_0$  (deposition) to  $t_n$  (evaluation time), unitless; and

**NOTE:** See Appendix F, Supplement 2 for details on calculating WF.

$2Path\_MTDP_{TP}$  = Two-Pathway Mixture Total Dose Parameter, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration ( $TP$ ), from the radionuclide mixture, mrem.

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## EXAMPLE 1

**Problem: Calculate the Total Effective Dose Four-Pathway DRLs for the First-Year Time Phase for the Following Mixture ( $t_n = 0$ ).**

Table 1.1-E1

Radionuclide	Integrated Air Activity ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )	Deposition ( $\mu\text{Ci}/\text{m}^2$ )	$t_{1/2}$ (s)
Co-60	6.67E+02	2	1.66E+08
Gd-148	3.33E+02	1	2.93E+09
Sr-90	1.00E+03	3	9.19E+08
Y-90	1.00E+03	3	2.30E+05

To determine the  $4\text{Path\_DRL}_{\bar{\lambda}}$ , the following intermediate terms are needed:

- Dp\_ExDP = Deposition External Dose Parameter for each radionuclide (mrem)
- Dp\_InhDP = Deposition Inhalation Dose Parameter for each radionuclide (mrem)
- Dp\_TDP = Deposition Total Dose Parameter for each radionuclide (mrem)
- Pl\_ExDP = Plume External Dose Parameter for each radionuclide ( $\text{mrem}\cdot\text{m}^3/\mu\text{Ci}\cdot\text{s}$ )
- Pl\_InhDP = Plume Inhalation Dose Parameter for each radionuclide ( $\text{mrem}\cdot\text{m}^3/\mu\text{Ci}\cdot\text{s}$ )
- Pl\_TDP = Plume Total Dose Parameter for each radionuclide ( $\text{mrem}\cdot\text{m}^3/\mu\text{Ci}\cdot\text{s}$ )

The Pl\_TDP is then added to the Dp\_TDP for each radionuclide to calculate the Four-Pathway Mixture Total Dose Parameter ( $4\text{Path\_MTDP}$ ).

**NOTE:** Values calculated using Turbo FRMAC<sup>®</sup> may differ from the values shown in this example because of truncation or rounding.

### E1.1 Calculating Pl\_InhDP (Equation 1.1-6)

This calculation requires the Inhalation Dose Coefficient (InhDC), and the Light Exercise Breathing Rate ( $\text{BR}_{\text{LE}}$ ).

Example Pl\_InhDP calculation for Co-60 and Pl\_InhDP values for the radionuclide mixture for the first-year time phase.

$$Pl\_InhDP_{60\text{Co}} = 1.14\text{E}+02 \frac{\text{mrem}}{\mu\text{Ci}} * 6.67\text{E}+02 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * 4.17\text{E}-04 \frac{\text{m}^3}{\text{s}} = 3.17\text{E}+01 \text{mrem}$$

Table 1.1-E2

Radionuclide	InhDC <sup>a</sup> (mrem/μCi)	Integrated Air Activity (μCi·s/m <sup>3</sup> )	Breathing Rate (Light Exercise) <sup>b</sup> (m <sup>3</sup> /s)	PI_InhDP First Year (mrem)
Co-60	1.14E+02	6.67E+02	4.17E-04	3.17E+01
Gd-148	9.55E+04	3.33E+02	4.17E-04	1.33E+04
Sr-90	5.81E+02	1.00E+03	4.17E-04	2.42E+02
Y-90	5.55E+00	1.00E+03	4.17E-04	2.31

<sup>a</sup> Value from DCFPAK 2.0 (ICRP 60+) for 1 micron particles. If particle size is known to be other than 1 micron, choose appropriate value.

<sup>b</sup> The light exercise breathing rate is used because it is assumed that the individual will be actively seeking to exit the plume.

## E1.2 Calculating PI\_ExDP (Equation 1.1-7)

The External Dose Parameter (PI\_ExDP) is simply the External Dose Coefficient for submersion in a plume multiplied by the Integrated Air activity ( $\tilde{A}$ ).

Example PI\_ExDP calculation for Co-60 and PI\_ExDP values for the radionuclide mixture for the first-year time phase.

$$PI\_ExDP_{60Co} = 4.40E-04 \frac{\text{mrem} \cdot \text{m}^3}{\mu\text{Ci} \cdot \text{s}} * 6.67E+02 \frac{\mu\text{Ci} \cdot \text{s}}{\text{m}^3} = 2.93E-01 \text{ mrem}$$

Table 1.1-E3

Radionuclide	PI_ExDC <sup>a</sup> (mrem·m <sup>3</sup> /μCi·s)	Integrated Air Activity (μCi·s/m <sup>3</sup> )	PI_ExDP First Year (mrem)
Co-60	4.40E-04	2.0E+03	2.93E-01
Gd-148	0	1.0E+03	0
Sr-90	3.64E-07	3.0E+03	3.64E-04
Y-90	2.93E-06	3.0E+03	2.93E-03

<sup>a</sup> Values from DCFPAK 2.0 (ICRP 60+).

## E1.3 Calculating Dp\_InhDP (Equation 1.1-9)

This calculation requires the Inhalation Dose Coefficient (InhDC), the Activity-Averaged Breathing Rate (BR<sub>AA</sub>) and the Resuspension Parameter (KP).

### E1.3.1 Calculating the Resuspension Parameter (See Appendix F, Supplement 2, Equation 3c)

Example KP calculation for Co-60 and KP values for the radionuclide mixture for the first-year time phase.

$$\begin{aligned}
 KP_{\text{Co-60}} &= 2 \frac{\mu\text{Ci}}{\text{m}^2} * \left[ \begin{aligned} & \frac{1.0\text{E-}05 * \left( e^{(-3.15\text{E}+07*(4.17\text{E-}09+8.1\text{E-}07))} - e^{(-0*(4.17\text{E-}09+8.1\text{E-}07))} \right)}{- (4.17\text{E-}09 + 8.1\text{E-}07)} \\ & + \frac{7.0\text{E-}09 * \left( e^{(-3.15\text{E}+07*(4.17\text{E-}09+2.31\text{E-}08))} - e^{(-0*(4.17\text{E-}09+2.31\text{E-}08))} \right)}{- (4.17\text{E-}09 + 2.31\text{E-}08)} \\ & + \frac{1.0\text{E-}09 * \left( e^{(-3.15\text{E}+07*(4.17\text{E-}09))} - e^{(-0*(4.17\text{E-}09))} \right)}{- (4.17\text{E-}09)} \end{aligned} \right] \frac{\text{s}}{\text{m}} \\
 &= 2.49\text{E}+01 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3}
 \end{aligned}$$

Table 1.1-E4

Radionuclide	Deposition ( $\mu\text{Ci}/\text{m}^2$ )	$\lambda_i$ ( $\text{s}^{-1}$ )	$t_1$ (s)	$t_2$ (s)	KP <sub>i</sub> – First Year ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )
Co-60	2	4.17E-09	0	3.15E+07	2.49E+01 <sup>a</sup>
Gd-148	1	2.36E-10	0	3.15E+07	1.25E+01 <sup>a</sup>
Sr-90	3	7.54E-10	0	3.15E+07	3.76E+01 <sup>a</sup>
Y-90	3	3.01E-06	0	3.15E+07	3.75E+01 <sup>b</sup>

<sup>a</sup> Values approximated using equations in Appendix F, Supplement 2.  
<sup>b</sup> Value from Turbo FRMAC 2011<sup>®</sup>. Calculations for daughters are more complicated than can be readily discussed here. See Appendix F, Supplements 1 and 2 for more information.

### E1.3.2 Calculating the Dp\_InhDP

Example Dp\_InhDP calculation for Co-60 and Dp\_InhDP values for the radionuclide mixture for the first-year time phase.

$$Dp\_InhDP_{\text{Co-60}} = 1.14\text{E}+02 \frac{\text{mrem}}{\mu\text{Ci}} * 2.49\text{E}+01 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * 2.56\text{E-}04 \frac{\text{m}^3}{\text{s}} = 7.27\text{E-}01 \text{mrem}$$

Table 1.1-E5

Radionuclide	InhDC <sup>a</sup> (mrem/μCi)	KP <sub>i</sub> – First Year (μCi•s/m <sup>3</sup> )	Breathing Rate (Activity-averaged) <sup>b</sup> (m <sup>3</sup> /s)	Dp_InhDP First Year (mrem)
Co-60	1.14E+02	2.49E+01	2.56E-04	7.27E-01
Gd-148	9.55E+04	1.25E+01	2.56E-04	3.06E+02
Sr-90	5.81E+02	3.76E+01	2.56E-04	5.59
Y-90	5.55E+00	3.75E+01 <sup>c</sup>	2.56E-04	5.34E-02

<sup>a</sup> Value from DCFPAK 2.0 (ICRP 60+) for 1 micron particles. If particle size is known to be other than 1 micron, choose appropriate value.  
<sup>b</sup> Standard activity-averaged breathing rate.  
<sup>c</sup> Value from Turbo FRMAC 2011<sup>®</sup>.

## E1.4 Calculating Dp\_ExDP (Equation 1.1-10)

This calculation requires the External Dose Coefficient (ExDC), the Weathering Parameter (WP) and the Ground Roughness Factor (GRF).

### E1.4.1 Calculating the Weathering Parameter (See Appendix F, Supplement 2, Equation 6c)

Example WP calculation for Co-60 and WP values for the radionuclide mixture for the first-year time phase.

$$\begin{aligned}
 WP_{\text{Co-60}} &= 2 \frac{\mu\text{Ci}}{\text{m}^2} * \left[ \frac{0.4 * \left( e^{(-3.15\text{E}+07 * (4.17\text{E}-09 + 1.46\text{E}-08))} - e^{(-0 * (4.17\text{E}-09 + 1.46\text{E}-08))} \right)}{-(4.17\text{E}-09 + 1.46\text{E}-08)} \right. \\
 &\quad \left. + \frac{0.6 * \left( e^{(-3.15\text{E}+07 * (4.17\text{E}-09 + 4.44\text{E}-10))} - e^{(-0 * (4.17\text{E}-09 + 4.44\text{E}-10))} \right)}{-(4.17\text{E}-09 + 4.44\text{E}-10)} \right] \text{ s} \\
 &= 5.43\text{E}+07 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^2}
 \end{aligned}$$

Table 1.1-E6

Radionuclide	Deposition ( $\mu\text{Ci}/\text{m}^2$ )	$\lambda_i$ ( $\text{s}^{-1}$ )	$t_1$ (s)	$t_2$ (s)	WP <sub>i</sub> – First Year ( $\mu\text{Ci}\cdot\text{s}/\text{m}^2$ )
Co-60	2	4.17E-09	0	3.15E+07	5.43E+07 <sup>a</sup>
Gd-148	1	2.36E-10	0	3.15E+07	2.88E+07 <sup>a</sup>
Sr-90	3	7.54E-10	0	3.15E+07	8.57E+07 <sup>a</sup>
Y-90	3	3.01E-06	0	3.15E+07	8.57E+07 <sup>b</sup>

<sup>a</sup> Values approximated using equations in Appendix F, Supplement 2.  
<sup>b</sup> Value from Turbo FRMAC 2011<sup>®</sup>. Calculations for daughters are more complicated than can be readily discussed here. See Appendix F, Supplements 1 and 2 for more information.

### E1.4.2 Calculating the Dp\_ExDP

Example Dp\_ExDP calculation for Co-60 and Dp\_ExDP values for the radionuclide mixture for the first-year time phase.

$$Dp\_ExDP_{\text{Co-60}} = 8.51\text{E-}06 \frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}\cdot\text{s}} * 0.82 * 5.43\text{E+}07 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^2} = 3.79\text{E+}02 \text{ mrem}$$

Table 1.1-E7

Radionuclide	Dp_ExDC <sup>a</sup> ( $\text{mrem}\cdot\text{m}^2/\text{s}\cdot\mu\text{Ci}$ )	GRF (unitless)	WP <sub>i</sub> – First Year ( $\mu\text{Ci}\cdot\text{s}/\text{m}^2$ )	Dp_ExDP First Year (mrem)
Co-60	8.51E-06	0.82	5.43E+07	3.79E+02
Gd-148	0	0.82	2.88E+07	0
Sr-90	6.07E-09	0.82	8.57E+07	4.27E-01
Y-90	4.07E-07	0.82	8.57E+07 <sup>b</sup>	2.86E+01

<sup>a</sup> Values from DCFPAK 2.0 (ICRP 60+).  
<sup>b</sup> Value from Turbo FRMAC 2011<sup>®</sup>.

### E1.5 Calculating Pl\_TDP and Dp\_TDP (Eq 1.1-5 & 1.1-8)

Example TDP calculations for Co-60 and TDP values for the radionuclide mixture for the first-year time phase.

$$Pl\_TDP_{60\text{Co}} = 3.17\text{E+}01 \text{ mrem} + 2.93\text{E-}01 \text{ mrem} = 3.20\text{E+}01 \text{ mrem}$$

$$Dp\_TDP_{60\text{Co}} = 7.27\text{E-}01 \text{ mrem} + 3.79\text{E+}02 \text{ mrem} = 3.80\text{E+}02 \text{ mrem}$$

Table 1.1-E8

Radionuclide	PI_InhDP First Year (mrem)	PI_ExDP First Year (mrem)	PI_TDP First Year (mrem)	Dp_InhDP First Year (mrem)	Dp_ExDP First Year (mrem)	Dp_TDP First Year (mrem)
Co-60	3.17E+01	2.93E-01	<b>3.20E+01</b>	7.27E-01	3.79E+02	<b>3.80E+02</b>
Gd-148	1.33E+04	0.00E+00	<b>1.33E+04</b>	3.06E+02	0.00E+00	<b>3.06E+02</b>
Sr-90	2.42E+02	3.64E-04	<b>2.42E+02</b>	5.59E+00	4.27E-01	<b>6.01</b>
Y-90	2.31E+00	2.93E-03	<b>2.32</b>	5.33E-02	2.86E+01	<b>2.87E+01</b>

## E1.6 Calculating 4Path\_MTDP (Equation 1.1-11)

The Four-Pathway Mixture Total Dose Parameter (4Path\_MTDP) includes the dose contributions from the plume-borne and ground-deposited radionuclide mixture, and is calculated by adding the PI\_TDPs and Dp\_TDPs for each radionuclide in the mixture.

Table 1.1-E9

Radionuclide	PI_TDP First Year (mrem)	Dp_TDP First Year (mrem)
Co-60	3.20E+01	3.80E+02
Gd-148	1.33E+04	3.06E+02
Sr-90	2.42E+02	6.01
Y-90	2.32	2.87E+01
<b>4Path_MTDP (mrem)</b>		<b>1.43E+04</b>

## E1.7 Calculating the Four-Pathway Derived Response Levels

### E1.7.1 Calculating 4Path\_DRL<sub>Ā</sub> (Equation 1.1-1)

Example 4Path\_DRL<sub>Ā</sub> calculation for Co-60 and 4Path\_DRL<sub>Ā</sub> values for the radionuclide mixture for the first-year time phase.

PAG = 2000 mrem

4Path\_MTDP = 1.43E+04 mrem

$$4Path\_DRL_{\bar{A}_{Co-60}} = \frac{2000 \text{ mrem} * 6.67E+02 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3}}{1.43E+04 \text{ mrem}} = 9.34E+01 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3}$$

**Table 1.1-E10**

Radionuclide	Integrated Air Activity ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )	1 <sup>st</sup> Year 4Path_DRL <sub><math>\bar{\lambda}</math></sub> <sup>a</sup> ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )
Co-60	6.67E+02	<b>9.34E+01</b>
Gd-148	3.33E+02	<b>4.67E+01</b>
Sr-90	1.0E+03	<b>1.40E+02</b>
Y-90	1.0E+03	<b>1.40E+02</b>

<sup>a</sup> Because this method uses a time integrated air activity, there is no need to account for decay during sample collection.

**E1.7.2 Calculating 4Path\_DRL<sub>Dp</sub> (Equation 1.1-2)**

Example 4Path\_DRL<sub>Dp</sub> calculation for Co-60 and 4Path\_DRL<sub>Dp</sub> values for the radionuclide mixture for the first-year time phase with an evaluation time ( $t_n$ ) of 0 (time of deposition).

PAG = 2000 mrem

4Path\_MTDP = 1.43+04 mrem

$$4Path\_DRL_{Dp_{Co-60}} = \frac{2000 \text{ mrem} * 2 \frac{\mu\text{Ci}}{\text{m}^2} * 1}{1.43\text{E}+04 \text{ mrem}} = 2.80\text{E}-01 \frac{\mu\text{Ci}}{\text{m}^2}$$

**Table 1.1-E11**

Radionuclide	Dp <sub>i,t0</sub> ( $\mu\text{Ci}/\text{m}^2$ )	WF <sub>tn</sub> <sup>a</sup> (unitless)	1 <sup>st</sup> Year 4Path_DRL <sub>Dp</sub> ( $\mu\text{Ci}/\text{m}^2$ )
Co-60	2	1	<b>0.28</b>
Gd-148	1	1	<b>0.14</b>
Sr-90	3	1	<b>0.42</b>
Y-90	3	1	<b>0.42</b>

<sup>a</sup> Because the evaluation time ( $t_n$ ) is zero, there is no adjustment for weathering.

**E1.8 Calculating DRLs for an Individual Organ**

The preceding calculations assume that the organ of interest is the whole body. The generic approach can be modified to calculate a Derived Response Level for a specific organ (e.g., skin, thyroid, etc.). To calculate DRLs for a specific organ, use the Dose Coefficients for the organ in question, calculate a MTDP for that organ and then compare that value to the organ-specific PAG to obtain the DRL.

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## EXAMPLE 2

**Problem: Calculate the Total Effective Dose Two-Pathway Deposition DRL for the First-Year Time Phase for the Following Mixture ( $t_n = 0$ ).**

Table 1.1-E12

Radionuclide	Deposition ( $\mu\text{Ci}/\text{m}^2$ )	$t_{1/2}$ (s)
Co-60	2	1.66E+08
Gd-148	1	2.93E+09
Sr-90	3	9.19E+08
Y-90	3	2.30E+05

To determine the  $2\text{Path\_DRL}_{\text{Dp}}$ , the following intermediate terms are needed:

- $\text{Dp\_ExDP}$  = Deposition External Dose Parameter for each radionuclide (mrem)
- $\text{Dp\_InhDP}$  = Deposition Inhalation Dose Parameter for each radionuclide (mrem)
- $\text{Dp\_TDP}$  = Deposition Total Dose Parameter for each radionuclide (mrem)

The  $\text{Dp\_TDP}$  for each radionuclide are then added to calculate the Two-Pathway Mixture Total Dose Parameter ( $2\text{Path\_MTDP}$ ).

**NOTE:** Values calculated using Turbo FRMAC<sup>®</sup> may differ from the values shown in this example because of truncation or rounding.

### E2.1 Calculating $\text{Dp\_InhDP}$ (Equation 1.1-9)

This calculation requires the Inhalation Dose Coefficient (InhDC), the Activity-Averaged Breathing Rate ( $\text{BR}_{\text{AA}}$ ) and the Resuspension Parameter (KP).

#### E2.1.1 Calculating the Resuspension Parameter (See Appendix F, Supplement 2, Equation 3c)

Example KP calculation for Co-60 and KP values for the radionuclide mixture for the first-year time phase.

$$\begin{aligned}
 KP_{\text{Co-60}} &= 2 \frac{\mu\text{Ci}}{\text{m}^2} * \left[ \begin{aligned} & \frac{1.0\text{E-}05 * \left( e^{(-3.15\text{E}+07*(4.17\text{E-}09+8.1\text{E-}07))} - e^{(-0*(4.17\text{E-}09+8.1\text{E-}07))} \right)}{- (4.17\text{E-}09 + 8.1\text{E-}07)} \\ & + \frac{7.0\text{E-}09 * \left( e^{(-3.15\text{E}+07*(4.17\text{E-}09+2.31\text{E-}08))} - e^{(-0*(4.17\text{E-}09+2.31\text{E-}08))} \right)}{- (4.17\text{E-}09 + 2.31\text{E-}08)} \\ & + \frac{1.0\text{E-}09 * \left( e^{(-3.15\text{E}+07*(4.17\text{E-}09))} - e^{(-0*(4.17\text{E-}09))} \right)}{- (4.17\text{E-}09)} \end{aligned} \right] \frac{\text{s}}{\text{m}} \\
 &= 2.49\text{E}+01 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3}
 \end{aligned}$$

Table 1.1-E13

Radionuclide	Deposition ( $\mu\text{Ci}/\text{m}^2$ )	$\lambda_i$ ( $\text{s}^{-1}$ )	$t_1$ (s)	$t_2$ (s)	$KP_i$ – First Year ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )
Co-60	2	4.17E-09	0	3.15E+07	2.49E+01 <sup>a</sup>
Gd-148	1	2.36E-10	0	3.15E+07	1.25E+01 <sup>a</sup>
Sr-90	3	7.54E-10	0	3.15E+07	3.76E+01 <sup>a</sup>
Y-90	3	3.01E-06	0	3.15E+07	3.75E+01 <sup>b</sup>

<sup>a</sup> Values approximated using equations in Appendix F, Supplement 2.  
<sup>b</sup> Value from Turbo FRMAC 2011<sup>®</sup>. Calculations for daughters are more complicated than can be readily discussed here. See Appendix F, Supplements 1 and 2 for more information.

### E2.1.2 Calculating the $Dp\_InhDP$

Example  $Dp\_InhDP$  calculation for Co-60 and  $Dp\_InhDP$  values for the radionuclide mixture for the first-year time phase.

$$Dp\_InhDP_{\text{Co-60}} = 1.14\text{E}+02 \frac{\text{mrem}}{\mu\text{Ci}} * 2.49\text{E}+01 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * 2.56\text{E-}04 \frac{\text{m}^3}{\text{s}} = 7.27\text{E-}01 \text{mrem}$$

Table 1.1-E14

Radionuclide	InhDC <sup>a</sup> (mrem/μCi)	KP <sub>i</sub> – First Year (μCi•s/m <sup>3</sup> )	Breathing Rate (Activity-averaged) <sup>b</sup> (m <sup>3</sup> /s)	Dp_InhDP First Year (mrem)
Co-60	1.14E+02	2.49E+01	2.56E-04	7.27E-01
Gd-148	9.55E+04	1.25E+01	2.56E-04	3.06E+02
Sr-90	5.81E+02	3.76E+01	2.56E-04	5.59
Y-90	5.55E+00	3.75E+01 <sup>c</sup>	2.56E-04	5.33E-02

<sup>a</sup> Value from DCFPAK 2.0 (ICRP 60+) for 1 micron particles. If particle size is known to be other than 1 micron, choose appropriate value.  
<sup>b</sup> Standard activity-averaged breathing rate.  
<sup>c</sup> Value from Turbo FRMAC 2011<sup>®</sup>.

## E2.2 Calculating Dp\_ExDP (Equation 1.1-10)

This calculation requires the External Dose Coefficient (ExDC), the Weathering Parameter (WP) and the Ground Roughness Factor (GRF).

### E2.2.1 Calculating the Weathering Parameter (See Appendix F, Supplement 2, Equation 6c)

Example WP calculation for Co-60 and WP values for the radionuclide mixture for the first-year time phase.

$$\begin{aligned}
 WP_{\text{Co-60}} &= 2 \frac{\mu\text{Ci}}{\text{m}^2} * \left[ \frac{0.4 * \left( e^{(-3.15\text{E}+07 * (4.17\text{E}-09 + 1.46\text{E}-08))} - e^{(-0 * (4.17\text{E}-09 + 1.46\text{E}-08))} \right)}{-(4.17\text{E}-09 + 1.46\text{E}-08)} \right. \\
 &\quad \left. + \frac{0.6 * \left( e^{(-3.15\text{E}+07 * (4.17\text{E}-09 + 4.44\text{E}-10))} - e^{(-0 * (4.17\text{E}-09 + 4.44\text{E}-10))} \right)}{-(4.17\text{E}-09 + 4.44\text{E}-10)} \right] \text{ s} \\
 &= 5.43\text{E}+07 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^2}
 \end{aligned}$$

Table 1.1-E15

Radionuclide	Deposition ( $\mu\text{Ci}/\text{m}^2$ )	$\lambda_i$ ( $\text{s}^{-1}$ )	$t_1$ (s)	$t_2$ (s)	$\text{WP}_i$ – First Year ( $\mu\text{Ci}\cdot\text{s}/\text{m}^2$ )
Co-60	2	4.17E-09	0	3.15E+07	5.43E+07 <sup>a</sup>
Gd-148	1	2.36E-10	0	3.15E+07	2.88E+07 <sup>a</sup>
Sr-90	3	7.54E-10	0	3.15E+07	8.57E+07 <sup>a</sup>
Y-90	3	3.01E-06	0	3.15E+07	8.57E+07 <sup>b</sup>

<sup>a</sup> Values approximated using equations in Appendix F, Supplement 2.  
<sup>b</sup> Value from Turbo FRMAC 2011<sup>®</sup>. Calculations for daughters are more complicated than can be readily discussed here. See Appendix F, Supplements 1 and 2 for more information.

### E2.2.2 Calculating the $Dp\_ExDP$

Example  $Dp\_ExDP$  calculation for Co-60 and  $Dp\_ExDP$  values for the radionuclide mixture for the first-year time phase.

$$Dp\_ExDP_{\text{Co-60}} = 8.51\text{E-}06 \frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}\cdot\text{s}} * 0.82 * 5.43\text{E+}07 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^2} = 3.79\text{E+}02 \text{ mrem}$$

Table 1.1-E16

Radionuclide	$Dp\_ExDC$ <sup>a</sup> ( $\text{mrem}\cdot\text{m}^2/\text{s}\cdot\mu\text{Ci}$ )	GRF (unitless)	$\text{WP}_i$ First Year ( $\mu\text{Ci}\cdot\text{s}/\text{m}^2$ )	$Dp\_ExDP$ First Year (mrem)
Co-60	8.51E-06	0.82	5.43E+07	3.79E+02
Gd-148	0	0.82	2.88E+07	0
Sr-90	6.07E-09	0.82	8.57E+07	4.27E-01
Y-90	4.07E-07	0.82	8.57E+07 <sup>b</sup>	2.86E+01

<sup>a</sup> Values from DCFPAK 2.0 (ICRP 60+).  
<sup>b</sup> Value from Turbo FRMAC 2011<sup>®</sup>.

### E2.3 Calculating $Dp\_TDP$ (Eq. 1.1-8)

Example TDP calculations for Co-60 and TDP values for the radionuclide mixture for the first-year time phase.

$$Dp\_TDP_{60\text{Co}} = 7.21\text{E-}01 \text{ mrem} + 3.79\text{E+}02 \text{ mrem} = 3.80\text{E+}02 \text{ mrem}$$

Table 1.1-E17

Radionuclide	Dp_InhDP First Year (mrem)	Dp_ExDP First Year (mrem)	Dp_TDP First Year (mrem)
Co-60	7.27E-01	3.79E+02	<b>3.80E+02</b>
Gd-148	3.06E+02	0	<b>3.06E+02</b>
Sr-90	5.59	4.27E-01	<b>6.01</b>
Y-90	5.29E-02	2.86E+01	<b>2.87E+01</b>

## E2.4 Calculating 2Path\_MTDP (Equation 1.1-12)

The Two-Pathway Mixture Total Dose Parameter (2Path\_MTDP) includes the dose contributions from the ground-deposited radionuclide mixture, and is calculated by summing the Dp\_TDP for all radionuclides in the mixture.

Table 1.1-E18

Radionuclide	Dp_TDP First Year (mrem)
Co-60	3.80E+02
Gd-148	3.06E+02
Sr-90	6.01
Y-90	2.87E+01
<b>2Path_MTDP =</b>	<b>7.21E+02</b>

## E2.5 Calculating the Two-Pathway Deposition Derived Response Level (Equation 1.1-4)

Example 2Path\_DRL<sub>Dp</sub> calculation for Co-60 and 2Path\_DRL<sub>Dp</sub> values for the radionuclide mixture for the first-year time phase with an evaluation time ( $t_n$ ) of 0 (time of deposition).

PAG = 2000 mrem

2Path\_MTDP = 7.21E+02 mrem

$$2Path\_DRL_{Dp_{Co-60}} = \frac{2000 \text{ mrem} * 2 \frac{\mu\text{Ci}}{\text{m}^2} * 1}{7.21\text{E}+02 \text{ mrem}} = 5.55 \frac{\mu\text{Ci}}{\text{m}^2}$$

**Table 1.1-E19**

<b>Radionuclide</b>	<b>Dp<sub>i,t0</sub></b> <b>(<math>\mu\text{Ci}/\text{m}^2</math>)</b>	<b>WF<sub>tn</sub><sup>a</sup></b> <b>(unitless)</b>	<b>1<sup>st</sup> Year 2Path_DRL<sub>Dp</sub></b> <b>(<math>\mu\text{Ci}/\text{m}^2</math>)</b>
Co-60	2	1	<b>5.55</b>
Gd-148	1	1	<b>2.78</b>
Sr-90	3	1	<b>8.33</b>
Y-90	3	1	<b>8.33</b>

<sup>a</sup> Because the evaluation time ( $t_n$ ) is zero, there is no adjustment for weathering.

## **E2.6 Calculating DRLs for an Individual Organ**

The preceding calculations assume that the organ of interest is the whole body. The generic approach can be modified to calculate a Derived Response Level for a specific organ (e.g., skin, thyroid, etc.). To calculate DRLs for a specific organ, the Dose Coefficients must be changed to that of the organ in question and then used to calculate an MTDP for that organ to be compared to an organ-specific PAG.

## **METHOD 1.2 DOSE AND EXPOSURE RATE DERIVED RESPONSE LEVELS (DRLS)**

### **Application**

This method has been developed to calculate Dose Rate DRLs and Exposure Rate DRLs for both Four-Pathway (4Path) and Two-Pathway (2Path) assessments of a radionuclide mixture.

The Dose Rate DRLs (4Path\_DRL<sub>DR</sub> and 2Path\_DRL<sub>DR</sub>):

Represent the external dose rate (mrem/hr, measured at 1 m above the ground) at a specific Evaluation Time ( $t_n$ ), from all radionuclides in a release that would produce a dose equal to the Protective Action Guide (PAG) over the time phase under consideration.

The Exposure Rate DRLs (4Path\_DRL<sub>XR</sub> and 2Path\_DRL<sub>XR</sub>):

Represent the external exposure rate (mR/hr, measured at 1 m above the ground) at a specific Evaluation Time ( $t_n$ ), from all radionuclides in a release that would produce a dose equal to the Protective Action Guide (PAG) over the time phase under consideration.

All DRLs derived in this Method are:

- 1) Derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA92), the Department of Homeland Security (DHS) (DHS08) or local Decision Makers. A projected or measured value greater than the DRL indicates the potential to exceed the PAG.
- 2) Used to create data products and define dose and/or exposure rates to help Decision Makers determine where protective actions (e.g., sheltering, evacuation, relocation) may be warranted.
- 3) Calculated using the appropriate Mixture Total Dose Parameter (4Path or 2Path) value calculated in Method 1.1.

### **Discussion**

The 4Path\_DRL<sub>DR</sub> and 4Path\_DRL<sub>XR</sub>:

- 1) Represent the external dose (or exposure) rate at which the total dose from all radionuclides in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.

- 2) Are based on the ratio of activities of each radionuclide in a mixture, not the individual activity values of those radionuclides.

The  $2\text{Path\_DRL}_{\text{DR}}$  and  $2\text{Path\_DRL}_{\text{XR}}$ :

- 1) Represent the external dose (or exposure) rate at which the total dose from all radionuclides in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.
- 2) Are based on the ratio of activities of each radionuclide in a mixture, not the individual activity values of those radionuclides.

## Assumptions

The following assumptions apply in addition to the Default Assumptions:

This method assumes that the dose (or exposure) rate measurements are taken after plume passage.

This method assumes that for Chronic Dose, 1 rad = 1 rem.

## Inputs

In addition to the Default Inputs, the following information is required to perform the calculations described in this method:

Four-Pathway Mixture Total Dose Parameter ( $4\text{Path\_MTDP}$ ) – Calculated using Method 1.1, Section 1.2.1.

or

Two-Pathway Mixture Total Dose Parameter ( $2\text{Path\_MTDP}$ ) – Calculated using Method 1.1, Section 1.2.2.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available and Decision Makers endorse their use.

## Outputs

### Final

The final output of this method is the  $4\text{Path\_DRL}_{\text{DR}}$ ,  $4\text{Path\_DRL}_{\text{XR}}$ ,  $2\text{Path\_DRL}_{\text{DR}}$  or  $2\text{Path\_DRL}_{\text{XR}}$  for a release of radioactive material.

$4Path\_DRL_{DR}$  = Four-Pathway Dose Rate Derived Response Level, the external dose rate, at time  $t_n$ , at which the total dose from all radionuclides in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ), mrem/hr.

$4Path\_DRL_{XR}$  = Four-Pathway Exposure Rate Derived Response Level, the external exposure rate, at time  $t_n$ , at which the total dose from all radionuclides in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ), mR/hr.

$2Path\_DRL_{DR}$  = Two-Pathway Dose Rate Derived Response Level, the external dose rate, at time  $t_n$ , at which the total dose from all radionuclides in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ), mrem/hr.

$2Path\_DRL_{XR}$  = Two-Pathway Exposure Rate Derived Response Level, the external exposure rate, at time  $t_n$ , at which the total dose from all radionuclides in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ), mR/hr.

Four-Pathway Assessment includes the dose contributions from the plume-borne and ground-deposited radionuclide mixture, while Two-Pathway Assessment only includes dose contribution from ground-deposited material.

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

$Dp\_MExDF$  = Deposition Mixture External Dose Factor for all radionuclides in the mixture of interest (mR/hr)

## Method 1.2.1 Dose Rate Derived Response Levels ( $4Path\_DRL_{DR}$ and $2Path\_DRL_{DR}$ )

### Calculation

The Dose Rate DRL relates a dose rate measurement from a survey instrument to the entire hazard posed by the deposition of a mixture of radioactive materials, over the time phase under consideration, relative to the regulatory PAG.

Calculating the Dose Rate DRL can be challenging, especially when considering complex radionuclide mixtures or a single radionuclide with multiple progeny in equilibrium. Therefore the user is urged to use a computer code, such as Turbo FRMAC<sup>®</sup>, to complete these calculations.

### 1.2.1.1 Calculating the Four-Pathway Dose Rate DRL

Equation 1.2-1 shows the final form of the  $4Path\_DRL_{DR,t_n,TP}$  calculation.

$$4Path\_DRL_{DR,t_n,TP} = PAG_{TP} * \frac{Dp\_MExDF_{t_n}}{4Path\_MTDP_{TP}} \quad (\text{Eq. 1.2-1})$$

$$\frac{\text{mrem}}{\text{hr}} = \text{mrem} * \frac{\frac{\text{mrem}}{\text{hr}}}{\text{mrem}}$$

where:

$4Path\_DRL_{DR, m, TP}$  = Four-Pathway Dose Rate Derived Response Level, the external dose rate, at time  $t_n$ , at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ), mrem/hr;

$PAG_{TP}$  = Protective Action Guide for total dose, as specified by the EPA, DHS or other Decision Makers, over the time phase under consideration ( $TP$ ), mrem;

$Dp\_MExDF_m$  = Deposition Mixture External Dose Factor, the external dose rate at time  $t_n$  from a radionuclide mixture deposited on the ground, mrem/hr; and

$4Path\_MTDP_{TP}$  = Four-Pathway Mixture Total Dose Parameter (See Method 1.1), mrem.

### 1.2.1.2 Calculating the Two-Pathway Dose Rate DRL

To calculate the Two-Pathway Dose Rate DRL, simply replace the  $4Path\_MTDP$  in the denominator of Equation 1.2-1 with the  $2Path\_MTDP$  as shown in Equation 1.2-2.

$$2Path\_DRL_{DR,t_n,TP} = PAG_{TP} * \frac{Dp\_MExDF_{t_n}}{2Path\_MTDP_{TP}} \quad (\text{Eq. 1.2-2})$$

$$\frac{\text{mrem}}{\text{hr}} = \text{mrem} * \frac{\frac{\text{mrem}}{\text{hr}}}{\text{mrem}}$$

where:

$2Path\_DRL_{DR, m, TP}$  = Two-Pathway Dose Rate Derived Response Level, the external dose rate, at time  $t_n$ , at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ), mrem/hr;

$PAG_{TP}$  = Protective Action Guide for total dose, as specified by the EPA, DHS or other Decision Makers, over the time phase under consideration ( $TP$ ), mrem;

$Dp\_MExDF_m$  = Deposition Mixture External Dose Factor, the external dose rate at time  $t_n$  from a radionuclide mixture deposited on the ground, mrem/hr; and

$2Path\_MTDP_{TP}$  = Two-Pathway Mixture Total Dose Parameter (See Method 1.1), mrem.

### 1.2.1.3 Calculating the Deposition Mixture External Dose Factor

The Deposition Mixture External Dose Factor ( $Dp\_MExDF$ ) for a specific Evaluation Time ( $t_n$ ) based on all the radionuclides in the mixture, is obtained by multiplying the areal activity at that time for each radionuclide by the associated Deposition External Dose Coefficient ( $Dp\_ExDC$ ) modified for ground roughness (GRF), summing those products for the entire mixture and then multiplying by the time-adjusted Weathering Factor.

$$Dp\_MExDF_{t_n} = WF_{t_n} * GRF * \sum_i (Dp_{i,t_n} * Dp\_ExDC_i) \quad (\text{Eq. 1.2-3})$$

$$\frac{\text{mrem}}{\text{hr}} = \text{unitless} * \text{unitless} * \sum \left( \frac{\mu\text{Ci}}{\text{m}^2} * \frac{\text{mrem} \cdot \text{m}^2}{\mu\text{Ci} \cdot \text{hr}} \right)$$

where:

$Dp\_MExDF_m$  = Deposition Mixture External Dose Factor, the external dose rate at time  $t_n$  from a radionuclide mixture deposited on the ground, mrem/hr;

$WF_m$  = Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind) from  $t_0$  (deposition) to  $t_n$  (evaluation time), unitless;

**NOTE:** See Appendix F, Supplement 2 for details on calculating WF.

$GRF$  = Ground Roughness Factor, a constant (0.82) that compensates for the fact that the external exposure is not coming from an infinite flat plane (An02), unitless;

$Dp_{i,m}$  = Deposition, the areal activity of radionuclide  $i$  at time  $t_n$ ,  $\mu\text{Ci}/\text{m}^2$ ; and

**NOTE:** See Appendix F, Supplement 1 for details on decay and in-growth calculations to estimate the activity at  $t_n$ .

**NOTE:** If deposition data is unavailable, it may be estimated from the integrated air activity of each radionuclide ( $\tilde{A}_i$ ). See Method 4.5.

$Dp\_ExDC_i$  = Deposition External Dose Coefficient, the external dose rate from radionuclide  $i$  per unit activity deposited on the ground,  $\text{mrem} \cdot \text{m}^2 / \mu\text{Ci} \cdot \text{hr}$ .

### 1.2.1.4 Comparing the $Dp\_MExDF$ to the PAG to Calculate DRLs

The  $Dp\_MExDF$  for the mixture at a specific time can be used to determine the Dose Rate DRL by comparing it to the PAG and the appropriate Mixture Total Dose Parameter ( $4Path\_MTDP$  or  $2Path\_MTDP$  from Method 1.1) value using the following equation.

$$4Path\_DRL_{DR,t_n} = PAG_{TP} * \frac{Dp\_MExDF_{t_n}}{4Path\_MTDP_{TP}} \quad (\text{Eq. 1.2-4a})$$

or

$$2Path\_DRL_{DR,t_n} = PAG_{TP} * \frac{Dp\_MExDF_{t_n}}{2Path\_MTDP_{TP}} \quad (\text{Eq. 1.2-4b})$$

$$\frac{\text{mrem}}{\text{hr}} = \text{mrem} * \frac{\text{hr}}{\text{mrem}}$$

where:

$4Path\_DRL_{DR, m, TP}$  = Four-Pathway Dose Rate Derived Response Level, the external dose rate, at time  $t_n$ , at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ), mrem/hr;

$PAG_{TP}$  = Protective Action Guide for total dose, as specified by the EPA, DHS or other Decision Makers, over the time phase under consideration ( $TP$ ), mrem;

$Dp\_MExDF_m$  = Deposition Mixture External Dose Factor, the external dose rate at time  $t_n$  from a radionuclide mixture deposited on the ground, mrem/hr;

$4Path\_MTDP_{TP}$  = Four-Pathway Mixture Total Dose Parameter (See Method 1.1), mrem;

$2Path\_DRL_{DR, m, TP}$  = Two-Pathway Dose Rate Derived Response Level, the external dose rate, at time  $t_n$ , at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ), mrem/hr; and

$2Path\_MTDP_{TP}$  = Two-Pathway Mixture Total Dose Parameter (See Method 1.1), mrem.

### Method 1.2.2 Exposure Rate Derived Response Levels (4Path\_DRL<sub>XR</sub> and 2Path\_DRL<sub>XR</sub>)

To calculate the Exposure Rate DRLs, simply divide the appropriate Dose Rate DRL by the Exposure to Dose Conversion Factor (XDCF).

$$4Path\_DRL_{XR,t_n} = \frac{4Path\_DRL_{DR,t_n}}{XDCF} \quad (\text{Eq. 1.2-5a})$$

or

$$2Path\_DRL_{XR,t_n} = \frac{2Path\_DRL_{DR,t_n}}{XDCF} \quad (\text{Eq. 1.2-5b})$$

$$\frac{\text{mR}}{\text{hr}} = \frac{\frac{\text{mrem}}{\text{hr}}}{\frac{\text{mrem}}{\text{mR}}}$$

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## EXAMPLE 1

**Problem: Calculate the Total Effective Dose Four-Pathway Dose Rate DRL for 1st-Year Time Phase for the Following Mixture ( $t_n=0$ ).**

**Table 1.2-E1**

Radionuclide	Deposition ( $\mu\text{Ci}/\text{m}^2$ )	$t_{1/2}$ (s)
Co-60	2	1.66E+08
Gd-148	1	2.93E+09
Sr-90	3	9.19E+08
Y-90	3	2.30E+05

To determine the  $4\text{Path\_DRL}_{\text{DR}}$ , the intermediate term for the Deposition Mixture External Dose Factor ( $\text{Dp\_MExDF}$ ) must first be calculated.

### E1.1 Calculating $\text{Dp\_MExDF}$ (Equation 1.2-3)

This calculation multiplies the Deposition External Dose Coefficient ( $\text{Dp\_ExDC}$ ) and the Ground Roughness Factor (GRF) by the time-adjusted areal activity ( $\text{Dp}_i$ ) for each radionuclide in the mixture and sums these products.

**Table 1.2-E2**

Radionuclide	$\text{Dp}_i$ ( $\mu\text{Ci}/\text{m}^2$ )	$\text{WF}_{\text{tn}}$ <sup>a</sup> (unitless)	$\text{Dp\_ExDC}$ <sup>b</sup> (mrem $\cdot\text{m}^2$ ) per ( $\mu\text{Ci}\cdot\text{hr}$ )	GRF (unitless)	$\text{WF}_{\text{tn}} \times \text{GRF} \times \text{Dp}_i \times \text{Dp\_ExDC}$ (mrem/hr)
Co-60	2	1	3.06E-02	0.82	5.02E-02
Gd-148	1	1	0	0.82	0
Sr-90	3	1	2.19E-05	0.82	5.40E-05
Y-90	3	1	1.47E-03	0.82	3.63E-03
$\text{Dp\_MExDF}$					5.39E-02

<sup>a</sup> Because the evaluation time ( $t_n$ ) is zero, there is no adjustment for weathering.  
<sup>b</sup> Values from DCFPAK 2.0 (ICRP 60+).

### E1.2 Calculating $4\text{Path\_DRL}_{\text{DR}}$ (Equation 1.2-1)

$4\text{Path\_DRL}_{\text{DR}}$  calculation for the radionuclide mixture for the first-year time phase.

Organ of Interest: Whole Body  
 PAG: 2000 mrem

4Path\_MTDP: 1.43E+04 mrem (from Method 1.1, Example 1, Table 1.1-E9)

$$4Path\_DRL_{DR} = \frac{2000 \text{ mrem} * 5.39\text{E-}02 \frac{\text{mrem}}{\text{hr}}}{1.43\text{E+}04 \text{ mrem}} = 7.55\text{E-}03 \frac{\text{mrem}}{\text{hr}}$$

This means that a dose rate of 7.55E-03 mrem/hr at the beginning of the first year indicates that the mixture has the potential to cause a Four Pathway Total Effective Dose (Internal + External) in excess of the PAG of 2000 mrem.

### **E1.3 Calculating the 4Path\_DRL<sub>DR</sub> for an Individual Organ**

The preceding calculations assume that the organ of interest is the whole body. The generic approach can be modified to calculate a Derived Response Level for a specific organ (e.g., skin, thyroid, etc.). To calculate the 4Path\_DRL<sub>DR</sub> for a specific organ, two changes from the default method must be made. The Deposition External Dose Coefficient (Dp\_ExDC) must be changed to that of the organ of interest and then used to calculate a Dp\_MExDF for that organ to be compared to an organ-specific PAG.

## EXAMPLE 2

**Problem: Calculate the Total Effective Dose Two-Pathway Dose Rate DRL for 1st-Year Time Phase for the Following Mixture ( $t_n=0$ ).**

Table 1.2-E3

Radionuclide	Deposition ( $\mu\text{Ci}/\text{m}^2$ )	$t_{1/2}$ (s)
Co-60	2	1.66E+08
Gd-148	1	2.93E+09
Sr-90	3	9.19E+08
Y-90	3	2.30E+05

To determine the  $2\text{Path\_DRL}_{\text{DR}}$ , the intermediate term for the Deposition Mixture External Dose Factor ( $\text{Dp\_MExDF}$ ) must first be calculated.

### E2.1 Calculating $\text{Dp\_MExDF}$ (Equation 1.2-3)

This calculation multiplies the Deposition External Dose Coefficient ( $\text{Dp\_ExDC}$ ) and the Ground Roughness Factor (GRF) by the time-adjusted areal activity ( $\text{Dp}_i$ ) for each radionuclide in the mixture and sums these products.

Table 1.2-E4

Radionuclide	$\text{Dp}_i$ ( $\mu\text{Ci}/\text{m}^2$ )	$\text{WF}_{\text{tn}}$ <sup>a</sup> (unitless)	$\text{Dp\_ExDC}$ <sup>b</sup> (mrem $\cdot\text{m}^2$ ) per ( $\mu\text{Ci}\cdot\text{hr}$ )	GRF (unitless)	$\text{WF}_{\text{tn}} \times \text{GRF} \times \text{Dp}_i \times \text{Dp\_ExDC}$ (mrem/hr)
Co-60	2	1	3.06E-02	0.82	5.02E-02
Gd-148	1	1	0	0.82	0
Sr-90	3	1	2.19E-05	0.82	5.40E-05
Y-90	3	1	1.47E-03	0.82	3.63E-03
$\text{Dp\_MExDF}$					5.39E-02

<sup>a</sup> Because the evaluation time ( $t_n$ ) is zero, there is no adjustment for weathering.  
<sup>b</sup> Values from DCFPAK 2.0 (ICRP 60+).

### E2.2 Calculating $2\text{Path\_DRL}_{\text{DR}}$ (Equation 1.2-2)

$2\text{Path\_DRL}_{\text{DR}}$  calculation for the radionuclide mixture for the first-year time phase.

Organ of Interest: Whole Body  
 PAG: 2000 mrem

2Path\_MTDP: 7.21E+02 mrem (from Method 1.1, Example 2, Table 1.1-E18)

$$2Path\_DRL_{DR} = \frac{2000 \text{ mrem} * 5.39E-02 \frac{\text{mrem}}{\text{hr}}}{7.21E+02 \text{ mrem}} = 0.15 \frac{\text{mrem}}{\text{hr}}$$

This means that an exposure rate of 0.15 mrem/hr at the beginning of the first year indicates that the mixture has the potential to cause a Two Pathway Total Effective Dose (Internal + External) in excess of the PAG of 2000 mrem.

### **E2.3 Calculating the 2Path\_DRL<sub>DR</sub> for an Individual Organ**

The preceding calculations assume that the organ of interest is the whole body. The generic approach can be modified to calculate a Derived Response Level for a specific organ (e.g., skin, thyroid, etc.). To calculate the 2Path\_DRL<sub>DR</sub> for a specific organ, two changes from the default method must be made. The Deposition External Dose Coefficient (Dp\_ExDC) must be changed to that of the organ of interest and then used to calculate a Dp\_MExDF for that organ to be compared to an organ-specific PAG.

## METHOD 1.3 ALPHA DERIVED RESPONSE LEVEL

### Application

This method has been developed to calculate an Alpha Derived Response Level for a release of radioactive material and the resultant deposition. Alpha DRLs can be based upon either integrated air activity ( $4\text{Path\_DRL}_{\alpha,\bar{A}}$  or  $2\text{Path\_DRL}_{\alpha,\bar{A}}$ ) or areal activity ( $4\text{Path\_DRL}_{\alpha,\text{Dp}}$  or  $2\text{Path\_DRL}_{\alpha,\text{Dp}}$ ).

The  $4\text{Path\_DRL}_{\alpha,\bar{A}}$ :

- 1) Represents the integrated air alpha activity ( $\mu\text{Ci}_{\alpha}\cdot\text{s}/\text{m}^3$ ), present in a release at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.
- 2) Is calculated using the Four-Pathway Air Derived Response Level calculated in Method 1.1, Section 1.3.1.

The  $4\text{Path\_DRL}_{\alpha,\text{Dp},t_n}$ :

- 1) Represents the areal alpha activity ( $\mu\text{Ci}_{\alpha}/\text{m}^2$ ), at a specific Evaluation Time ( $t_n$ ), present in a release at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.
- 2) Is calculated using the Four-Pathway Deposition Derived Response Level value calculated in Method 1.1, Section 1.3.2.

The  $2\text{Path\_DRL}_{\alpha,\bar{A}}$ :

- 1) Represents the integrated air alpha activity ( $\mu\text{Ci}_{\alpha}\cdot\text{s}/\text{m}^3$ ), present in a release at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.
- 2) Is calculated using the Two-Pathway Air Derived Response Level calculated in Method 1.1, Section 1.3.3.

The  $2\text{Path\_DRL}_{\alpha,\text{Dp},t_n}$ :

- 1) Represents the areal alpha activity ( $\mu\text{Ci}_{\alpha}/\text{m}^2$ ), at a specific Evaluation Time ( $t_n$ ), present in a release at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.

- 2) Is calculated using the Two-Pathway Deposition Derived Response Level value calculated in Method 1.1, Section 1.3.4.

All DRLs developed in this Method are:

- 1) Derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA92), the Department of Homeland Security (DHS) (DHS08) or local Decision Makers. A projected or measured value greater than the DRL indicates the potential to exceed the PAG.
- 2) Used to create data products and define activity levels for the mixture to help Decision Makers determine where protective actions (e.g., sheltering, evacuation, relocation) may be warranted.

It is not appropriate for the FRMAC Assessment Division to calculate instrument-specific Alpha DRLs in units of counts per minute (cpm) per a given probe area (e.g., 550  $\alpha$  cpm/100 cm<sup>2</sup>) for a given radionuclide mixture because it is difficult to foresee what instruments will be used by monitoring personnel. Rather, the value calculated by this method is an intermediate value and must be adjusted for conditions in the field (e.g., instrument efficiency, active probe area, surface conditions, and environmental conditions). Therefore, the FRMAC Monitoring and Sampling Division is responsible for converting between the units presented in this method ( $\mu\text{Ci}_\alpha \cdot \text{s}/\text{m}^3$  or  $\mu\text{Ci}/\text{m}^2$ ) and the units generated in the field (i.e., cpm/filter or cpm/100 cm<sup>2</sup>).

## Discussion

The Alpha DRL is a value obtained by multiplying the calculated DRL for each radionuclide present in a mixture by the alpha yield ( $Y_\alpha$ , alpha activity per nuclear transformation) and then summing those products over the entire mixture. Because the DRL for each radionuclide is determined using a PAG, this summation represents the number of “alpha events” that would indicate the presence of a mixture of radionuclides that is projected to cause an individual to receive a dose equal to the PAG.

Calculating an Alpha DRL for a single radionuclide or a radionuclide mixture is complicated by factors that affect the detection efficiency (alpha counts per nuclear transformation), including:

- Energy variance: varying energies (and corresponding efficiencies) of alpha emissions from different radionuclides;
- Self-absorption: the alpha detection efficiency is likely to be lower for clumps of source material than for finely divided source material;
- Surface characteristics: e.g., soil, pavement, and grass, because these factors affect the fraction of the alpha radiation that is shielded; and
- Environmental conditions: e.g., rain and dust, due to shielding effects.

## Assumptions

The following assumptions apply in addition to the Default Assumptions:

This method assumes that detection efficiencies and probe area correction factors will be applied by Monitoring and Sampling Division personnel for the specific instrumentation used in the field.

## Inputs

In addition to the Default Inputs, the following information is used to perform the calculations described in this method:

- 1) For each radionuclide in the mixture, one of the following must be known:
  - 1) Four-Pathway Air Derived Response Level, (See Method 1.1),
  - 2) Four-Pathway Deposition Derived Response Level, (See Method 1.1)
  - 3) Two-Pathway Air Derived Response Level, (See Method 1.1), or
  - 4) Two-Pathway Deposition Derived Response Level, (See Method 1.1).

**NOTE:** The same type must be used for the each radionuclide in the mixture.

- 2) Alpha Yield, the alpha activity per total (nuclear transformation) activity of radionuclide  $i$ ,  $\mu\text{Ci}_\alpha/\mu\text{Ci}_{\text{nt}}$ .

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available and Decision Makers endorse their use.

## Outputs

### Final

The final output of this method is the Alpha Derived Response Level for a release of radioactive material.

$4\text{Path\_DRL}_{\alpha,\bar{A}}$  = Four-Pathway Air Alpha Derived Response Level, the integrated air alpha activity of the mixture at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration,  $\mu\text{Ci}_\alpha \cdot \text{s}/\text{m}^3$ .

$4\text{Path\_DRL}_{\alpha,\text{Dp},t_n}$  = Four-Pathway Deposition Alpha Derived Response Level, the areal alpha activity of the mixture, at time  $t_n$ , of the mixture at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration,  $\mu\text{Ci}_\alpha/\text{m}^2$ .

$2\text{Path\_DRL}_{\alpha,\bar{A}}$  = Two-Pathway Air Alpha Derived Response Level, the integrated air alpha activity of the mixture at which the total dose from *all*

*radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration,  $\mu\text{Ci}_\alpha \cdot \text{s}/\text{m}^3$ .

$2\text{Path\_DRL}_{\alpha, \text{Dp}, \text{tn}}$  = Two-Pathway Deposition Alpha Derived Response Level, the areal alpha activity of the mixture, at time  $t_n$ , of the mixture at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration,  $\mu\text{Ci}_\alpha/\text{m}^2$ .

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

None.

## Method 1.3.1 Four-Pathway Air Alpha Derived Response Level ( $4\text{Path\_DRL}_{\alpha, \tilde{A}}$ )

### Calculation

The  $4\text{Path\_DRL}_{\alpha, \tilde{A}}$  specifies the integrated air alpha activity of the mixture at which the total dose from all radionuclides in a release would equal the PAG over the time phase under consideration.

$$4\text{Path\_DRL}_{\alpha, \tilde{A}, TP} = \sum_i \left( 4\text{Path\_DRL}_{\tilde{A}, i, TP} * Y_{\alpha, i} \right) \quad (\text{Eq. 1.3-1})$$

$$\frac{\mu\text{Ci}_\alpha \cdot \text{s}}{\text{m}^3} = \frac{\mu\text{Ci}_{\text{nt}} \cdot \text{s}}{\text{m}^3} * \frac{\mu\text{Ci}_\alpha}{\mu\text{Ci}_{\text{nt}}}$$

where:

$4\text{Path\_DRL}_{\alpha, \tilde{A}, TP}$  = Four-Pathway Air Alpha Derived Response Level, the integrated air alpha activity of the mixture at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ),  $\mu\text{Ci}_\alpha \cdot \text{s}/\text{m}^3$ ;

$4\text{Path\_DRL}_{\tilde{A}, i, TP}$  = Four-Pathway Air Derived Response Level, the integrated air activity ( $\tilde{A}$ ) of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ),  $\mu\text{Ci} \cdot \text{s}/\text{m}^3$ ; and

$Y_{\alpha i}$  = Yield, the alpha activity per total (nuclear transformation) activity of radionuclide  $i$ ,  $\mu\text{Ci}_\alpha/\mu\text{Ci}_{\text{nt}}$ .

## Method 1.3.2 Four-Pathway Deposition Alpha Derived Response Level (4Path\_DRL<sub>α,Dp</sub>)

### Calculation

The 4Path\_DRL<sub>α,Dp</sub> specifies the areal alpha activity of the mixture at which the total dose from all radionuclides in a release would equal the PAG over the time phase under consideration.

$$4Path\_DRL_{\alpha,Dp,t_n,TP} = \sum_i \left( 4Path\_DRL_{Dp,i,t_n,TP} * Y_{\alpha,i} \right) \quad (\text{Eq. 1.3-2})$$

$$\frac{\mu\text{Ci}_\alpha}{\text{m}^2} = \frac{\mu\text{Ci}_{\text{nt}}}{\text{m}^2} * \frac{\mu\text{Ci}_\alpha}{\mu\text{Ci}_{\text{nt}}}$$

where:

4Path\_DRL<sub>α,Dp,m, TP</sub> = Four-Pathway Deposition Alpha Derived Response Level, the areal alpha activity of the mixture, at time  $t_n$ , at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration (TP),  $\mu\text{Ci}_\alpha/\text{m}^2$ ;

4Path\_DRL<sub>Dp,i,m, TP</sub> = Four-Pathway Deposition Derived Response Level, the areal activity, at time  $t_n$ , of radionuclide  $i$  at which the total dose from all radionuclides in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration (TP),  $\mu\text{Ci}/\text{m}^2$ ; and

$Y_{\alpha,i}$  = Yield, the alpha activity per total (nuclear transformation) activity of radionuclide  $i$ ,  $\mu\text{Ci}_\alpha/\mu\text{Ci}_{\text{nt}}$ .

## Method 1.3.3 Two-Pathway Air Alpha Derived Response Level (2Path\_DRL<sub>α,Ã</sub>)

### Calculation

The 2Path\_DRL<sub>α,Ã</sub> specifies the integrated air alpha activity of the mixture at which the total dose from all radionuclides in a release would equal the PAG over the time phase under consideration.

$$2Path\_DRL_{\alpha,\tilde{A},TP} = \sum_i \left( 2Path\_DRL_{\tilde{A},i,TP} * Y_{\alpha,i} \right) \quad (\text{Eq. 1.3-3})$$

$$\frac{\mu\text{Ci}_\alpha \cdot \text{s}}{\text{m}^3} = \frac{\mu\text{Ci}_{\text{nt}} \cdot \text{s}}{\text{m}^3} * \frac{\mu\text{Ci}_\alpha}{\mu\text{Ci}_{\text{nt}}}$$

where:

$2Path\_DRL_{\alpha,\tilde{A},TP}$  = Two-Pathway Air Alpha Derived Response Level, the integrated air alpha activity of the mixture at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration (*TP*),  $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ ;

$2Path\_DRL_{\tilde{A},i,TP}$  = Two-Pathway Air Derived Response Level, the integrated air activity ( $\tilde{A}$ ) of radionuclide *i* at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration (*TP*),  $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ ; and

$Y_{\alpha i}$  = Yield, the alpha activity per total (nuclear transformation) activity of radionuclide *i*,  $\mu\text{Ci}_{\alpha}/\mu\text{Ci}_{\text{nt}}$ .

### Method 1.3.4 Two-Pathway Deposition Alpha Derived Response Level ( $2Path\_DRL_{\alpha,Dp}$ )

#### Calculation

The  $2Path\_DRL_{\alpha,Dp}$  specifies the areal alpha activity of the mixture at which the total dose from all radionuclides in a release would equal the PAG over the time phase under consideration.

$$2Path\_DRL_{\alpha,Dp,t_n,TP} = \sum_i \left( 2Path\_DRL_{Dp,i,t_n,TP} * Y_{\alpha,i} \right) \quad (\text{Eq. 1.3-4})$$

$$\frac{\mu\text{Ci}_{\alpha}}{\text{m}^2} = \frac{\mu\text{Ci}_{\text{nt}}}{\text{m}^2} * \frac{\mu\text{Ci}_{\alpha}}{\mu\text{Ci}_{\text{nt}}}$$

where:

$2Path\_DRL_{\alpha,Dp,t_n,TP}$  = Two-Pathway Deposition Alpha Derived Response Level, the areal alpha activity of the mixture, at time  $t_n$ , at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration (*TP*),  $\mu\text{Ci}/\text{m}^2$ ;

$2Path\_DRL_{Dp,i,t_n,TP}$  = Two-Pathway Deposition Derived Response Level, the areal activity, at time  $t_n$ , of radionuclide *i* at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration (*TP*),  $\mu\text{Ci}/\text{m}^2$ ; and

$Y_{\alpha i}$  = Yield, the alpha activity per total (nuclear transformation) activity of radionuclide *i*,  $\mu\text{Ci}_{\alpha}/\mu\text{Ci}_{\text{nt}}$ .

## EXAMPLE 1

**Problem:** Calculate the Four-Pathway Air Alpha DRL for the Start of the 1<sup>st</sup>-Year Time Phase for the following mixture (evaluated at  $t_n = 0$ ):

Table 1.3-E1

Radionuclide	Integrated Air Activity ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )	Deposition ( $\mu\text{Ci}/\text{m}^2$ )	$t_{1/2}$ (s)
Co-60	6.67E+02	2	1.66E+08
Gd-148	3.33E+02	1	2.93E+09
Sr-90	1.0E+03	3	9.19E+08
Y-90	1.0E+03	3	2.30E+05

This calculation requires the Four-Pathway Air Derived Response Level ( $4\text{Path\_DRL}_{\bar{A}}$ ) for each radionuclide from the mixture for the early phase. Table 1.3-E2 shows the values calculated using Method 1.1.

Table 1.3-E2

Radionuclide	Integrated Air Activity ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )	$\text{WF}_{t_n}$	Alpha Yield	1 <sup>st</sup> -Year $4\text{Path\_DRL}_{\bar{A}}$ ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )
Co-60	6.67E+02	1	0	9.34E+01
Gd-148	3.33E+02	1	1	4.78E+01
Sr-90	1.0E+03	1	0	1.40E+02
Y-90	1.0E+03	1	0	1.40E+02

Because the evaluation time  $t_n$  is zero, there is no need to adjust for radioactive decay or weathering to determine the DRL at the start of the time phase.

Applying these values in equation 1.3-1 yields:

$$\begin{aligned}
 4\text{Path\_DRL}_{\alpha,\bar{A}} &= \left( 4.78\text{E}+01 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * 1 \frac{\mu\text{Ci}_{\alpha}}{\mu\text{Ci}} \right) \\
 &= 4.78\text{E}+01 \frac{\mu\text{Ci}_{\alpha}\cdot\text{s}}{\text{m}^3}
 \end{aligned}$$

**NOTE:** Co-60, Sr-90 and Y-90 do not have an alpha decay component and are therefore not included in this calculation.

**EXAMPLE 2**

**Problem: Calculate the Two-Pathway Deposition Alpha DRL for the Start of the 1<sup>st</sup>-Year Time Phase for the following mixture (evaluated at  $t_n = 0$ ):**

**Table 1.3-E3**

Radionuclide	Deposition ( $\mu\text{Ci}/\text{m}^2$ )	$t_{1/2}$ (s)
Co-60	2	1.66E+08
Gd-148	1	2.93E+09
Sr-90	3	9.19E+08
Y-90	3	2.30E+05

This calculation requires the Two-Pathway Deposition Derived Response Level ( $2\text{Path\_DRL}_{Dp}$ ) for each radionuclide from the mixture for the early phase. Table 1.3-E4 shows the values calculated using Method 1.1.

**Table 1.3-E4**

Radionuclide	Deposition ( $\mu\text{Ci}/\text{m}^2$ )	$WF_{tn}$	Alpha Yield	1 <sup>st</sup> -Year $2\text{Path\_DRL}_{Dp}$ ( $\mu\text{Ci}/\text{m}^2$ )
Co-60	2	1	0	5.55
Gd-148	1	1	1	2.78
Sr-90	3	1	0	8.33
Y-90	3	1	0	8.33

Because the evaluation time  $t_n$  is zero, there is no need to adjust for radioactive decay or weathering to determine the DRL at the start of the time phase.

Applying these values in equation 1.3-3 yields:

$$\begin{aligned}
 2\text{Path\_DRL}_{\alpha, Dp} &= \left( 2.78 \frac{\mu\text{Ci}}{\text{m}^2} * 1 \frac{\mu\text{Ci}_{\alpha}}{\mu\text{Ci}} \right) \\
 &= 2.78 \frac{\mu\text{Ci}_{\alpha}}{\text{m}^2}
 \end{aligned}$$

**NOTE:** Co-60, Sr-90 and Y-90 do not have an alpha decay component and are therefore not included in this calculation.

## METHOD 1.4 BETA DERIVED RESPONSE LEVEL

### Application

This method has been developed to calculate a Beta Derived Response Level for a release of radioactive material and the resultant deposition. DRLs can be based upon either integrated air activity ( $4Path\_DRL_{\beta,\bar{A}}$  or  $2Path\_DRL_{\beta,\bar{A}}$ ) or areal activity ( $4Path\_DRL_{\beta,Dp}$  or  $2Path\_DRL_{\beta,Dp}$ ).

The  $4Path\_DRL_{\beta,\bar{A}}$ :

- 1) Represents the integrated air beta activity ( $\mu Ci_{\beta}\cdot s/m^3$ ), present in a release at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.
- 2) Is calculated using the Four-Pathway Air Activity Derived Response Level calculated in Method 1.1, Section 1.3.1.

The  $4Path\_DRL_{\beta,Dp,t_n}$ :

- 1) Represents the areal beta activity ( $\mu Ci_{\beta}/m^2$ ), at a specific Evaluation Time ( $t_n$ ), present in a release at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.
- 2) Is calculated using the Four-Pathway Deposition Derived Response Level value calculated in Method 1.1, Section 1.3.2.

The  $2Path\_DRL_{\beta,\bar{A}}$ :

- 1) Represents the integrated air beta activity ( $\mu Ci_{\beta}\cdot s/m^3$ ), present in a release at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.
- 2) Is calculated using the Four-Pathway Air Activity Derived Response Level calculated in Method 1.1, Section 1.3.3.

The  $2Path\_DRL_{\beta,Dp,t_n}$ :

- 1) Represents the areal beta activity ( $\mu Ci_{\beta}/m^2$ ), at a specific Evaluation Time ( $t_n$ ), present in a release at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.

- 2) Is calculated using the Two-Pathway Deposition Derived Response Level value calculated in Method 1.1, Section 1.3.4.

All DRLs developed in this Method are:

- 1) Derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA92), the Department of Homeland Security (DHS) (DHS08) or local Decision Makers. A projected or measured value greater than the DRL indicates the potential to exceed the PAG.
- 2) Used to create data products and define activity levels for the mixture to help Decision Makers determine where protective actions (e.g., sheltering, evacuation, relocation) may be warranted.

It is not appropriate for the FRMAC Assessment Division to calculate instrument-specific Beta DRLs in units of counts per minute (cpm) per a given probe area (e.g., 550  $\beta^-$  cpm/100  $\text{cm}^2$ ) for a given radionuclide mixture because it is difficult to foresee what instruments will be used by monitoring personnel. Rather, the value calculated by this method is an intermediate value and must be adjusted for conditions in the field (e.g., instrument efficiency, active probe area, surface conditions, and environmental conditions). Therefore, the FRMAC Monitoring and Sampling Division is responsible for converting between the units presented in this method ( $\mu\text{Ci}\beta\cdot\text{s}/\text{m}^3$  or  $\mu\text{Ci}/\text{m}^2$ ) and the units generated in the field (i.e., cpm/filter or cpm/100  $\text{cm}^2$ ).

## Discussion

The Beta DRL is a value obtained by multiplying the calculated DRL for each radionuclide present in a mixture by the beta yield ( $Y_\beta$ , beta activity per nuclear transformation) and then summing those products over the entire mixture. Because the DRL for each radionuclide is determined using a PAG, this summation represents the number of “beta events” that would indicate the presence of a mixture of radionuclides that is projected to cause an individual to receive a dose equal to the PAG.

Calculating a Beta DRL for a single radionuclide or a radionuclide mixture is complicated by factors that affect the detection efficiency (beta counts per nuclear transformation), including:

- Beta decay spectrum: beta particles are emitted over an energy range from zero up to a maximum value that is characteristic of the excited nucleus. Some fraction of the beta particles emitted by a radionuclide is not detectable because the beta particles lack sufficient energy to penetrate the detector’s window and are unable to enter the detector’s sensitive volume. Therefore there is a threshold energy below which beta particles are not detectable. FRMAC Assessment uses a default energy threshold of 70 keV to determine which decays to include in this calculation;
- Energy variance: varying maximum energies (and corresponding efficiencies) of beta emissions from different radionuclides;
- Detector characteristics: The mass thickness ( $\text{mg}/\text{cm}^2$ ) of the detector’s window and walls varies between detector types and manufacturers. Therefore the detectable

fraction of the beta particle energy spectrum varies with the detector and with the window condition (i.e., open vs. closed);

- Surface characteristics: e.g., soil, pavement, and grass, because these factors affect the fraction of the beta radiation that is shielded or backscattered; and
- Environmental conditions: e.g., rain and dust, due to shielding effects.

The Turbo FRMAC<sup>®</sup> software package and the associated radiological database include contributions from standard beta decay and other modes of decay (e.g., internal conversion electrons) which produce beta-like particles that would be interpreted by detectors as “beta decay.” Each of these beta-like particles that exceed the threshold energy is included in the DRL calculation.

## Assumptions

The following assumptions apply in addition to the Default Assumptions:

This method assumes that detection efficiencies and probe area correction factors will be applied by Monitoring and Sampling Division personnel for the specific instrumentation used in the field.

## Inputs

In addition to the Default Inputs, the following information is required to perform the calculations described in this method:

- 1) For each radionuclide in the mixture, one of the following must be known:
  - Four-Pathway Air Derived Response Level, (See Method 1.1),
  - Four-Pathway Deposition Derived Response Level, (See Method 1.1), or
  - Two-Pathway Deposition Derived Response Level, (See Method 1.1).

**NOTE:** The same type must be used for each radionuclide in the mixture.

- 2) Beta Yield, the beta activity per total (nuclear transformation) activity of radionuclide *i*,  $\mu\text{Ci}_\beta/\mu\text{Ci}_{\text{nt}}$ .

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available and Decision Makers endorse their use.

## Outputs

### Final

The final output of this method is the Beta Derived Response Level for a release of radioactive material.

- $4Path\_DRL_{\beta,\tilde{A}}$  = Four-Pathway Air Beta Derived Response Level, the integrated air beta activity of the mixture at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration,  $\mu Ci_{\beta} \cdot s/m^3$ .
- $4Path\_DRL_{\beta,Dp,tn}$  = Four-Pathway Deposition Beta Derived Response Level, the areal beta activity of the mixture, at time  $t_n$ , at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration,  $\mu Ci_{\beta}/m^2$ .
- $2Path\_DRL_{\beta,\tilde{A}}$  = Two-Pathway Air Beta Derived Response Level, the integrated air beta activity of the mixture at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration,  $\mu Ci_{\beta} \cdot s/m^3$ .
- $2Path\_DRL_{\beta,Dp,tn}$  = Two-Pathway Deposition Beta Derived Response Level, the areal beta activity of the mixture, at time  $t_n$ , at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration,  $\mu Ci_{\beta}/m^2$ .

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

None

## Method 1.4.1 Four-Pathway Air Beta Derived Response Level ( $4Path\_DRL_{\beta,\tilde{A}}$ )

### Calculation

The  $4Path\_DRL_{\beta,\tilde{A}}$  specifies the integrated air beta activity of the mixture at which the total dose from all radionuclides in a release would equal the PAG over the time phase under consideration.

$$4Path\_DRL_{\beta,\tilde{A},TP} = \sum_i \left( 4Path\_DRL_{\tilde{A},i,TP} * Y_{\beta,i} \right) \quad (\text{Eq. 1.4-1})$$

$$\frac{\mu Ci_{\beta} \cdot s}{m^3} = \frac{\mu Ci_{nt} \cdot s}{m^3} * \frac{\mu Ci_{\beta}}{\mu Ci_{nt}}$$

where:

$4Path\_DRL_{\beta,\tilde{A},TP}$  = Four-Pathway Air Beta Derived Response Level, the integrated air beta activity of the mixture at which the total dose from *all radionuclides* in a release (considering plume and ground dose

pathways) would equal the PAG over the time phase under consideration ( $TP$ ),  $\mu\text{Ci}_\beta \cdot \text{s}/\text{m}^3$ .

$4Path\_DRL_{\bar{A},i,TP}$  = Four-Pathway Air Derived Response Level, the integrated air activity ( $\bar{A}$ ) of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ),  $\mu\text{Ci} \cdot \text{s}/\text{m}^3$ ; and

$Y_{\beta i}$  = Yield, the beta activity per total (nuclear transformation) activity of radionuclide  $i$ ,  $\mu\text{Ci}_\beta/\mu\text{Ci}_{nt}$ .

## Method 1.4.2 Four-Pathway Deposition Beta Derived Response Level ( $4Path\_DRL_{\beta,Dp}$ )

### Calculation

The  $4Path\_DRL_{\beta,Dp}$  specifies the areal beta activity of the mixture at which the total dose from all radionuclides in a release would equal the PAG over the time phase under consideration.

$$4Path\_DRL_{\beta,Dp,t_n,TP} = \sum_i \left( 4Path\_DRL_{Dp,i,t_n,TP} * Y_{\beta,i} \right) \quad (\text{Eq. 1.4-2})$$

$$\frac{\mu\text{Ci}_\beta}{\text{m}^2} = \frac{\mu\text{Ci}_{nt}}{\text{m}^2} * \frac{\mu\text{Ci}_\beta}{\mu\text{Ci}_{nt}}$$

where:

$4Path\_DRL_{\beta,Dp,t_n,TP}$  = Four-Pathway Deposition Beta Derived Response Level, the areal beta activity of the mixture, at time  $t_n$ , at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ),  $\mu\text{Ci}_\beta/\text{m}^2$ ;

$4Path\_DRL_{Dp,i,t_n,TP}$  = Four-Pathway Deposition Derived Response Level, the areal activity, at time  $t_n$ , of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ),  $\mu\text{Ci}_{nt}/\text{m}^2$ ; and

$Y_{\beta i}$  = Yield, the beta activity per total (nuclear transformation) activity of radionuclide  $i$ ,  $\mu\text{Ci}_\beta/\mu\text{Ci}_{nt}$ .

### Method 1.4.3 Two-Pathway Air Beta Derived Response Level (2Path\_DRL<sub>β,Ã</sub>)

#### Calculation

The 2Path\_DRL<sub>β,Ã</sub> specifies the integrated air beta activity of the mixture at which the total dose from all radionuclides in a release would equal the PAG over the time phase under consideration.

$$2Path\_DRL_{\beta,\tilde{A},TP} = \sum_i \left( 2Path\_DRL_{\tilde{A},i,TP} * Y_{\beta,i} \right) \quad (\text{Eq. 1.4-3})$$

$$\frac{\mu\text{Ci}_{\beta} \cdot \text{s}}{\text{m}^3} = \frac{\mu\text{Ci}_{\text{nt}} \cdot \text{s}}{\text{m}^3} * \frac{\mu\text{Ci}_{\beta}}{\mu\text{Ci}_{\text{nt}}}$$

where:

2Path\_DRL<sub>β,Ã,TP</sub> = Two-Pathway Air Beta Derived Response Level, the integrated air beta activity of the mixture at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration (TP), μCi<sub>β</sub>•s/m<sup>3</sup>.

2Path\_DRL<sub>Ã,i,TP</sub> = Two-Pathway Air Derived Response Level, the integrated air activity (Ã) of radionuclide *i* at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration (TP), μCi•s/m<sup>3</sup>; and

Y<sub>β*i*</sub> = Yield, the beta activity per total (nuclear transformation) activity of radionuclide *i*, μCi<sub>β</sub>/μCi<sub>nt</sub>.

### Method 1.4.4 Two-Pathway Deposition Beta Derived Response Level (2Path\_DRL<sub>β,Dp</sub>)

#### Calculation

The 2Path\_DRL<sub>β,Dp</sub> specifies the areal beta activity of the mixture at which the total dose from all radionuclides in a release would equal the PAG over the time phase under consideration.

$$2Path\_DRL_{\beta,Dp,t_n,TP} = \sum_i \left( 2Path\_DRL_{Dp,i,t_n,TP} * Y_{\beta,i} \right) \quad (\text{Eq. 1.4-4})$$

$$\frac{\mu\text{Ci}_{\beta}}{\text{m}^2} = \frac{\mu\text{Ci}_{\text{nt}}}{\text{m}^2} * \frac{\mu\text{Ci}_{\beta}}{\mu\text{Ci}_{\text{nt}}}$$

where:

$2Path\_DRL_{\beta,Dp,t_n,TP}$  = Two-Pathway Deposition Beta Derived Response Level, the areal beta activity of the mixture, at time  $t_n$ , at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration (*TP*),  $\mu\text{Ci}/\text{m}^2$ ;

$2Path\_DRL_{Dp,i,t_n,TP}$  = Two-Pathway Deposition Derived Response Level, the areal activity, at time  $t_n$ , of radionuclide  $i$  at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration (*TP*),  $\mu\text{Ci}/\text{m}^2$ ; and

$Y_{\beta,i}$  = Yield, the beta activity per total (nuclear transformation) activity of radionuclide  $i$ ,  $\mu\text{Ci}_{\beta}/\mu\text{Ci}_{\text{nt}}$ .

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**EXAMPLE 1**

**Problem: Calculate the Four-Pathway Air Beta DRL for the Start of the 1<sup>st</sup>-Year Time Phase for the following mixture (evaluated at  $t_n = 0$ ):**

**Table 1.4-E1**

Radionuclide	Integrated Air Activity ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )	Deposition ( $\mu\text{Ci}/\text{m}^2$ )	$t_{1/2}$ (s)
Co-60	6.67E+02	2	1.66E+08
Gd-148	3.33E+02	1	2.93E+09
Sr-90	1.0E+03	3	9.19E+08
Y-90	1.0E+03	3	2.30E+05

This calculation requires the Four-Pathway Air Derived Response Level ( $4\text{Path\_DRL}_{\bar{A}}$ ) for each radionuclide from the mixture for the early phase. Table 1.4-E2 shows the values calculated using Method 1.1.

**Table 1.4-E2**

Radionuclide	Integrated Air Activity ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )	$\text{WF}_{t_n}$	Beta Yield	1 <sup>st</sup> -Year $4\text{Path\_DRL}_{\bar{A}}$ ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )
Co-60	6.67E+02	1	1	9.34E+01
Gd-148	3.33E+02	1	0	4.78E+01
Sr-90	1.0E+03	1	1	1.40E+02
Y-90	1.0E+03	1	1	1.40E+02

Because the evaluation time  $t_n$  is zero, there is no need to adjust for weathering to determine the DRL at the start of the time phase.

Applying these values in equation 1.4-1 yields:

$$\begin{aligned}
 4\text{Path\_DRL}_{\beta,\bar{A}} &= \left( 9.34\text{E}+01 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * 1 \frac{\mu\text{Ci}_{\beta}}{\mu\text{Ci}} \right) \\
 &+ \left( 1.40\text{E}+02 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * 1 \frac{\mu\text{Ci}_{\beta}}{\mu\text{Ci}} \right) + \left( 1.40\text{E}+02 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * 1 \frac{\mu\text{Ci}_{\beta}}{\mu\text{Ci}} \right) \\
 &= 3.74\text{E}+02 \frac{\mu\text{Ci}_{\beta}\cdot\text{s}}{\text{m}^3}
 \end{aligned}$$

NOTE: Gd-148 does not have a beta decay component and is therefore not included in this calculation.

## EXAMPLE 2

**Problem: Calculate the Two-Pathway Deposition Beta DRL for the Start of the 1<sup>st</sup>-Year Time Phase for the following mixture (evaluated at  $t_n = 0$ ):**

Table 1.4-E3

Radionuclide	Deposition ( $\mu\text{Ci}/\text{m}^2$ )	$t_{1/2}$ (s)
Co-60	2	1.66E+08
Gd-148	1	2.93E+09
Sr-90	3	9.19E+08
Y-90	3	2.30E+05

This calculation requires the Two-Pathway Deposition Derived Response Level ( $2\text{Path\_DRL}_{\text{Dp}}$ ) for each radionuclide from the mixture for the early phase. Table 1.4-E4 shows the values calculated using Method 1.1.

Table 1.4-E4

Radionuclide	Integrated Air Activity ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )	$\text{WF}_{\text{tn}}$	Beta Yield	1 <sup>st</sup> -Year $2\text{Path\_DRL}_{\text{Dp}}$ ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )
Co-60	2.0E+03	1	1	5.55
Gd-148	1.0E+03	1	0	2.78
Sr-90	3.0E+03	1	1	8.33
Y-90	3.0E+03	1	1	8.33

Because the evaluation time  $t_n$  is zero, there is no need to adjust for weathering to determine the DRL at the start of the time phase.

Applying these values in equation 1.4-3 yields:

$$\begin{aligned}
 2\text{Path\_DRL}_{\beta,\text{Dp}} &= \left( 5.55 \frac{\mu\text{Ci}}{\text{m}^2} * 1 \frac{\mu\text{Ci}_{\beta}}{\mu\text{Ci}} \right) \\
 &+ \left( 8.33 \frac{\mu\text{Ci}}{\text{m}^2} * 1 \frac{\mu\text{Ci}_{\beta}}{\mu\text{Ci}} \right) + \left( 8.33 \frac{\mu\text{Ci}}{\text{m}^2} * 1 \frac{\mu\text{Ci}_{\beta}}{\mu\text{Ci}} \right) \\
 &= 2.22\text{E}+01 \frac{\mu\text{Ci}_{\beta}}{\text{m}^2}
 \end{aligned}$$

**NOTE:** Gd-148 does not have a beta decay component and is therefore not included in this calculation.

## **METHOD 1.5 PROJECTED PUBLIC DOSE**

### **Application**

This method has been developed to calculate the dose received by members of the public from exposure to a release of radioactive material. The dose can be calculated using either a Four-Pathway (4Path\_PPD) or a Two-Pathway (2Path\_PPD) Assessment. Four-Pathway Assessment includes the dose contributions from the plume-borne and ground-deposited radionuclide mixture, while Two-Pathway Assessment only includes dose contribution from ground-deposited material. Projected Public Doses may be calculated either from sample data showing the radionuclide mixture or a field dose rate measurement in comparison to the Dose Rate DRL.

The 4Path\_PPD:

- 1) Uses a measured integrated air activity and a measured ground deposition of a radionuclide, or a measured dose rate to calculate the dose that a receptor is projected to receive over a specified time phase due to the passage of a plume and the material deposited on the ground by the plume.
- 2) Is calculated from the:
  - a. Plume Total Dose Parameter (Pl\_TDP) and the Deposition Total Dose Parameter (Dp\_TDP) values calculated in Method 1.1, Section 1.1.1 and Section 1.1.2, or
  - b. Four-Pathway Dose Rate Derived Response Level (4Path\_DRL<sub>DR</sub>) value calculated in Method 1.2, Section 1.2.1.3.

The 2Path\_PPD:

- 1) Uses a measured ground deposition of a radionuclide or a measured dose rate to calculate the dose that a receptor is projected to receive over a specified time phase due to the passage of a plume and the material deposited on the ground by the plume.
- 2) Is calculated from the:
  - a. Deposition Total Dose Parameter (Dp\_TDP) value calculated in Method 1.1, Section 1.1.2, or
  - b. Two-Pathway Dose Rate Derived Response Level (2Path\_DRL<sub>DR</sub>) value calculated in Method 1.2, Section 1.2.1.3.

Both types of PPDs are:

- 1) Compared to Protective Action Guides (PAGs) for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA92), the Department of Homeland Security (DHS) (DHS08) or local Decision Makers.

- 2) Used to create data products and define dose levels to help Decision Makers determine where protective actions (e.g., sheltering, evacuation, relocation) may be warranted.

## Discussion

The Four-Pathway Projected Public Dose (4Path\_PPD) includes the dose contributions from the plume-borne and ground-deposited radionuclide mixture, and is calculated by:

- 1) Summing the  $PI\_TDPs$  and  $Dp\_TDPs$  for each radionuclide in the mixture.
- or
- 2) Comparing a measured dose rate (mrem/hr) to the calculated  $4Path\_DRL_{DR}$  for a mixture. Because the  $4Path\_DRL_{DR}$  is determined using a PAG, the ratio of the measured value to the appropriate DRL can be used to calculate a projected dose relative to the PAG.

The Two-Pathway Projected Public Dose (2Path\_PPD) includes the dose contributions from the ground-deposited radionuclide mixture, and is calculated by:

- 1) Summing the  $Dp\_TDPs$  for each radionuclide in the mixture.
- or
- 2) Comparing a measured dose rate (mrem/hr) to the calculated  $2Path\_DRL_{DR}$  for a mixture. Because the  $2Path\_DRL_{DR}$  is determined using a PAG, the ratio of the measured value to the appropriate DRL can be used to calculate a projected dose relative to the PAG.

**NOTE:** These DRLs may be calculated for Stochastic (Chronic) or Deterministic (Acute) doses by using either Acute or Chronic Dose Coefficients.

## Assumptions

There are no additional assumptions beyond the default assumptions.

## Inputs

In addition to the default inputs, the following information is required to perform the calculations described in this method:

- 1) Plume Total Dose Parameter ( $PI\_TDP$ ) and Deposition Total Dose Parameter ( $Dp\_TDP$ ) for each radionuclide, calculated using Method 1.1.
- or
- 2) Four-Pathway or Two-Pathway Dose Rate DRLs ( $4Path\_DRL_{DR}$  or  $2Path\_DRL_{DR}$ ) for the mixture, calculated using Method 1.2.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available and Decision Makers endorse their use.

## Outputs

The final output of this method is the Projected Public Dose for a deposition of radioactive material.

### Final

$4Path\_PPD_{TP}$  = Four-Pathway Projected Public Dose, the sum of the external dose from submersion and groundshine and the committed dose from inhalation of plume-borne and resuspended material, over the time phase under consideration ( $TP$ ), from the radionuclide mixture, mrem

$2Path\_PPD_{TP}$  = Two-Pathway Projected Public Dose, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration ( $TP$ ), from the radionuclide mixture, mrem

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

None

## Method 1.5.1 Calculating the Projected Public Dose from radionuclide mixture data.

### Calculation

#### 1.5.1.1 Calculating the Four-Pathway Projected Public Dose

The Four-Pathway Projected Public Dose ( $4Path\_PPD$ ) includes the dose contributions from the plume-borne and ground-deposited radionuclide mixture, and is calculated by adding the  $Pl\_TDPs$  and  $Dp\_TDPs$  for each radionuclide in the mixture.

$$4Path\_PPD_{TP} = \sum_i (Pl\_TDP_{i,TP} + Dp\_TDP_{i,TP}) \quad (\text{Eq. 1.5-1})$$

$$mrem = mrem + mrem$$

where:

$4Path\_PPD_{TP}$  = Four-Pathway Projected Public Dose, the sum of the external dose from submersion and groundshine and the committed dose from inhalation of plume-borne and resuspended material, over the time phase under consideration ( $TP$ ), from the radionuclide mixture, mrem;

$Pl\_TDP_{i, TP}$  = Plume Total Dose Parameter, the sum of the external dose from submersion in, and the committed dose from inhalation of, plume-borne radionuclide  $i$  over the time phase under consideration ( $TP$ ), mrem; and

$Dp\_TDP_{i, TP}$  = Deposition Total Dose Parameter, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration ( $TP$ ), from the deposition of radionuclide  $i$ , mrem.

### 1.5.1.2 Calculating the Two-Pathway Projected Public Dose

The Two-Pathway Projected Public Dose ( $2Path\_PPD$ ) includes the dose contributions from the ground-deposited radionuclide mixture, and is calculated by summing the  $Dp\_TDPs$  for each radionuclide in the mixture.

$$2Path\_PPD_{TP} = \sum_i Dp\_TDP_{i, TP} \quad (\text{Eq. 1.5-2})$$

mrem = mrem

where:

$2Path\_PPD_{TP}$  = Two-Pathway Projected Public Dose, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration ( $TP$ ), from the radionuclide mixture, mrem; and

$Dp\_TDP_{i, TP}$  = Deposition Total Dose Parameter, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration ( $TP$ ), from the deposition of radionuclide  $i$ , mrem.

## Method 1.5.2 Calculating the Projected Public Dose from a dose rate measurement.

### Calculation

Because the Dose Rate DRL is the dose rate at which an individual would receive a total dose equal to the PAG, it is possible to calculate the Projected Public Dose by comparing a measured dose rate with the time-adjusted Dose Rate DRL for the mixture to establish a ratio of the projected dose to the PAG and estimate the projected dose over a specified time phase.

### 1.5.2.1 Calculating the Four-Pathway Projected Public Dose

$$\frac{ExDR_{t_n}}{4Path\_DRL_{DR,t_n,TP}} = \frac{4Path\_PPD_{TP}}{PAG_{TP}} \quad (\text{Eq. 1.5-3a})$$

Solving for 4Path\_PPD, (Eq. 1.5-3a) can be rewritten as:

$$4Path\_PPD_{TP} = \frac{ExDR_{t_n} * PAG_{TP}}{4Path\_DRL_{DR,t_n,TP}} \quad (\text{Eq. 1.5-3b})$$

$$\text{mrem} = \frac{\frac{\text{mrem}}{\text{hr}} * \text{mrem}}{\frac{\text{mrem}}{\text{hr}}}$$

where:

$4Path\_PPD_{TP}$  = Four-Pathway Projected Public Dose, the sum of the external dose from submersion and groundshine and the committed dose from inhalation of plume-borne and resuspended material, over the time phase under consideration ( $TP$ ), from the radionuclide mixture, mrem;

$ExDR_{t_n}$  = External dose rate at time  $t_n$ , mrem/hr;

$PAG_{TP}$  = Protective Action Guide for total dose, as specified by the EPA, DHS or other Decision Makers, over the time phase under consideration ( $TP$ ), mrem; and

$4Path\_DRL_{DR, t_n, TP}$  = Four-Pathway Dose Rate Derived Response Level, the external dose rate, at time  $t_n$ , at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ), mrem/hr.

### 1.5.2.2 Calculating the Two-Pathway Projected Public Dose

$$2Path\_PPD_{TP} = \frac{ExDR_{t_n} * PAG_{TP}}{2Path\_DRL_{DR,t_n,TP}} \quad (\text{Eq. 1.5-4})$$

$$\text{mrem} = \frac{\frac{\text{mrem}}{\text{hr}} * \text{mrem}}{\frac{\text{mrem}}{\text{hr}}}$$

where:

$2Path\_PPD_{TP}$  = Two-Pathway Projected Public Dose, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration ( $TP$ ), from the radionuclide mixture, mrem;

$ExDR_m$  = External dose rate at time  $t_n$ , mrem/hr;

$PAG_{TP}$  = Protective Action Guide for total dose, as specified by the EPA, DHS or other Decision Makers, over the time phase under consideration ( $TP$ ), mrem; and

$2Path\_DRL_{DR, m, TP}$  = Two-Pathway Dose Rate Derived Response Level, the external dose rate, at time  $t_n$ , at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration ( $TP$ ), mrem/hr;

## EXAMPLE 1

**Problem:** Calculate the Four-Pathway Projected Public Total Effective Dose for the First-year Time Phase for the following mixture ( $t_n = 0$ ).

Table 1.5-E1

Radionuclide	Integrated Air Activity ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )	Deposition ( $\mu\text{Ci}/\text{m}^2$ )	$t_{1/2}$ (s)
Co-60	6.67E+02	2	1.66E+08
Gd-148	3.33E+02	1	2.93E+09
Sr-90	1.0E+03	3	9.19E+08
Y-90	1.0E+03	3	2.30E+05

### E1.1 Calculating 4Path\_PPD (Equation 1.5-1)

This calculation requires the Plume Total Dose Parameter (PI\_TDP) and the Deposition Total Dose Parameter (Dp\_TDP) for each radionuclide in the mixture. Table 1.5-E2 shows the values calculated in Method 1.1 (Table 1.1-E9) for the first-year time phase evaluated at deposition ( $t_n = 0$ ).

Table 1.5-E2

Radionuclide	PI_TDP First Year (mrem)	Dp_TDP First Year (mrem)
Co-60	3.20E+01	3.80E+02
Gd-148	1.33E+04	3.06E+02
Sr-90	2.42E+02	6.01
Y-90	2.32	2.87E+01

Applying the values from this table, Equation 1.5-1 becomes:

$$\begin{aligned}
 4Path\_PPD_{TP} &= \left[ \begin{aligned} &(3.20\text{E}+01 \text{ mrem}) + (3.80\text{E}+02 \text{ mrem}) \\ &+ (1.33\text{E}+04 \text{ mrem}) + (3.06\text{E}+02 \text{ mrem}) \\ &+ (2.42\text{E}+02 \text{ mrem}) + (6.01 \text{ mrem}) \\ &+ (2.32 \text{ mrem}) + (2.87\text{E}+01 \text{ mrem}) \end{aligned} \right] \\
 &= 1.43\text{E}+04 \text{ mrem}
 \end{aligned}$$

## **E1.2      Calculating a 4Path\_PPD for an Individual Organ**

The preceding calculations assume that the organ of interest is the whole body. The generic approach can be modified to calculate a Projected Public Dose for a specific organ (e.g., skin, thyroid, etc.). To calculate PPDs for a specific organ, the Dose Coefficients must be changed to that of the organ in question and then used to calculate the  $PI\_TDP$  and  $Dp\_TDP$  for that organ, which are used to calculate the PPD as shown above.

## EXAMPLE 2

**Problem: Calculate the Four-Pathway Dose Rate Projected Public Dose for the First-year Time Phase for the following mixture deposited at  $t = 0$ .**

Assume the dose rate measurement was 5 mrem/hr at  $t_n = 0$ .

**Table 1.5-E3**

Radionuclide	Integrated Air Activity ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )	Deposition ( $\mu\text{Ci}/\text{m}^2$ )	$t_{1/2}$ (s)
Co-60	6.67E+02	2	1.66E+08
Gd-148	3.33E+02	1	2.93E+09
Sr-90	1.0E+03	3	9.19E+08
Y-90	1.0E+03	3	2.30E+05

### E2.1 Calculating $4\text{Path\_PPD}_{\text{TP}}$ (Equation 1.5-3b)

This calculation requires the Four-Pathway Dose Rate DRL for the time ( $t_n$ ) at which the measurement ( $ExDR_m$ ) was taken.

Organ of Interest: Whole Body  
 PAG: 2000 mrem  
 $4\text{Path\_DRL}_{\text{DR}}$ : 7.55E-03 mrem/hr (from Method 1.2, Example 1, Section E1.3)

Applying these values to Equation 1.5-3b yields:

$$4\text{Path\_PPD}_{\text{TP}} = \frac{5 \frac{\text{mrem}}{\text{hr}} * 2000 \text{ mrem}}{7.55\text{E-}03 \frac{\text{mrem}}{\text{hr}}} = 1.32\text{E+}06 \text{ mrem}$$

### E2.2 Calculating a $4\text{Path\_PPD}$ for an Individual Organ

The preceding calculations assume that the organ of interest is the whole body. The generic approach can be modified to calculate a Projected Public Dose for a specific organ (e.g., skin, thyroid, etc.). To calculate a PPD for a specific organ, determine the  $4\text{Path\_DRL}_{\text{DR}}$  for the organ and use Equation 1.5-3 as demonstrated above (see Method 1.2, Example 1, Section E1.4).

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## **METHOD 1.6 PUBLIC SKIN DOSE**

**This method is reserved for future development.**

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## METHOD 1.7 ASSESSING NUCLEAR DETONATIONS

### Application

This method has been developed to calculate Doses, Stay Times, and Nuclear Fallout Derived Response Levels (NF\_DRLs) for a deposition of radioactive fallout after a nuclear detonation.

The NF\_DRL:

- 1) Represents the external dose rate (mrem/hr, measured at 1 m above the ground) at a given time ( $t_n$ ), at which the external dose from *all radionuclides* in a fallout deposition mixture may equal the appropriate Protective Action Guide (PAG) over the time phase under consideration.
- 2) Is derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA92) or the Department of Homeland Security (DHS) (DHS08). A projected or measured value greater than the NF\_DRL indicates the potential to exceed the PAG.
- 3) Is used to create data products and define dose rates to assist decision makers in determining where implementing protective actions (e.g., sheltering, evacuation, relocation) may be advisable.
- 4) Should only be used until the fallout mixture has been characterized. After radionuclide activities have been quantified, the other Methods in Section 1 should be used for Assessment.

### Discussion

The NF\_DRL relates a measured dose rate to the external dose from material deposited on the ground (i.e., groundshine). The inhalation dose from nuclear weapon fallout is insignificant over the time phase where this method will be applied, and therefore this method only considers external dose.

The NF\_DRL is based on the dose rate of the entire fallout mixture, not on concentrations of individual radionuclides.

In cases of nuclear detonation, external radiation levels decrease rapidly. Due to the “front weighting” of doses, strong consideration should be given to setting the time phase to start as early as possible (however, see Assumption 2) even if protective actions are not able to be implemented until later. This should produce a more accurate total dose projection to the affected population.

## Assumptions

- 1) Prompt radiation (e.g., neutron, gamma) is NOT included in this method.
- 2) Doses and NF\_DRLs are based on external gamma exposure only. Assume one rad external dose is equivalent to one rem.
- 3) During the time from 0.5 to 5,000 hours, the decay of fallout activity at a given location may be approximated by Equation 1.7-1 (GI77):

$$ExDR_t = ExDR_r * t^{-x} \quad (\text{Eq. 1.7-1})$$

where:

$ExDR_t$  = External dose rate at time t (hours after detonation), mrem/hr;

$ExDR_r$  = Reference external dose rate at 1 hour after nuclear detonation, mrem/hr;

$x$  = Power Function Exponent, the value that represents the decay of fallout radioactivity at a given location. Default value = 1.2, see Section 1.7.4 for instructions on calculating this value if requested.

**NOTE:** Because of the limitations on this method stated above, calculations starting before 0.5 hours after detonation are **not valid**.

- 4) The time phase of interest must begin **after** complete deposition of fallout material at a given location.

## Inputs

In addition to the default inputs, the following information is required to perform the calculations described in this method:

Power Function Exponent (x) – Default of 1.2.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available and Decision Makers endorse their use.

## Outputs

### Final

NF\_DRL = Nuclear Fallout Derived Response Level, the external dose rate, at time  $t_n$ , at which the external dose from all radionuclides in a fallout deposition mixture would equal the PAG for the time phase under consideration, mrem/hr

Dose = The total external dose received over a specified time period.

Stay Time = The length of time that an individual may remain in an area and be expected to receive less than a specified dose.

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

$ExDR_{r,PAG}$  = Reference external dose rate at 1 hour after nuclear detonation which would produce a dose for the time phase equal to the PAG, mR/hr

$x$  = Power Function Exponent, the value that represents the decay of fallout radioactivity at a given location. Default value = 1.2, see Method 1.7.4 for instructions on calculating this value if requested.

## Method 1.7.1 Nuclear Fallout Dose

### Calculation

This method is used to estimate the external dose from fallout produced by a nuclear detonation over a specified time phase.

The external dose received from radioactive fallout over a given time phase can be expressed by Equation 1.7-2:

$$\text{Dose} = ExDR_r * \int_{t_1}^{t_2} t^{-x} dt \quad (\text{Eq. 1.7-2})$$

$$\text{mrem} = \frac{\text{mrem}}{\text{hr}} * \text{hr}$$

where:

$ExDR_r$  = Reference external dose rate at 1 hour after nuclear detonation, mrem/hr;

$t_1$  = the start of the time phase (integration period) under consideration, hr;

$t_2$  = the end of the time phase (integration period) under consideration, hr;

$x$  = Power Function Exponent, the value that represents the decay of fallout radioactivity at a given location. Default value = 1.2, see Method 1.7.4 for instructions on calculating this value if requested.

Integrating this equation produces:

$$\text{Dose} = ExDR_r * \left( \frac{t_2^{-x+1} - t_1^{-x+1}}{-x+1} \right) \quad (\text{Eq. 1.7-3})$$

$$\text{mrem} = \frac{\text{mrem}}{\text{hr}} * \text{hr}$$

The reference external dose rate ( $ExDR_r$ ) can be determined using a dose rate measurement taken at a known time (in hours) after detonation and a modified version of Equation 1.7-1:

$$ExDR_r = \frac{ExDR_t}{t^{-x}} \quad (\text{Eq. 1.7-1, Modified})$$

## Method 1.7.2 Nuclear Fallout DRL

### Calculation

This calculation requires knowledge of when the detonation occurred, what time the evaluation of NF\_DRL will be made relative to that time, and the PAG to be applied.

When the limit for dose received over the time phase is set to the PAG, Equation 1.7-2 becomes:

$$PAG_{TP} = ExDR_{r,PAG} * \int_{t_1}^{t_2} t^{-x} dt \quad (\text{Eq. 1.7-4})$$

$$\text{mrem} = \frac{\text{mrem}}{\text{hr}} * \text{hr}$$

where:

- $PAG_{TP}$  = Protective Action Guide, as specified by the EPA, DHS or other Decision Makers for the time phase under consideration ( $TP$ ), mrem;
- $ExDR_{r,PAG}$  = Reference external dose rate at 1 hour after nuclear detonation which would produce a dose for the time phase equal to the PAG, mrem/hr;
- $t_1$  = the start of the time phase (integration period) under consideration, hr;
- $t_2$  = the end of the time phase (integration period) under consideration, hr;
- $x$  = Power Function Exponent, the value that represents the decay of fallout radioactivity at a given location. Default value = 1.2, see Method 1.7.4 for instructions on calculating this value if requested.

Integrating this equation produces:

$$PAG_{TP} = ExDR_{r,PAG} * \left( \frac{t_2^{-x+1} - t_1^{-x+1}}{-x+1} \right) \quad (\text{Eq. 1.7-5a})$$

$$\text{mrem} = \frac{\text{mrem}}{\text{hr}} * \text{hr}$$

Solving this equation for  $ExDR_r$  yields:

$$ExDR_{r,PAG} = PAG_{TP} * \left( \frac{-x+1}{t_2^{-x+1} - t_1^{-x+1}} \right) \quad (\text{Eq. 1.7-5b})$$

$$\frac{\text{mrem}}{\text{hr}} = \text{mrem} * \frac{1}{\text{hr}}$$

This represents the external dose rate at 1 hour after detonation that would cause the fallout mixture to produce a dose over the time phase of interest equal to the PAG.

To calculate the NF\_DRL for a measurement time  $t_n$ , apply the power function to the  $ExDR_r$  calculated above.

$$NF\_DRL_{t_n} = ExDR_{t_n} = ExDR_{r,PAG} * t_n^{-x} \quad (\text{Eq. 1.7-6})$$

$$\frac{\text{mrem}}{\text{hr}} = \frac{\text{mrem}}{\text{hr}} = \frac{\text{mrem}}{\text{hr}} * \text{unitless}$$

where:

$t_n$  = Evaluation Time, the point in time, relative to the start of the release, at which the measurement, prediction or evaluation is performed, hr

Therefore the NF\_DRL for time  $t_n$  in terms of the PAG is:

$$NF\_DRL_{t_n} = PAG_{TP} * \left( \frac{-x+1}{t_2^{-x+1} - t_1^{-x+1}} \right) * t_n^{-x} \quad (\text{Eq. 1.7-7a})$$

$$\frac{\text{mrem}}{\text{hr}} = \text{mrem} * \frac{1}{\text{hr}} * \text{unitless}$$

Or, for the default value of  $x = 1.2$ :

$$NF\_DRL_{t_n} = PAG_{TP} * \left( \frac{-0.2}{t_2^{-0.2} - t_1^{-0.2}} \right) * t_n^{-1.2} \quad (\text{Eq. 1.7-7b})$$

## Method 1.7.3 Nuclear Fallout Stay Time:

### Calculation

This calculation uses the reference external dose rate ( $ExDR_r$ ) and the exponent of the power function ( $x$ ) to determine the stay time for an individual in an area of nuclear fallout starting at a particular time ( $t_1$ ). This could apply to worker shifts or to members of the public returning to their homes to collect needed items.

This is done by solving the dose equation (Equation 1.7-3) for the end of the time phase ( $t_2$ ), the time interval from  $t_1$  to  $t_2$  is the “stay time” for that individual in the area that would produce a dose equal to the PAG.

$$\text{Dose} = ExDR_r * \left( \frac{t_2^{-x+1} - t_1^{-x+1}}{-x+1} \right) \quad (\text{Eq. 1.7-3})$$

$$\text{mrem} = \frac{\text{mrem}}{\text{hr}} * \text{hr}$$

Solving for  $t_2$ :

$$t_2^{-x+1} = \frac{\text{Dose} * (-x+1)}{ExDR_r} + t_1^{-x+1} \quad (\text{Eq. 1.7-8a})$$

Taking the natural log of both sides:

$$(-x+1) \ln t_2 = \ln \left[ \frac{\text{Dose} * (-x+1)}{ExDR_r} + t_1^{-x+1} \right] \quad (\text{Eq. 1.7-8b})$$

Solving for  $t_2$ :

$$\ln t_2 = \frac{\ln \left[ \frac{\text{Dose} * (-x+1)}{ExDR_r} + t_1^{-x+1} \right]}{-x+1} \quad (\text{Eq. 1.7-8c})$$

Therefore:

$$t_2 = e^{\left\{ \frac{\ln \left[ \frac{\text{Dose} * (-x+1)}{ExDR_r} + t_1^{-x+1} \right]}{-x+1} \right\}} \quad (\text{Eq. 1.7-8d})$$

**To obtain the stay time, subtract  $t_1$  from  $t_2$ .**

## Method 1.7.4 Calculating the “power function” exponent (-x):

### Calculation

The decay of fission products after a nuclear detonation can be approximated by the power function,  $t^{-x}$ . FRMAC uses a default value of 1.2 for the exponent (x) (GI77). If desired, the exponent of the power function can be calculated using two dose rate measurements taken at the same location at two different known times after detonation.

Let:

$ExDR_a$  = External dose rate measured at time  $t_a$ , mrem/hr;

$ExDR_b$  = External dose rate measured at time  $t_b$ , mrem/hr;

$ExDR_r$  = Reference external dose rate at 1 hour after detonation, mrem/hr;

By the rule of the power function:

$$ExDR_a = ExDR_r * t_a^{-x} \quad \text{and} \quad ExDR_b = ExDR_r * t_b^{-x} \quad (\text{Eq. 1.7-9a})$$

Therefore:

$$ExDR_r = \frac{ExDR_a}{t_a^{-x}} = \frac{ExDR_b}{t_b^{-x}} \quad (\text{Eq. 1.7-9b})$$

and,

$$\frac{ExDR_b}{ExDR_a} = \frac{t_b^{-x}}{t_a^{-x}} \Rightarrow \left( \frac{t_b}{t_a} \right)^{-x} \quad (\text{Eq. 1.7-9c})$$

Taking the natural log of both sides:

$$\ln \left( \frac{ExDR_b}{ExDR_a} \right) = -x \ln \left( \frac{t_b}{t_a} \right) \quad (\text{Eq. 1.7-9d})$$

Solving for -x:

$$-x = \frac{\ln \left( \frac{ExDR_b}{ExDR_a} \right)}{\ln \left( \frac{t_b}{t_a} \right)} \quad (\text{Eq. 1.7-9e})$$

## Method 1.7.5 Handling the case when the “power function” ( $t^{-x}$ ) exponent is 1:

### Calculation

Under certain conditions, the calculated power function exponent ( $x$ ) may be precisely equal to one. When this occurs, the integrations shown above cannot be used because the denominator term becomes zero. This section shows how the equations in this method are changed for cases where the power function exponent is one.

Calculating Dose using Equation 1.7-3,

$$\text{Dose} = ExDR_r * \left( \frac{t_2^{-x+1} - t_1^{-x+1}}{-x+1} \right) \quad (\text{Eq. 1.7-3})$$

when  $x=1$ , this is changed to:

$$\text{Dose} = ExDR_r * (\ln t_2 - \ln t_1)$$

Calculating NF\_DRL using Equation 1.7-7a,

$$NF\_DRL_{t_n} = PAG_{TP} * \left( \frac{-x+1}{t_2^{-x+1} - t_1^{-x+1}} \right) * t_n^{-x} \quad (\text{Eq. 1.7-7a})$$

when  $x=1$ , this is changed to:

$$NF\_DRL_{t_n} = \frac{PAG_{TP}}{(\ln t_2 - \ln t_1)} * t_n^{-x}$$

And, calculating Stay Time using Equation 1.7-9d:

$$t_2 = e^{\left\{ \frac{\ln \left[ \frac{\text{Dose} * (-x+1)}{ExDR_r} + t_1^{-x+1} \right]}{-x+1} \right\}} \quad (\text{Eq. 1.7-8d})$$

when  $x=1$ , this is changed to:

$$t_2 = e^{\left( \frac{\text{Dose}}{ExDR_r} + \ln t_1 \right)}$$

**EXAMPLE 1**

**Problem: Calculate the NF\_DRL for fallout for a time 48 hours after detonation assuming an Early Phase (96 hour) PAG of 100 rad (100 rem) and a start time ( $t_I$ ) of 1 hour after detonation.**

Assume two dose rate measurements were taken at a given location:

- 1) 5.1 rem/hr, 12 hours after detonation, and
- 2) 3.6 rem/hr, 16 hours after detonation.

**E1.1 Calculating “-x” using Equation 1.7-8e**

$$-x = \frac{\ln\left(\frac{ExDR_b}{ExDR_a}\right)}{\ln\left(\frac{t_b}{t_a}\right)} = \frac{\ln\left(\frac{3.6}{5.1}\right)}{\ln\left(\frac{16}{12}\right)} = \frac{\ln(0.706)}{\ln(1.33)} = \frac{-0.348}{0.288} = -1.21$$

**E1.2 Calculating NF\_DRL at  $t_n = 48$  hours using Equation 1.7-7a**

$$NF\_DRL_{t_n} = PAG * \left( \frac{-x+1}{t_2^{-x+1} - t_1^{-x+1}} \right) * t_n^{-x}$$

$$NF\_DRL_{48hours} = 100 \text{ rem} * \left( \frac{-0.21}{97^{-0.21} - 1^{-0.21}} \right) * 48^{-1.21}$$

$$= 0.314 \frac{\text{rem}}{\text{hr}}$$

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**EXAMPLE 2**

**Problem: Calculate the external dose received from fallout over the 96 hour period beginning 1 hour after detonation.**

Assume two dose rate measurements were taken at a given location:

- 1) 5.1 rem/hr, 12 hours after detonation, and
- 2) 3.6 rem/hr, 16 hours after detonation.

The external dose is calculated using equation 1.7-3:

$$\text{Dose} = \text{ExDR}_r * \left( \frac{t_2^{-x+1} - t_1^{-x+1}}{-x+1} \right)$$

$x = 1.21$  from Example 1,

$\text{ExDR}_r$  is calculated using the modified form of Equation 1.7-1:

$$\text{ExDR}_r = \frac{\text{ExDR}_t}{t^{-x}} = \frac{5.1 \frac{\text{rem}}{\text{hr}}}{12^{-1.21}} = 103 \frac{\text{rem}}{\text{hr}}$$

Then:

$$\text{Dose} = 103 \frac{\text{rem}}{\text{hr}} * \left( \frac{97^{-0.21} - 1^{-0.21}}{-0.21} \right) \text{hr} \approx 303 \text{ rem}$$

For the 96 hour period beginning 12 hours after detonation, the dose would be:

$$\text{Dose} = 103 \frac{\text{rem}}{\text{hr}} * \left( \frac{108^{-0.21} - 12^{-0.21}}{-0.21} \right) \text{hr} \approx 107 \text{ rem}$$

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**EXAMPLE 3**

**Problem: Calculate the Stay Time for a worker with a chronic dose limit of 5 rem for a work shift starting 24 hours after detonation ( $t_1$ ).**

Assume two dose rate measurements were taken at a given location:

- 1) 5.1 rem/hr, 12 hours after detonation, and
- 2) 3.6 rem/hr, 16 hours after detonation.

$x = 1.21$  from Example 1,

$ExDR_r = 103$  rem/hr from Example 2,

The end of the work shift is calculated using equation 1.7-9d:

$$e^{\left\{ \frac{\ln \left[ \frac{5 \text{ rem} * (-0.21)}{103 \frac{\text{rem}}{\text{hr}}} + 24^{-0.21} \text{ hr} \right]}{-0.21} \right\}} = t_2 = 26.4 \text{ hr}$$

Subtracting the start time for the work shift (24 hours) gives a stay time of 2.4 hours.

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**SECTION 2.      WORKER PROTECTION METHODS**

		<u>Effective Date</u>
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Method 2.1 Basic Worker Protection.....	2.1-1	6/2012
Method 2.2 Worker Protection - Doses and Integrated Turn Back Limits.....	2.2-1	6/2012
Method 2.3 Worker Protection - Stay Time .....	2.3-1	Reserved
Method 2.4 Worker Protection - Skin Dose.....	2.4-1	Reserved

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## INTRODUCTION TO WORKER PROTECTION METHODS

These methods describe calculations for establishing the emergency worker turn-back limits (TBL) and Stay Times (ST) that are applied by the Health and Safety Division. The methods consider the dose received from external exposure and inhalation of resuspended material. The EPA established dose limits for workers performing emergency services (EPA92). Table 2-1 summarizes the EPA emergency worker dose guidance in terms of the projected Total Effective Dose (TED). When possible, TBLs and STs should be based on measured and projected work area conditions. Limits should be established for each worker and revised after shift-specific monitoring data is available, if necessary.

### Default Assumptions

FRMAC radiological assessment calculations utilize the default assumptions established by the FRMAC AWG.

The following default assumptions are used in the methods in this section:

- 1) The dose projections from this section include contributions from external exposure (groundshine) and the inhalation of resuspended material.
- 2) Inhalation of material from the passage of a plume of radioactive material is not considered in these calculations. The plume is considered to have already passed. Dose consequences from direct inhalation, submersion, and cloud shine are not included in the calculations. (See Section 1 of this Volume for Plume Phase calculations.)
- 3) The effects of radioactive decay, weathering and resuspension are included in the calculations.
- 4) Ingestion is not included in these methods. If ingestion is a significant dose pathway (i.e., >10% of the total dose), it should be addressed separately and included in protective action decisions. (See Section 3 – Ingestion Methods.)
- 5) Default calculations assume:
  - a. the receptor is outside in the contaminated area continuously during the time phase under consideration without any protective measures (e.g., shielding, respiratory protection);
  - b. chronic exposure; calculations addressing acute exposures are planned for future methods.
  - c. use of ICRP 60+ dosimetry model;
  - d. adult receptor;
  - e. Light Exercise Breathing Rate (Adult Male) of 1.5 m<sup>3</sup>/hr; and
  - f. inhalation of 1-micron Activity Median Aerodynamic Diameter (AMAD) particles in the Maximum lung clearance class.
- 6) The Bateman Equations (Ba1910) are used to model the decay and in-growth of all radionuclides. See Appendix F, Supplement 1 for details.

- 7) FRMAC's Worker Protection Methods generally assume that the organ of interest is the whole body. However, other organs may be evaluated against applicable Protective Action Guides (PAGs) by changing the Dose Coefficients and PAGs used. (See Method 1.1 Example 1, Section E1.8.)

## Default Inputs

The following information is required for the methods described in this section:

- 1) Data – This information may come from predictive analysis (models) or field data (monitoring and/or samples):
  - Composition of the deposited radionuclide mixture (radionuclides and areal radioactivity, concentration, activity ratio or mass ratio) and/or external dose (or exposure) rates.
- 2) Other Factors:
  - Ground roughness;
  - Weathering;
  - Resuspension; and
  - Decay of radionuclides during the time period under consideration.
- 3) Constants:
  - Breathing rate (default: Light-Exercise Breathing Rate of 1.5 m<sup>3</sup>/hr based on the ICRP 60+ lung model);
  - Inhalation dose coefficient (defaults from ICRP 60+ dosimetry model);
  - External dose coefficient (defaults from ICRP 60+ dosimetry model);
  - Dose limits (e.g., PAGs – defaults from EPA/DHS guidance); and
  - Exposure to Dose conversion factor (default of 1.0 mrem/mR).
- 4) Time Phase: The start ( $t_1$ ) and end ( $t_2$ ) time of the worker shift under consideration.

**NOTE:** Many of the terms in the methods are dependent on variables (e.g., time phase, target organ, PAG, etc.). When critical, these dependencies are shown as subscripts to the appropriate terms. (See Appendix B for the variable list.)

## METHOD 2.1 BASIC WORKER PROTECTION

### Application

This method provides a means to establish emergency worker turn-back and stay time guidance based on monitoring results. These results may be from hand-held instruments, self-reading dosimeters (SRDs), or other mechanisms used to measure (or predict) Dose (or Exposure) rates.

The results of this calculation will be used to develop turn-back and stay time guidance for emergency workers based on comparison to the PAGs for radiological emergency planning established by the EPA (EPA92), DHS (DHS08) or others established for the specific incident by Decision Makers.

### Discussion

This method is primarily used to calculate the Dose (or Exposure) Rate Turn-Back Limit ( $TBL_{DR}$  or  $TBL_{XR}$ ) (e.g., mrem/hr or mR/hr) for workers entering a contaminated area for a work shift. If workers do not enter areas that exceed the TBL during the shift, they should not exceed the dose limit for the shift.

This method may also be used to calculate a Stay Time (ST) if workers will be performing activities in an area with a reasonably uniform radiation field.

**NOTE:** This method is only useful if deposited radionuclides are primarily an external radiation hazard (i.e., inhalation is not a significant dose pathway). This condition may exist due to either the radionuclide composition of the hazard or the use of respiratory protection.

### Assumptions

The following are exceptions to the default assumptions:

- 1) The dose projections from this method only include contributions from groundshine; inhalation is not addressed.
- 2) The composition of the mixture does not change significantly, either through radioactive decay or weathering, over the time phase (worker shift) in question.

**NOTE:** To include effects from inhalation of resuspended material or a mixture containing radionuclides with short half lives, see Method 2.2.

## Inputs

In addition to the default inputs, the following information is required to perform the calculations described in this method:

Constants – Dose Limits for Workers Performing Emergency Services.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available and Decision Makers endorse their use.

## Outputs

### Final

The final output of this method is the Turn-Back Limit or Stay Time for a given work shift.

$$\begin{aligned} TBL_{DR} &= \text{Worker Dose Rate Turn-Back Limit (mrem/hr)} \\ TBL_{XR} &= \text{Worker Exposure Rate Turn-Back Limit (mR/hr)} \\ ST &= \text{Stay Time (hr)} \end{aligned}$$

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

None

## Calculation

The calculation of the Worker Turn-Back Limit is based on the Dose Limit chosen by the decision makers for the incident and the shift length for the worker(s) being evaluated.

$$TBL_{DR} = \frac{\text{Dose Limit}}{ST} \quad (\text{Eq. 2.1-1})$$

$$\frac{\text{mrem}}{\text{hr}} = \frac{\text{mrem}}{\text{hr}}$$

where:

$TBL_{DR}$  = Worker Dose Rate Turn-Back Limit, mrem/hr;  
*Dose Limit* = Dose that the worker is allowed to receive for the shift, mrem; and  
 $ST$  = Stay Time, how long the worker is expected to work in the contaminated area, hr.

This method also may be used to calculate a Stay Time when the external dose rate in the work area is expected to remain relatively constant over the work shift.

$$ST = \frac{Dose\ Limit}{ExDR} \quad (Eq. 2.1-2)$$

$$hr = \frac{\frac{mrem}{mrem}}{hr}$$

where:

*ST* = Stay Time, how long the worker will be allowed to work in the contaminated area, hr;

*ExDR* = External dose rate, mrem/hr; and

*Dose Limit* = Dose that the worker is allowed to receive for the shift, mrem.

**NOTE:** Either of these equations may be modified to apply to exposure rates rather than dose rates by applying the Exposure to Dose Conversion Factor ( $XDCF_{A\ or\ C}$ ) of 0.7 mrem/mR (acute) or 1.0 mrem/mR (chronic) to calculate a TBL or ST when readings in mR/hr are needed. (See Examples for application.)

**EXAMPLE 1**

**Problem:** Calculate the worker Turn-Back Limit for the following conditions.

Dose Limit: 25000 mrem

Shift Length: 8 hours

$$TBL = \frac{25000 \text{ mrem}}{8 \text{ hr}} = 3125 \frac{\text{mrem}}{\text{hr}}$$

Workers should turn back from (avoid) areas with an external dose rate  $\geq 3125$  mrem/hr.

**EXAMPLE 2**

**Problem:** Calculate the worker Stay Time (in hr) for the following conditions.

Dose Limit: 5000 mrem

Dose Rate: 500 mrem/hr

$$ST = \frac{5000 \text{ mrem}}{500 \frac{\text{mrem}}{\text{hr}}} = 10 \text{ hr}$$

Workers may stay in the field for 10 hours.

## **METHOD 2.2    WORKER PROTECTION DOSES AND INTEGRATED TURN BACK LIMITS**

### **Application**

This method is used to calculate the turn-back limit (TBL) for integrated dose (or exposure) for workers entering a contaminated area for a work shift.

The TBL:

- Represents the integrated external dose (or exposure) that would produce a total dose (external and internal) over a worker's shift equal to the appropriate Protective Action Guide (PAG).
- Is derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA92) or the Department of Homeland Security (DHS) (DHS08) or other dose limits established for worker protection. A projected or measured value greater than the TBL indicates the potential to exceed the PAG.
- Is calculated from the Deposition Inhalation Dose Parameter (Dp\_InhDP) and the Deposition External Dose Parameter (Dp\_ExDP) values calculated in Method 1.1.

### **Discussion**

This method provides a means to establish emergency worker turn-back guidance based on monitoring results. These results may be from hand-held instruments, self-reading dosimeters (SRDs), or other mechanisms used to measure (or predict) integrated dose (or exposure).

### **Assumptions**

The following is an exception to the default assumptions:

- 1) The use of respiratory protection is addressed by this method.

### **Inputs**

In addition to the default inputs, the following information is required to perform the calculations described in this method:

- 1) Other Factors – Assigned protection factor (APF) for respirator use, Potassium Iodide protection factor (KIPF).
- 2) Deposition Inhalation and External Dose Parameters (Dp\_InhDP and Dp\_ExDP) for each radionuclide in the mixture, based on the start and end times and dose limit for the worker's shift (calculated using Method 1.1).

**NOTE:** Consult with Health and Safety personnel to determine appropriate input values for the planned worker shift.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available and Decision Makers endorse their use.

## Outputs

### Final

The final output of this method is the turn-back limit (mrem or mR) for a given work shift.

TBL\_D = Worker Turn-Back Limit for Integrated External Dose (mrem)

TBL\_X = Worker Turn-Back Limit for Integrated External Exposure (mR)

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

$ExTDCF_{TP}$  = External to Total Dose Conversion Factor, the ratio of the total dose (external + inhalation) to the external dose for a deposition of radioactive material over the time phase under consideration (*TP*),  $mrem_{inh+external}/mrem_{external}$ .

**NOTE:** This value is used to convert a measurement from a self-reading dosimeter into a dose that includes the effects of inhalation of resuspended material.

## Calculation

### 1) Calculating the Worker Turn-Back Limit

The calculation of the Turn-Back Limit for Integrated External Dose (TBL\_D) is based on the Dose Limit chosen by the decision makers for the incident and the ratio of total (inhalation + external) dose to external dose.

**NOTE:** The default assumption is that this calculation will be performed to evaluate Whole-Body (Effective) dose. This method can also be used to evaluate TBLs for other organs by calculating the ExTDCF for that organ.

$$TBL\_D_{TP} = \frac{Dose\ Limit}{ExTDCF_{TP}} \quad (\text{Eq. 2.2-1})$$

$$mrem_{external} = \frac{mrem_{inh+external}}{mrem_{inh+external} / mrem_{external}}$$

where:

$TBL\_D_{TP}$  = Turn-Back Limit for Integrated External Dose, the integrated external dose, as recorded by the self-reading dosimeter, received from a radionuclide mixture deposited on the ground over the time phase under consideration ( $TP$ ) that would result in the worker receiving their dose limit,  $mrem_{external}$ ;

$Dose\ Limit$  = Worker (or receptor) dose limit,  $mrem$ ; and

$ExTDCF_{TP}$  = External to Total Dose Conversion Factor, the ratio of the total dose (external + inhalation) to the external dose for a deposition of radioactive material over the time phase under consideration ( $TP$ ),  $mrem_{inh+external}/mrem_{external}$ .

When the worker's self-reading dosimeter reaches the calculated integrated external dose, this indicates that the worker has potentially received the dose limit (external plus inhalation dose) from the radionuclides deposited on the ground.

If workers are using dosimeters that read out in units of exposure ( $mR$ ), divide the  $TBL\_D$  by the Exposure to Dose Conversion Factor ( $XDCF_{A\ or\ C}$ ) to determine the Turn-Back Limit for Integrated External Exposure ( $TBL\_X$ ) in  $mR_{external}$ .

$$TBL\_X_{TP} = \frac{TBL\_D_{TP}}{XDCF_{A\ or\ C}} \quad (\text{Eq. 2.2-2})$$

$$mR_{external} = \frac{mrem_{external}}{mrem / mR}$$

where:

$TBL\_X_{TP}$  = Turn-Back Limit for Integrated External Exposure, the integrated external exposure, as recorded by the self-reading dosimeter, received from a radionuclide mixture deposited on the ground over the time phase under consideration ( $TP$ ) that would result in the worker receiving their dose limit,  $mR_{external}$ ;

$TBL\_D_{TP}$  = Turn-Back Limit for Integrated External Dose, the integrated external dose, as recorded by the self-reading dosimeter, received from a radionuclide mixture deposited on the ground over the time phase under consideration ( $TP$ ) that would result in the worker receiving their dose limit,  $mrem_{external}$ ;

$XDCF_A$  = Exposure to Dose Conversion Factor (acute), the constant used to convert external exposure (mR) to midline (bone marrow) dose (mrem), 0.7; and

$XDCF_C$  = Exposure to Dose Conversion Factor (chronic), the constant used to convert external exposure (mR) to deep tissue (1 cm) dose (mrem), 1.0.

These limits should be used as the Dose (or Exposure) Limit in the calculation of stay time shown in Method 2.1.

## 2) Calculating the External to Total Dose Conversion Factor

**NOTE:** See Method 1.1, Section 1.1.2 for the Derivation of  $Dp\_InhDP$  and  $Dp\_ExDP$ .

The External to Total Dose Conversion Factor ( $ExtDCF_{TP}$ ) for the time phase of interest can be calculated by adding the contributions to total dose from external exposure and respiration of resuspended material and dividing the total by the external contribution as shown in Equations 2.2-3(a-c).

$$ExtDCF_{TP} = \frac{\sum_i \left( \frac{Dp\_InhDP_{i,TP}}{KIPF * APF} \right) + \sum_i (Dp\_ExDP_{i,TP})}{\sum_i (Dp\_ExDP_{i,TP})} \quad (\text{Eq. 2.2-3a})$$

which can be expanded to:

$$ExtDCF_{TP} = \frac{\sum_i \left( \frac{Dp\_InhDP_{i,TP}}{KIPF * APF} \right) + \sum_i (Dp\_ExDP_{i,TP})}{\sum_i (Dp\_ExDP_{i,TP})} + \frac{\sum_i (Dp\_ExDP_{i,TP})}{\sum_i (Dp\_ExDP_{i,TP})} \quad (\text{Eq.2.2-3b})$$

which simplifies to:

$$ExtDCF_{TP} = \frac{\sum_i \left( \frac{Dp\_InhDP_{i,TP}}{KIPF * APF} \right)}{\sum_i (Dp\_ExDP_{i,TP})} + 1 \quad (\text{Eq. 2.2-3c})$$

$$\frac{mrem_{inh+external}}{mrem_{external}} = \frac{\left( \frac{mrem_{inh}}{\text{unitless} * \text{unitless}} \right)}{(mrem_{external})} + \frac{mrem_{external}}{mrem_{external}}$$

where:

$ExtDCF_{TP}$  = External to Total Dose Conversion Factor, the ratio of the total dose (external + inhalation) to the external dose for a deposition of radioactive material over the time phase under consideration ( $TP$ ),  $mrem_{inh+external}/mrem_{external}$ ;

$Dp\_InhDP_{i,TP}$  = Deposition Inhalation Dose Parameter, the committed dose from radionuclide  $i$  deposited on the ground from the inhalation of the resuspended fraction of the radionuclide over the time phase under consideration ( $TP$ ), mrem;

**NOTE:** For Worker Protection Calculations,  $Dp\_InhDP$  should be calculated using the Light Exercise Breathing Rate for an Adult Male ( $BR_{LE}$ ) ( $4.17E-04 \text{ m}^3/\text{s}$ ) rather than the Activity Averaged Breathing Rate ( $BR_{AA}$ ).

$Dp\_ExDP_{i,TP}$  = Deposition External Dose Parameter, the external dose from groundshine from radionuclide  $i$  over the time phase under consideration ( $TP$ ), mrem;

$KIPF$  = Potassium Iodide Protection Factor (Default of 1 for all non-iodine isotopes or when no KI is administered), unitless; and

$APF$  = Assigned Protection Factor, the level of respiratory protection that a respirator is expected to provide (Default of 1 when no respirators are used), unitless.

**NOTE:** Consult Health and Safety personnel for appropriate values for  $APF$  and/or  $KIPF$ . Typical  $APF$  values are:

Half-face Air-purifying Respirator: 10

Full-face Air-purifying Respirator: 50

Pressure-Demand SCBA: 10,000

### 3) Comparison of the ExtTCDF to the workers' Dose Limit.

When the ExtTCDF has been calculated, the following equation may be used to calculate the turn-back limit for the workers.

$$TBL\_D_{TP} = \frac{\text{Dose Limit}}{ExtDCF_{TP}} \quad (\text{Eq. 2.2-4})$$

$$mrem_{external} = \frac{mrem_{inh+external}}{mrem_{inh+external} / mrem_{external}}$$

where:

$TBL\_D_{TP}$  = Turn-Back Limit for Integrated External Dose, the integrated external dose as recorded by the self-reading dosimeter, received from a radionuclide mixture deposited on the ground over the time phase under consideration ( $TP$ ) that would result in the worker receiving their dose limit,  $mrem_{external}$ ;

$Dose\ Limit$  = Worker (or receptor) dose limit, mrem; and

$ExtDCF_{TP}$  = External to Total Dose Conversion Factor, the ratio of the total dose (external + inhalation) to the external dose for a deposition of

radioactive material over the time phase under consideration (*TP*),  
 $\text{mrem}_{\text{inh+external}}/\text{mrem}_{\text{external}}$ .

**NOTE:** This equation is identical to Eq. 2.2-1.

#### 4) Calculation of Worker Dose

To calculate a worker's dose at any point during the shift, multiply the current reading on the worker's dosimeter by the ExTDCF.

$$\text{Dose} = \text{SRD Readout} * \text{ExTDCF}_{TP} \quad (\text{Eq. 2.2-5})$$

$$\text{mrem}_{\text{inh+external}} = \text{mrem}_{\text{external}} * \frac{\text{mrem}_{\text{inh+external}}}{\text{mrem}_{\text{external}}}$$

where:

*Dose* = Worker (or receptor) dose, mrem;

SRD Readout = Current reading on Self-Reading Dosimeter, mrem; and

*ExTDCF<sub>TP</sub>* = External to Total Dose Conversion Factor, the ratio of the total dose (external + inhalation) to the external dose for a deposition of radioactive material over the time phase under consideration (*TP*),  
 $\text{mrem}_{\text{inh+external}}/\text{mrem}_{\text{external}}$ .

If the dosimeter reads out in units of exposure (mR), the *XDCF<sub>A or C</sub>* must be included.

$$\text{Dose} = \text{SRD Readout} * \text{XDCF}_{A \text{ or } C} * \text{ExTDCF}_{TP} \quad (\text{Eq. 2.2-6})$$

$$\text{mrem}_{\text{inh+external}} = \text{mrem}_{\text{external}} * \frac{\text{mrem}_{\text{external}}}{\text{mR}_{\text{external}}} * \frac{\text{mrem}_{\text{inh+external}}}{\text{mrem}_{\text{external}}}$$

where:

*XDCF<sub>A</sub>* = Exposure to Dose Conversion Factor (acute), the constant used to convert external exposure (mR) to midline (bone marrow) dose (mrem), 0.7 mrem/mR.

*XDCF<sub>C</sub>* = Exposure to Dose Conversion Factor (chronic), the constant used to convert external exposure (mR) to deep tissue (1 cm) dose (mrem), 1.0 mrem/mR.

## EXAMPLE 1

**Problem:** Calculate the worker Turn-Back Limit for an 8-hour shift with and without a full-face air-purifying respirator (APF=50) with a worker Dose Limit of 5000 mrem for the following mixture (measured at the start of the work shift).

Table 2.2-E1

Radionuclide	Deposition ( $\mu\text{Ci}/\text{m}^2$ )	$t_{1/2}$ (s)
Co-60	2	1.66E+08
Gd-148	1	2.93E+09
Sr-90	3	9.19E+08
Y-90	3	2.30E+05

### E1.1 Calculating the ExTDCF (Equation 2.2-3c)

This calculation requires values for  $Dp\_InhDP$  and  $Dp\_ExDP$ . See Method 1.1 for development of these quantities.

Table 2.2-E2

Radionuclide	$Dp_i$ ( $\mu\text{Ci}/\text{m}^2$ )	$Dp\_ExDP^a$ (mrem)	$Dp\_InhDP^a$ (mrem)
Co-60	2	4.02E-01	2.70E-02
Gd-148	1	0	1.13E+01
Sr-90	3	4.30E-04	2.07E-01
Y-90	3	2.88E-02	1.98E-03
$\Sigma$		<b>4.31E-01</b>	<b>1.15E+01</b>

<sup>a</sup> Values from Turbo FRMAC 2011<sup>®</sup> – Breathing rate for “Light Exercise”.

With a respirator:

$$ExTDCF_{TP} = \frac{1.15E+01}{4.31E-01} + 1 = 1.54 \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}$$

Without a respirator:

$$ExTDCF_{TP} = \frac{1.15E+01}{4.31E-01} + 1 = 2.78E+01 \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}$$

## E1.2 Calculating the TBL\_D and TBL\_X (Equation 2.2-1, 2.2-2)

The Turn-Back Limits for Integrated External Dose and Exposure for this radionuclide mixture with a Dose limit of 5000 mrem would be:

With a respirator:

$$TBL\_D_{TP} = \frac{5000 \text{ mrem}_{inh+external}}{1.54 \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}} \approx 3260 \text{ mrem}_{external}$$

$$TBL\_X_{TP} = \frac{3260 \text{ mrem}_{external}}{1.0 \text{ mrem}/\text{mR}} \approx 3260 \text{ mR}_{external}$$

This means that when a worker's dosimeter indicates an external dose of **3260** mrem (exposure of 3260 mR), the worker has potentially received 5000 mrem of total (external + inhalation) dose and should exit the work area.

Without a respirator:

$$TBL\_D_{TP} = \frac{5000 \text{ mrem}_{inh+external}}{27.8 \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}} \approx 180 \text{ mrem}_{external}$$

$$TBL\_X_{TP} = \frac{180 \text{ mrem}_{external}}{1.0 \text{ mrem}/\text{mR}} = 180 \text{ mR}_{external}$$

This means that when a worker's dosimeter indicates an external dose of **180** mrem (exposure of 180 mR), the worker has potentially received 5000 mrem of total (external + inhalation) dose and should exit the work area.

## **METHOD 2.3    WORKER PROTECTION - STAY TIME CALCULATION**

**This method is reserved for future development.**

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## **METHOD 2.4    WORKER PROTECTION - SKIN DOSE**

**This method is reserved for future development.**

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### SECTION 3.      INGESTION PATHWAY METHODS

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## INTRODUCTION TO INGESTION PATHWAY METHODS

These methods are used to assess measured or projected environmental measurements for comparison to the FDA DILs for radioactive contamination in food (FDA98).

The FDA has established DILs for contamination in food for a list of radionuclides and has specified a method to calculate DILs for all other radionuclides. The DILs are based on PAGs of 0.5 rem Committed Effective Dose (E) and 5 rem to any specific organ ( $H_T$ ), whichever is more limiting. FDA Ingestion PAGs are presented in Appendix C, Table 2-2, and DILs for selected radionuclides (including the full FDA list) are presented in Appendix C, Table 8.

Dose calculations assume radionuclide concentrations are for foods as prepared for consumption and ingestion is assumed to take place for a period of one year (or less for radionuclides with half lives < 54 days – See Method 4.1).

These methods may include the use of Transfer Factors (TFs) to estimate the concentration of radionuclides in food products. Transfer factors are the ratio of the concentration of a radionuclide in food products to the concentration in the source medium such as soil, plant forage, or water (PNNL03).

The equations presented in these methods use the following assumptions about Transfer Factors:

- 1) Transfer Factors assume a long-term exposure during which equilibrium is reached.
- 2) Transfer Factors used in these methods for terrestrial plants are based on dry weight.
- 3) Transfer Factors used in these methods for animal products and aquatic plants are based on wet weight.

These methods consider both mature (ready for harvest) and immature food products. Calculations for mature products assume that the product will enter the food supply immediately and therefore do not include the effects of weathering and radioactive decay. Calculations for immature products include the effects of weathering and radioactive decay until the crops are ready for harvest and consumption. Both types of calculations address decay during transport from the field to the table.

For the ingestion pathway, daughter radionuclides in transient (or secular) equilibrium are excluded from independent analysis because their contribution to dose is included in the dose coefficient of the ultimate parent. Daughter radionuclides with a half life greater than 6 hours **are analyzed separately from the parent radionuclide** because it may be possible to get food prepared for consumption before significant decay occurs.

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## **METHOD 3.1 DERIVED INTERVENTION LEVELS**

### **Application**

This method has been developed to calculate Derived Intervention Levels (DILs) for radioactive material deposited on consumables.

The DIL:

- 1) Represents the concentration ( $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ) of radioactive material in food that, in the absence of any intervention, could lead to an individual receiving a dose equal to the appropriate Protective Action Guide (PAG) if consumed over 1 year.
- 2) Is derived from the PAG for radiological emergency planning established by the Food and Drug Agency (FDA) (FDA98). A projected or measured value greater than the DIL indicates the potential to exceed the PAG.
- 3) Applies to the activity concentration in the food “as prepared for consumption” or “wet.”
- 4) Is applied during the first year after an incident and based on the most sensitive population (age group) and target organ to provide a large margin of safety to the public.
- 5) Is used to create data products and define activity concentration levels to assist decision makers in determining where it may be advisable to implement protective actions (e.g., sheltering livestock, embargos, special product handling).

### **Discussion**

DILs were recommended by the FDA in 1998 as the radionuclide activity concentration in food at which point protective actions should be considered. Food with activity concentrations below the DIL is permitted to move in commerce without restriction. However, local decision makers have the flexibility to apply alternate limits in special circumstances.

The FDA established DILs for 9 principle isotopes in 5 groups, 15 secondary isotopes, and provided a method to calculate DILs. The nuclides with FDA-provided DILs are shown in Table 3.1-1 below and in Appendix C, Table 8.

FRMAC does not have the authority to calculate or use different DILs for radionuclides for which the FDA has provided recommended values unless alternate values are requested by the Advisory Team or local decision makers. FRMAC can calculate DILs for the radionuclides for which the FDA does not provide recommended values, but these values are

not automatically approved by the FDA and must receive approval from the Advisory Team or local decision makers before they are used.

## Assumptions

The FRMAC radiological assessment calculations use the default assumptions established by the FDA. The following default assumptions are used in this method:

- 1) DILs apply to individual radionuclides (or FDA-specified groups of radionuclides); there is no sum-of-fraction rule (except for  $^{103}\text{Ru}$  and  $^{106}\text{Ru}$ ).
- 2) DILs apply only to the parent radionuclide in a chain. DO NOT calculate a DIL for a daughter radionuclide independently unless it exists in the mixture as a separate parent (i.e., in excess of its equilibrium concentration).
- 3) DILs are based on average annual dietary intake ( $\text{kg}_{\text{wet}}/\text{yr}$ ) of all dietary components (e.g., produce, grains, meat, etc.), including tap water used for drinking.
- 4) Annual intake is adjusted for short-lived ( $t_{1/2} < 54$  days) radionuclides to account for radioactive decay.
- 5) Annual intake varies by age group (3 month, 1 yr, 5 yr, 10 yr, 15 yr, and adult).
- 6) DILs are applicable to foods as prepared for consumption or “wet”. To compare with analytical results it may be necessary to convert to “dry weight,” see Method 4.2.
- 7) ICRP 26 Ingestion Dose Conversion Factors should not be used to calculate DILs because they only consider the adult receptor (ICRP77).
- 8) The default Ingestion PAGs are:
  - 500 mrem to the whole body or
  - 5000 mrem to an individual organ, whichever is more limiting.
- 9) Inadvertent ingestion of soil is not included in these methods. If ingestion of soil is a significant dose pathway (i.e., >10% of the total dose), it should be addressed separately. (See Method 3.7).
- 10) Default calculations for non-FDA-listed radionuclides use the International Commission on Radiological Protection (ICRP) 60+ dosimetry model.

## Inputs

The following information is required to perform the methods described in this section:

- 1) Data – Composition of the deposited radionuclide mixture (radionuclides and concentration). This information may come from predictive analysis (models) or field data (monitoring and/or samples).
- 2) Other Factors – Decay of radionuclides during the time period under consideration.

- 3) Constants – Fraction of diet contaminated, daily food intake rate, ingestion dose coefficient, dose limits (e.g., FDA PAGs).

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available and Decision Makers endorse their use.

**NOTE:** Many of the terms in the methods are dependent on variables (e.g., time phase, target organ, PAG, etc.). When critical, these dependencies are shown as subscripts to the appropriate terms. (See Appendix B for the variable list.)

## Outputs

### Final

The final output of this method is the DIL for a radionuclide contaminant.

$DIL_i$  = Derived Intervention Level, the concentration of radionuclide  $i$  in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ .

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

None

### Method 3.1.1 DILs for FDA-Listed Radionuclides

Table 3.1-1 provides the DILs for the FDA-listed radionuclides. These values must be used when evaluating the radionuclides (and groups of radionuclides) in the table unless an alternate DIL is requested by the Advisory Team or local decision makers. Follow the calculation steps in Method 3.1.2 for all other radionuclides.

**Table 3.1-1 FDA-Listed Ingestion DILs (FDA 1998)**

Radionuclide Group	FDA DIL <sup>a</sup> (Bq/kg <sub>wet</sub> )	FDA DIL <sup>a</sup> (μCi/kg <sub>wet</sub> )
<b>Principal Nuclides</b>		
<sup>90</sup> Sr	160	4.3E-03
<sup>131</sup> I	170	4.6E-03
<sup>134</sup> Cs + <sup>137</sup> Cs	1200	3.2E-02
<sup>134</sup> Cs	930	2.5E-02
<sup>137</sup> Cs	1360	3.7E-02
<sup>238</sup> Pu + <sup>239</sup> Pu + <sup>241</sup> Am	2	5.4E-05
<sup>238</sup> Pu	2.5	6.8E-05
<sup>239</sup> Pu	2.2	6.0E-05
<sup>241</sup> Am	2	5.4E-05
<sup>103</sup> Ru + <sup>106</sup> Ru	( <sup>103</sup> Ru/6800) + ( <sup>106</sup> Ru/450) <1	( <sup>103</sup> Ru/0.18) + ( <sup>106</sup> Ru/1.2E-02) <1
<sup>103</sup> Ru	6800	0.18
<sup>106</sup> Ru	450	1.2E-02
<b>Other Nuclides</b>		
<sup>89</sup> Sr	1400	3.8E-02
<sup>91</sup> Y	1200	3.2E-02
<sup>95</sup> Zr	4000	0.11
<sup>95</sup> Nb	12000	0.32
<sup>132</sup> Te	4400	0.12
<sup>129</sup> I	56	1.5E-03
<sup>133</sup> I	7000	0.19
<sup>140</sup> Ba	6900	0.19
<sup>141</sup> Ce	7200	0.19
<sup>144</sup> Ce	500	1.4E-02
<sup>237</sup> Np	4	1.1E-04
<sup>239</sup> Np	28000	0.76
<sup>241</sup> Pu	120	3.2E-03
<sup>242</sup> Cm	19	5.1E-04
<sup>244</sup> Cm	2	5.4E-05
<sup>a</sup> A food sample is considered to exceed the DIL if it meets or exceeds the DIL for any individual nuclide. Analysis results are not summed across nuclides except the combinations specifically stated (i.e., <sup>134</sup> Cs + <sup>137</sup> Cs, <sup>238</sup> Pu + <sup>239</sup> Pu + <sup>241</sup> Am, and <sup>103</sup> Ru + <sup>106</sup> Ru).		

## Method 3.1.2 DILs for Non-FDA-Listed Radionuclides

### Calculation

This method uses the FDA approach for all calculations.

DIL calculations can be complex, given the number of age group/organ combinations that need to be calculated to determine the most restrictive value for each radionuclide. Therefore the user is urged to use a computer code, such as Turbo FRMAC<sup>®</sup>, to complete these calculations. All calculated values must be approved by an FDA representative on the Advisory Team prior to publication.

Equation 3.1-1 shows the DIL calculation.

$$DIL_{organ,age,i} = \frac{PAG_{organ}}{FDC_{age,i} * DFIR_{age} * EDI_i * IngDC_{organ,age,i}} \quad (\text{Eq. 3.1-1})$$

$$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} = \frac{\text{mrem}}{\text{unitless} * \frac{\text{kg}_{\text{wet}}}{\text{d}} * \text{d} * \frac{\text{mrem}}{\mu\text{Ci}}}$$

where:

$DIL_{organ,age,i}$  = Derived Intervention Level, the concentration of radionuclide  $i$  in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ;

$PAG_{organ}$  = Protective Action Guide, as specified by the FDA or other Decision Makers, for the target organ, mrem;

$FDC_{age,i}$  = Fraction of Diet Contaminated, unitless;

**NOTE:** See Appendix C, Table 11 for default  $FDC$  values. If there is convincing local information that the actual  $FDC$  is considerably different, local authorities may decide to use a different  $FDC$ .

$DFIR_{age}$  = Daily Food Intake Rate, the daily intake rate (as prepared for consumption, i.e. wet mass) for a specific age group (see Appendix C, Table 10),  $\text{kg}_{\text{wet}}/\text{d}$ ;

$EDI_i$  = Effective Days of Intake, the number of days required for the radionuclide to decay to <1% of its initial activity (maximum of 365), d; and

$$EDI_i = \frac{-\ln(0.01)}{\lambda_i} \quad \text{where } \lambda_i = \frac{\ln 2}{t_{1/2,i}} \quad (\text{Eq. 3.1-2})$$

**NOTE:** If the radionuclide half life is greater than 54 days, the  $EDI_i = 365$  days.

$IngDC_{organ,age,i}$  = Ingestion Dose Coefficient, the ingestion pathway dose coefficient for the target organ for a specific age group for radionuclide  $i$ , mrem/ $\mu$ Ci.

This calculation will determine a DIL for one age group and one organ. To determine the most restrictive value for a given radionuclide:

- Calculate the DIL for the whole body and for the organ with the highest IngDC for each age group.
- Apply the DIL for the age group and organ with the most conservative (lowest) activity concentration level ( $\mu$ Ci/kg<sub>wet</sub>).

## EXAMPLE 1

### Problem: Calculate the Derived Intervention Level for $^{136}\text{Cs}$ .

$^{136}\text{Cs}$  is not an FDA-listed radionuclide; therefore the DIL must be calculated according to Method 3.1.2. Determining a final DIL requires calculating the DIL for each age group for each organ and choosing the most conservative value.

$$DIL_{organ,age,i} = \frac{PAG_{organ}}{FDC_{age,i} * DFIR_{age} * EDI_i * IngDC_{organ,age,i}} \quad (\text{Eq. 3.1-1})$$

$$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} = \frac{\text{mrem}}{\text{unitless} * \frac{\text{kg}_{\text{wet}}}{\text{d}} * \text{d} * \frac{\text{mrem}}{\mu\text{Ci}}}$$

The  $EDI_i$  for  $^{136}\text{Cs}$  ( $t_{1/2} = 13.1$  d):

$$EDI_i = \frac{4.6}{5.29\text{E-}02} = 87 \text{ d} \quad \text{where } \lambda_i = \frac{0.693}{13.1} = 5.29\text{E-}02 \quad (\text{Eq. 3.1-2})$$

Table 3.1-E1 shows the values, calculated using Equation 3.1-1, for each age group for the Whole Body and for the organ with the highest IngDC.

**Table 3.1-E1**

Age Group	Organ	IngDC (mrem/ $\mu\text{Ci}$ )	FDC	DFIR ( $\text{kg}_{\text{wet}}/\text{d}$ )	EDI (d)	PAG (mrem)	DIL ( $\mu\text{Ci}/\text{kg}_{\text{wet}}$ )
Infant (3 month)	Whole Body	53.7	0.3	1.14	87	500	0.31
	LLI <sup>a</sup>	85.1	0.3			5000	1.97
1 year	Whole Body	35.6	0.3	1.38	87	500	0.39
	LLI	58.1	0.3			5000	2.39
5 year	Whole Body	22.6	0.3	1.81	87	500	0.47
	LLI	34.2	0.3			5000	3.09
10 year	Whole Body	16.2	0.3	2.14	87	500	0.55
	LLI	22	0.3			5000	4.07
15 year	Whole Body	12.7	0.3	2.38	87	500	0.63
	Pancreas	14.6	0.3			5000	5.51
Adult	Whole Body	11.4	0.3	2.59	87	500	0.65
	LLI	13.7	0.3			5000	5.40
Most Restrictive DIL							<b>0.31</b>

<sup>a</sup> Lower Large Intestine

The reported DIL should be 0.31  $\mu\text{Ci}/\text{kg}_{\text{wet}}$  for  $^{136}\text{Cs}$  based on the (most restrictive) Infant/Whole Body value.

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## **METHOD 3.2 CROP/PRODUCE INGESTION DERIVED RESPONSE LEVELS**

### **Application**

This method has been developed to calculate Ingestion Derived Response Levels for radioactive material deposited on crop/produce.

The Crop/Produce Ingestion Derived Response Level (Crop\_DRL):

- 1) Represents the areal activity ( $\mu\text{Ci}/\text{m}^2$ ), of radionuclide *i* that would cause the crop/produce growing in that area to equal the Derived Intervention Level (DIL) for that radionuclide.
- 2) Is indirectly derived (through the DIL) from the PAG for radiological emergency planning established by the Food and Drug Agency (FDA) (FDA98). A projected or measured value greater than the Crop\_DRL indicates the potential to exceed the PAG.
- 3) Is applied during the first year after an incident and based on the most sensitive population (age group) and target organ to provide a large margin of safety to the public.
- 4) Is used to create data products and define contamination levels to assist decision makers in determining where it may be advisable to conduct sampling to evaluate the potential for implementing protective actions (e.g., sheltering livestock, embargos, special product handling).
- 5) Is calculated using the DIL calculated in Method 3.1

### **Discussion**

The Crop\_DRL predicts the amount of radioactivity deposited on a crop ( $\mu\text{Ci}/\text{m}^2$ ) that would cause the crop to equal the DIL. Crop sampling efforts should concentrate on the area where the contamination is equal to or greater than the Crop\_DRL to determine if the DIL has been exceeded in those areas. Protective actions should be considered in areas where the DIL is exceeded. FDA guidance permits food with radioactivity concentrations below the DIL to move in commerce without restriction. However, the FDA and local decision makers have flexibility in whether to apply restrictions in special circumstances.

FRMAC does not have the authority to calculate or use different DILs for radionuclides for which the FDA has provided recommended values unless alternate values are requested by the Advisory Team or local decision makers. FRMAC can calculate DILs for the radionuclides for which the FDA does not provide recommended values, but these values are

not automatically approved by the FDA and must receive approval from the Advisory Team or local decision makers before they are used.

## Assumptions

The FRMAC radiological assessment calculations use the default assumptions established by the FRMAC Assessment Working Group. The following default assumptions are used in this method:

Crop DRLs:

- 1) Apply to individual radionuclides; there is no sum-of-fraction rule (except for the FDA-listed  $^{103}\text{Ru}$  and  $^{106}\text{Ru}$ ).
- 2) Are based on the most restrictive DIL for each radionuclide based on age group and target organ. See Method 3.1 for DIL calculation assumptions.
- 3) Apply to the plant as a whole and do not predict contamination of only the edible portions (e.g., apples on the tree.)
- 4) Assume a crop yield of  $2 \text{ kg}_{\text{wet}}/\text{m}^2$  for fresh produce.
- 5) Assume a soil density of  $1600 \text{ kg}_{\text{soil}}/\text{m}^3$ .
- 6) Assume a mixing depth of  $1.0\text{E}-03 \text{ m}$  for the first growing season (EPA89) and  $0.15$  after plowing.
- 7) Assume a half life of 15 days for material weathering off plant material
- 8) Assume a Time to Market of 1 day for fresh produce.
- 9) Assume, for immature crops, that the crop will remain growing in the contaminated soil for a period of time sufficient to reach equilibrium.
- 10) Are calculated for food as prepared for consumption. To compare with analytical results it may be necessary to convert to “dry weight,” see Method 4.2.
- 11) Use Crop Retention Factors for fresh produce of:
  - 1.0 for radioiodine and
  - 0.2 for all other radionuclides.
- 12) DRLs for FDA grouped radionuclides (e.g.,  $^{134}\text{Cs} + ^{137}\text{Cs}$ ) are adjusted for decay during Field Time and Time to Market using the decay constant for the longest-lived group member.

## Inputs

The following information is required to perform the methods described in this section:

- 1) Data – Composition of the deposited radionuclide mixture (radionuclides and concentration). This information may come from predictive analysis (models) or field data (monitoring and/or samples).

- 2) Constants – Crop Retention Factor, Crop Yield, Transfer Factors for different food types and for each radionuclide.
- 3) Other Factors – Decay and weathering of radionuclides during the time period under consideration, soil mixing depth.
- 4) Appropriate DIL for each radionuclide – Calculated using Method 3.1.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available and Decision Makers endorse their use.

**NOTE:** Many of the terms in the methods are dependent on variables (e.g., time phase, target organ, PAG, etc.). When critical, these dependencies are shown as subscripts to the appropriate terms. (See Appendix B for the variable list.)

## Outputs

### Final

The final output of this method is the Crop\_DRL value for a radionuclide contaminant on the growing area.

$Crop\_DRL_{mat,i}$  = Ingestion Derived Response Level for mature Crop/Produce, the areal activity ( $\mu Ci/m^2$ ), of radionuclide  $i$  that would cause the crop/produce growing in that area to equal the applicable Derived Intervention Level (DIL) at the time of contamination,  $\mu Ci/kg_{wet}$ .

$Crop\_DRL_{imm,i}$  = Ingestion Derived Response Level for immature Crop/Produce, the areal activity ( $\mu Ci/m^2$ ), of radionuclide  $i$  that would cause the crop/produce growing in that area to equal the applicable Derived Intervention Level (DIL) at the time of harvest,  $\mu Ci/kg_{wet}$ .

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

None

## Method 3.2.1 Crop\_DRL for Mature Crop/Produce

This method is used to evaluate fresh produce that will be harvested for immediate consumption. Because of the short time frame involved, the following have not been included in this method:

- Reduction in radioactivity due to weathering.
- Reduction in radioactivity due to biological processes in the crop.

- Increase in radioactivity due to root uptake from contaminated soil.
- Increase in radioactivity due to redeposition of resuspended material.

## Calculation

Equation 3.2-1 shows the  $Crop\_DRL_{mat,i}$  calculation.

$$Crop\_DRL_{mat,i} = \frac{DIL_{organ,age,i} * Y}{CRF_i * e^{-\lambda_i t_m}} \quad (\text{Eq. 3.2-1})$$

$$\frac{\mu\text{Ci}}{\text{m}^2} = \frac{\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \frac{\text{kg}_{\text{wet}}}{\text{m}^2}}{\text{unitless} * \text{unitless}}$$

where:

$Crop\_DRL_{mat,i}$  = Ingestion Derived Response Level for mature Crop/Produce, the areal activity ( $\mu\text{Ci}/\text{m}^2$ ), of radionuclide  $i$  that would cause the crop/produce growing in that area to equal the applicable Derived Intervention Level (DIL) at the time of contamination,  $\mu\text{Ci}/\text{kg}$ ;

$DIL_{organ,age,i}$  = Derived Intervention Level, the concentration of radionuclide  $i$  in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ;

$Y$  = Crop Yield, the mass of crop grown per area of land,  $\text{kg}_{\text{wet}}/\text{m}^2$ ;

$CRF$  = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop, unitless;

$\lambda_i$  = Decay constant for radionuclide  $i$ ,  $\text{d}^{-1}$ ; and

$t_m$  = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d.

### Method 3.2.2 Crop\_DRL for Immature Crop/Produce

This method is used to predict the level of radioactive material (e.g.,  $\mu\text{Ci}/\text{kg}$ ) present in food which has reached maturity while growing in a field that was:

- Contaminated by a deposition of radioactive material during the first growing season (i.e., after the crop was planted), or
- Contaminated and then plowed before the crop was planted.

This method accounts for the following processes that change the level of radioactive material present in a crop:

1. Reduction in radioactivity level due to radioactive decay over the growing season,

2. Reduction in radioactivity level due to material weathering off the crop over the growing season,
3. Reduction in radioactivity level due to transport time to market,
4. Reduction in radioactivity level due to biological processes in the crop,
5. Increase in radioactivity level due to root uptake from contaminated soil, and
6. Increase in radioactivity level due to re-deposition of resuspended material.

The method models processes 1, 2, and 3 independently, while 4, 5, and 6 are combined into an element-dependent Transfer Factor (TF) for a crop type (e.g., leafy vegetable, root vegetable, fruit, or grain). (See PNNL-13421 for details on TFs).

## Calculation

Equation 3.2-2 shows the  $Crop\_DRL_{imm,i}$  calculation.

$$Crop\_DRL_{imm,i} = \frac{DIL_{organ,age,i}}{\left( \frac{CRF * \left( \frac{1-e^{-\lambda_w t_f}}{\lambda_w * t_f} \right)}{Y} + \frac{TF_{crop,i} * MCF_{D-W,f}}{d_m * \rho_{soil}} \right) * \left( \frac{1-e^{-\lambda_i t_f}}{\lambda_i * t_f} \right) * e^{-\lambda_i t_m}} \quad (\text{Eq. 3.2-2})$$

$$\frac{\mu\text{Ci}}{\text{m}^2} = \frac{\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}}{\left( \frac{\text{unitless} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}}}{\frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \frac{\left( \frac{\mu\text{Ci}}{\text{kg}_{\text{dry}}} / \frac{\mu\text{Ci}}{\text{kg}_{\text{soil}}} \right) * \frac{\text{kg}_{\text{dry}}}{\text{kg}_{\text{wet}}}}{\text{m} * \frac{\text{kg}_{\text{soil}}}{\text{m}^3}} \right) * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \text{unitless}}$$

where:

$Crop\_DRL_{imm,i}$  = Ingestion Derived Response Level for immature Crop/Produce, the areal activity ( $\mu\text{Ci}/\text{m}^2$ ), of radionuclide  $i$  that would cause the crop/produce growing in that area to equal the applicable Derived Intervention Level (DIL) at the time of harvest,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ .

$DIL_{organ,age,i}$  = Derived Intervention Level, the concentration of radionuclide  $i$  in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ;

$CRF$  = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop, unitless;

**NOTE:** For crops planted AFTER deposition, the  $CRF=0$ .

$\lambda_w$  = Decay constant for weathering radioactive material off plants (See Appendix C, Table 11),  $\text{d}^{-1}$ ;

$t_f$  = Field Time, the time the crop spends growing in the field from deposition or sampling to harvest, d;

$$\left( \frac{1 - e^{-\lambda_w t_f}}{\lambda_w * t_f} \right) = \text{Integrated average weathering of radioactive material off plants during the time the crop is growing in the field (the integral of the weathering over the Field Time divided by the Field Time), unitless;}$$

$Y$  = Crop Yield, the mass of crop grown per area of land (See Appendix C, Table 11), kg<sub>wet</sub>/m<sup>2</sup>;

$TF_{crop,i}$  = Transfer Factor for a food crop, the fraction of radionuclide  $i$  deposited on the growing medium that is transferred to the plant during the growing season, μCi/kg<sub>dry</sub> per μCi/kg<sub>soil</sub>;

$MCF_{D-W,f}$  = Mass Conversion Factor (dry to wet), the ratio of dry mass to wet mass for a food type  $f$  (See Appendix C, Table 9), kg<sub>dry</sub>/kg<sub>wet</sub>;

$d_m$  = Mixing Depth (See Appendix C, Table 11), m;

$\rho_{soil}$  = Soil density (See Appendix C, Table 11), kg<sub>soil</sub>/m<sup>3</sup>;

$\lambda_i$  = Decay constant for radionuclide  $i$ , d<sup>-1</sup>;

$$\left( \frac{1 - e^{-\lambda_i t_f}}{\lambda_i * t_f} \right) = \text{Integrated average decay of radioactive material during the time the crop is growing in the field (the integral of radioactive decay over the Field Time divided by the Field Time), unitless; and}$$

$t_m$  = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d.

**EXAMPLE 1**

**Problem: Calculate the Mature Crop/Produce Ingestion DRL for  $^{60}\text{Co}$ .**

The most conservative DIL for  $^{60}\text{Co}$  is  $0.02 \mu\text{Ci}/\text{kg}_{\text{wet}}$  (3 month old, whole body).

Assuming that the crop is ready for immediate harvest, Equation 3.2-1 can be used to calculate the DRL.

$$\text{Crop} - \text{DRL}_{\text{mat},i} = \frac{\text{DIL}_{\text{organ,age},i} * Y}{\text{CRF}_i * e^{-\lambda_i t_m}} \quad (\text{Eq. 3.2-1})$$

$$\frac{\mu\text{Ci}}{\text{m}^2} = \frac{\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \frac{\text{kg}_{\text{wet}}}{\text{m}^2}}{\text{unitless} * \text{unitless}}$$

Assuming:

$$\begin{aligned} \text{CRF} &= 0.2 \text{ (fresh produce),} \\ Y &= 2.0 \text{ kg}_{\text{wet}}/\text{m}^2; \\ \lambda_{\text{Co}} &= 3.6\text{E-}04 \text{ d}^{-1}; \text{ and} \\ t_m &= 1 \text{ d.} \end{aligned}$$

$$\text{Crop} - \text{DRL}_{^{60}\text{Co}} = \frac{0.02 \frac{\mu\text{Ci}}{\text{kg}} * 2 \frac{\text{kg}}{\text{m}^2}}{0.2 * e^{-3.6\text{E-}04\text{d}^{-1} * 1\text{d}}} = 0.2 \frac{\mu\text{Ci}}{\text{m}^2}$$

**EXAMPLE 2**

**Problem: Calculate the Immature Crop/Produce Ingestion DRL for  $^{60}\text{Co}$  on Lettuce.**

The most conservative DIL for  $^{60}\text{Co}$  is  $0.02 \mu\text{Ci}/\text{kg}_{\text{wet}}$  (3 month old, whole body).

Assuming that the lettuce has already been planted and will be harvested in 90 days, Equation 3.2-2 can be used to calculate the DRL.

$$\text{Crop\_DRL}_{\text{imm},i} = \frac{\text{DIL}_{\text{organ,age},i}}{\left( \frac{\text{CRF} * \left( \frac{1 - e^{-\lambda_w t_f}}{\lambda_w * t_f} \right)}{Y} + \frac{\text{TF}_{\text{crop},i} * \text{MCF}_{\text{D-W},f}}{d_m * \rho_{\text{soil}}} \right) * \left( \frac{1 - e^{-\lambda_i t_f}}{\lambda_i * t_f} \right) * e^{-\lambda_i t_m}} \quad (\text{Eq. 3.2-2})$$

Assuming:

$$\begin{aligned} \text{CRF} &= 0.2 \text{ (fresh produce)} \\ \lambda_w &= 4.62\text{E-}02 \text{ d}^{-1}; \\ t_f &= 90 \text{ d}; \\ Y &= 2.0 \text{ kg}_{\text{wet}}/\text{m}^2; \\ \text{TF}_{\text{lettuce},i} &= 0.23 \mu\text{Ci}/\text{kg}_{\text{dry}} \text{ per } \mu\text{Ci}/\text{kg}_{\text{soil}}; \\ \text{MCF}_{\text{D-W},f} &= 0.2 \text{ kg}_{\text{dry}}/\text{kg}_{\text{wet}} \text{ for leafy vegetables}; \\ d_m &= 1.0\text{E-}03 \text{ m}; \\ \rho_{\text{soil}} &= 1600 \text{ kg}_{\text{soil}}/\text{m}^3; \\ \lambda_{\text{Co}} &= 3.6\text{E-}04 \text{ d}^{-1}; \text{ and} \\ t_m &= 1 \text{ d}. \end{aligned}$$

$$\begin{aligned} \text{Crop\_DRL}_{\text{imm},^{60}\text{Co}} &= \frac{0.02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}}{\left( \frac{0.2 * \frac{1 - e^{-4.62\text{E-}02\text{d}^{-1} * 90\text{d}}}{4.62\text{E-}02\text{d}^{-1} * 90\text{d}}}{2.0 \frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \frac{0.23 \left( \frac{\mu\text{Ci}}{\text{kg}_{\text{dry}}} / \frac{\mu\text{Ci}}{\text{kg}_{\text{soil}}} \right) * 0.2 \frac{\text{kg}_{\text{dry}}}{\text{kg}_{\text{wet}}}}{1.0\text{E-}03 \text{ m} * 1600 \frac{\text{kg}_{\text{soil}}}{\text{m}^3}} \right) * \frac{1 - e^{-3.6\text{E-}04\text{d}^{-1} * 90\text{d}}}{3.6\text{E-}04\text{d}^{-1} * 90\text{d}} * e^{-3.6\text{E-}04\text{d}^{-1} * 1\text{d}} } \\ &= 0.39 \frac{\mu\text{Ci}}{\text{m}^2} \end{aligned}$$

## METHOD 3.3 MILK INGESTION DERIVED RESPONSE LEVEL

### Application

This method has been developed to calculate Ingestion Derived Response Levels for radioactive material deposited on animal forage/water for the milk pathway.

The Milk Ingestion Derived Response Level:

- 1) Represents:
  - a. Milk\_DRL<sub>area,A,i</sub>: The areal activity ( $\mu\text{Ci}/\text{m}^2$ ), of radionuclide *i* deposited over a grazing area that would result in a grazing animal's milk equaling the Derived Intervention Level (DIL) for that radionuclide;
  - b. Milk\_DRL<sub>mass,A,i</sub>: The mass concentration ( $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ), of radionuclide *i* in animal feed that would result in the animal's milk equaling the Derived Intervention Level (DIL) for that radionuclide; or
  - c. Milk\_DRL<sub>water,A,i</sub>: The water concentration ( $\mu\text{Ci}/\text{l}$ ), of radionuclide *i* in an animal's drinking water that would result in the animal's milk equaling the Derived Intervention Level (DIL) for that radionuclide.
- 2) Is indirectly derived (through the DIL) from the PAG for radiological emergency planning established by the Food and Drug Agency (FDA) (FDA98). A projected or measured concentration value greater than the Milk\_DRL indicates the potential to exceed the PAG.
- 3) Is applied during the first year after an incident and based on the most sensitive population (age group) and target organ to provide a large margin of safety to the public.
- 4) Is used to create data products and define contamination levels to assist decision makers in determining where it may be advisable to conduct sampling to evaluate the potential for implementing protective actions (e.g., sheltering livestock, embargos, special product handling).
- 5) Is calculated using the DIL calculated in Method 3.1.

### Discussion

The Milk\_DRL predicts the amount of radioactivity deposited either on an animal's grazing area ( $\mu\text{Ci}/\text{m}^2$ ) or in an animal's feed or water ( $\mu\text{Ci}/\text{kg}_{\text{wet}}$  or  $\mu\text{Ci}/\text{l}$ ) that would cause the animal's milk to equal the DIL. Sampling efforts should concentrate on the area where the contamination is equal to the Milk\_DRL to determine if the DIL has been exceeded in those areas. Protective actions (e.g., use of stored feed) should be considered in areas where the

DIL is exceeded. Milk embargo protective actions should be considered after milk samples indicate that the DIL has actually been exceeded. FDA guidance permits food with radioactivity concentrations below the DIL to move in commerce without restriction. However the FDA and local decision makers have flexibility in whether to apply restrictions in special circumstances.

FRMAC does not have the authority to calculate or use different DILs for radionuclides for which the FDA has provided recommended values unless alternate values are requested by the Advisory Team or local decision makers. FRMAC can calculate DILs for the radionuclides for which the FDA does not provide recommended values, but these values are not automatically approved by the FDA and must receive approval from the Advisory Team or local decision makers before they are used.

Because milk is obtained from grazing animals daily this method treats milk as a “mature product” and there is no consideration for weathering or radioactive decay during grazing.

## Assumptions

The FRMAC radiological assessment calculations use the default assumptions established by the FRMAC Assessment Working Group. The following default assumptions are used in this method:

Milk DRLs:

- 1) Apply to individual radionuclides; there is no sum-of-fraction rule (except for the FDA-listed  $^{103}\text{Ru}$  and  $^{106}\text{Ru}$ ).
- 2) Are based on the most restrictive DIL for each radionuclide based on age group and target organ. See Method 3.1 for DIL calculation assumptions.
- 3) Assume only one intake pathway is present (i.e., if forage/soil is contaminated, drinking water is clean).
- 4) Animal intake rates are assumed to be
  - Cow – 50  $\text{kg}_{\text{wet}}/\text{d}$  for feed, 60 l/d for water, and 0.5  $\text{kg}_{\text{soil}}/\text{d}$  for soil.
  - Goat – 6  $\text{kg}_{\text{wet}}/\text{d}$  for feed, 8 l/d for water, and 0.06  $\text{kg}_{\text{soil}}/\text{d}$  for soil.
- 5) Assume a forage yield of 0.7  $\text{kg}_{\text{wet}}/\text{m}^2$  for pastureland.
- 6) Assume a milk density of 1.04  $\text{kg}_{\text{wet}}/\text{l}$ .
- 7) Assume a soil density of 1600  $\text{kg}_{\text{soil}}/\text{m}^3$ .
- 8) Assume a mixing depth of 1.0E-03 m for the first growing season (EPA89) and 0.15 after plowing.
- 9) Assume a time to market of 2 days.
- 10) Assume the animal consumes the contaminated feed/water over a period of time sufficient for the animal product intended for human consumption to reach equilibrium.

- 11) Assume that 100% of the contaminated pathway (feed or water) is contaminated.
- 12) Are calculated for food (milk or animal feed) as prepared for consumption. To compare with analytical results it may be necessary to convert to “dry weight,” see Method 4.2.
- 13) Use Crop Retention Factors for pastureland of:
  - 1.0 for radioiodine and
  - 0.5 for all other radionuclides.
- 14) DRLs for FDA grouped radionuclides (e.g.,  $^{134}\text{Cs}+^{137}\text{Cs}$ ) are adjusted for decay during Time to Market using the decay constant for the longest-lived group member.

## Inputs

The following information is required to perform the methods described in this section:

- 1) Data – Composition of the deposited radionuclide mixture (radionuclides and concentration). This information may come from predictive analysis (models) or field data (monitoring and/or samples).
- 2) Constants – Crop Retention Factor, Crop Yield, Animal Daily Intake Rates (Feed, Water, Soil), Transfer Factor for Milk for each radionuclide, density of milk.
- 3) Other Factors – Decay of radionuclides during the time period under consideration, fraction of animals’ diet contaminated, soil mixing depth.
- 4) Appropriate DIL for each radionuclide – Calculated using Method 3.1.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available and Decision Makers endorse their use.

**NOTE:** Many of the terms in the methods are dependent on variables (e.g., time phase, target organ, PAG, etc.). When critical, these dependencies are shown as subscripts to the appropriate terms. (See Appendix B for the variable list.)

## Outputs

### Final

The final output of this method is the Milk\_DRL value for a radionuclide contaminant for the growing area.

Milk\_DRL<sub>*i*</sub> = Milk Ingestion Derived Response Level, expressed as one of the following:

- a. Milk\_DRL<sub>area</sub>: The areal activity ( $\mu\text{Ci}/\text{m}^2$ ), of radionuclide *i* deposited over a grazing area that would result in the grazing

- animal's milk equaling the Derived Intervention Level (DIL) for that radionuclide;
- b.  $Milk\_DRL_{mass}$ : The mass concentration ( $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ) of radionuclide  $i$  in animal feed that would result in the animal's milk equaling the Derived Intervention Level (DIL) for that radionuclide; or
  - c.  $Milk\_DRL_{\text{water}}$ : The water concentration ( $\mu\text{Ci}/\text{l}$ ) of radionuclide  $i$  in an animal's drinking water that would result in the animal's milk equaling the Derived Intervention Level (DIL) for that radionuclide.

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

None

## Method 3.3.1 Ingestion DRL for Milk based on areal activity ( $\mu\text{Ci}/\text{m}^2$ ) on forage

This method calculates the areal activity level ( $\mu\text{Ci}/\text{m}^2$ ) of a radionuclide deposited over a grazing area that would result in a grazing animal's milk equaling the DIL for the radionuclide.

### Calculation

Equation 3.3-1 shows this  $Milk\_DRL_{area}$  calculation.

$$Milk\_DRL_{area,A,i} = \frac{DIL_{organ,age,i} * \rho_{milk}}{\left[ \frac{(CRF * AFDIR)}{Y} + \frac{ASDIR}{\rho_{soil} * d_m} \right] * FDC_F * TF_{Milk,A,i} * e^{-\lambda_i t_m}} \quad (\text{Eq. 3.3-1})$$

$$\frac{\mu\text{Ci}}{\text{m}^2} = \frac{\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \frac{\text{kg}_{\text{wet}}}{\text{l}}}{\left[ \frac{\left( \text{unitless} * \frac{\text{kg}_{\text{wet}}}{\text{d}} \right)}{\frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \frac{\frac{\text{kg}_{\text{soil}}}{\text{d}}}{\frac{\text{kg}_{\text{soil}}}{\text{m}^3} * \text{m}} \right] * \text{unitless} * \frac{\mu\text{Ci}/\text{l}}{\mu\text{Ci}/\text{d}} * \text{unitless}}$$

where:

$Milk\_DRL_{area,A,i}$  = Milk Ingestion Derived Response Level – Area, the areal activity of radionuclide  $i$  deposited over a grazing area that would result in the

- grazing animal's (A) milk equaling the DIL for that radionuclide,  $\mu\text{Ci}/\text{m}^2$ ;
- $DIL_{organ, age, i}$  = Derived Intervention Level, the concentration of radionuclide  $i$  in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ;
- $\rho_{\text{milk}}$  = Milk density (See Appendix C, Table 11),  $\text{kg}_{\text{wet}}/\text{l}$ ;
- $CRF$  = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop, unitless;
- $AFDIR$  = Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed,  $\text{kg}_{\text{wet}}/\text{d}$ ;
- $Y$  = Crop Yield, the mass of crop grown per area of land,  $\text{kg}_{\text{wet}}/\text{m}^2$ ;
- $ASDIR$  = Animal Soil Daily Ingestion Rate, the daily rate at which an animal consumes soil,  $\text{kg}_{\text{soil}}/\text{d}$ ;
- $\rho_{\text{soil}}$  = Soil density (See Appendix C, Table 11),  $\text{kg}_{\text{soil}}/\text{m}^3$ ;
- $d_m$  = Mixing Depth (See Appendix C, Table 11), m;
- $FDC_F$  = Fraction of Diet Contaminated (feed), the fraction of the animal's diet that is from contaminated feed, unitless;
- NOTE:** See Appendix C, Table 11 for default  $FDC$  values. If there is convincing local information that the actual  $FDC$  is considerably different, local authorities may decide to use a different  $FDC$ .
- $TF_{\text{Milk}, A, i}$  = Transfer Factor for Milk, the fraction of radionuclide  $i$  consumed by an animal (A) that is transferred to the milk produced by the animal,  $\mu\text{Ci}/\text{l}$  per  $\mu\text{Ci}/\text{d}$ ;
- $\lambda_i$  = Decay constant for radionuclide  $i$ ,  $\text{d}^{-1}$ ;
- $t_m$  = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d; and
- $e^{-\lambda t_m}$  = Radioactive Decay adjustment for radionuclide  $i$  over time  $t_m$ , unitless.

### Method 3.3.2 Ingestion DRL for Milk based on radionuclide concentration ( $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ) in forage mass

This method calculates the mass concentration level ( $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ) of a radionuclide in animal feed that would result in the animal's milk equaling the DIL for the radionuclide.

#### Calculation

Equation 3.3-2 shows this  $Milk\_DRL_{\text{mass}}$  calculation.

$$Milk\_DRL_{\text{mass}, A, i} = \frac{DIL_{organ, age, i} * \rho_{\text{milk}}}{AFDIR * FDC_F * TF_{\text{Milk}, A, i} * e^{-\lambda t_m}} \quad (\text{Eq. 3.3-2})$$

$$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} = \frac{\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \frac{\text{kg}_{\text{wet}}}{1}}{\frac{\text{kg}_{\text{wet}}}{\text{d}} * \text{unitless} * \frac{\mu\text{Ci}/1}{\mu\text{Ci}/\text{d}} * \text{unitless}}$$

where:

$Milk\_DRL_{mass,A,i}$  = Milk Ingestion Derived Response Level – Mass, the mass concentration of radionuclide  $i$  in animal feed that would result in the grazing animal's ( $A$ ) milk equaling the DIL for that radionuclide,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ;

$DIL_{organ, age, i}$  = Derived Intervention Level, the concentration of radionuclide  $i$  in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ;

$\rho_{milk}$  = Milk density (See Appendix C, Table 11),  $\text{kg}_{\text{wet}}/\text{l}$ ;

$AFDIR$  = Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed,  $\text{kg}_{\text{wet}}/\text{d}$ ;

$FDC_F$  = Fraction of Diet Contaminated (feed), the fraction of the animal's diet that is from contaminated feed, unitless;

**NOTE:** See Appendix C, Table 11 for default  $FDC$  values. If there is convincing local information that the actual  $FDC$  is considerably different, local authorities may decide to use a different  $FDC$ .

$TF_{Milk,A,i}$  = Transfer Factor for Milk, the fraction of radionuclide  $i$  consumed by an animal ( $A$ ) that is transferred to the milk produced by the animal,  $\mu\text{Ci}/\text{l}$  per  $\mu\text{Ci}/\text{d}$ ;

$\lambda_i$  = Decay constant for radionuclide  $i$ ,  $\text{d}^{-1}$ ;

$t_m$  = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11),  $\text{d}$ ; and

$e^{-\lambda t_m}$  = Radioactive Decay adjustment for radionuclide  $i$  over time  $t_m$ , unitless.

**NOTE:** Soil ingestion is not included in this method because any soil (and any radioactivity) included in the fodder being analyzed would inherently be included in the mass and activity values determined by the measurement process.

### Method 3.3.3 Ingestion DRL for Milk based on radionuclide concentration ( $\mu\text{Ci}/\text{l}$ ) in water

This method calculates the concentration level ( $\mu\text{Ci}/\text{l}$ ) of a radionuclide in an animal's drinking water that would result in the animal's milk equaling the DIL for the radionuclide.

#### Calculation

Equation 3.3-3 shows this  $Milk\_DRL_{water}$  calculation.

$$Milk\_DRL_{water,A,i} = \frac{DIL_{organ,age,i} * \rho_{milk}}{AWDIR * FDC_W * TF_{Milk,A,i} * e^{-\lambda_i t_m}} \quad (\text{Eq. 3.3-3})$$

$$\frac{\mu\text{Ci}}{1} = \frac{\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \frac{\text{kg}_{\text{wet}}}{1}}{\frac{1}{\text{d}} * \text{unitless} * \frac{\mu\text{Ci}}{\mu\text{Ci}} * \frac{1}{\text{d}} * \text{unitless}}$$

where:

$Milk\_DRL_{water,A,i}$  = Milk Ingestion Derived Response Level – Water, the water concentration of radionuclide  $i$  in an animal's drinking water that would result in the grazing animal's (A) milk equaling the DIL for that radionuclide,  $\mu\text{Ci/l}$ ;

$DIL_{organ,age,i}$  = Derived Intervention Level, the concentration of radionuclide  $i$  in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG,  $\mu\text{Ci/kg}_{\text{wet}}$ ;

$\rho_{milk}$  = Milk density (See Appendix C, Table 11),  $\text{kg}_{\text{wet}}/\text{l}$ ;

$AWDIR$  = Animal Water Daily Ingestion Rate, the daily rate at which an animal consumes water,  $\text{l/d}$ ;

$FDC_W$  = Fraction of Diet Contaminated (water), the fraction of an animal's diet that is from contaminated water, unitless;

**NOTE:** See Appendix C, Table 11 for default  $FDC$  values. If there is convincing local information that the actual  $FDC$  is considerably different, local authorities may decide to use a different  $FDC$ .

$TF_{Milk,A,i}$  = Transfer Factor for Milk, the fraction of radionuclide  $i$  consumed by an animal (A) that is transferred to the milk produced by the animal,  $\mu\text{Ci/l}$  per  $\mu\text{Ci/d}$ ;

$\lambda_i$  = Decay constant for radionuclide  $i$ ,  $\text{d}^{-1}$ ;

$t_m$  = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11),  $\text{d}$ ; and

$e^{-\lambda_i t_m}$  = Radioactive Decay adjustment for radionuclide  $i$  over time  $t_m$ , unitless.

**NOTE:** Soil ingestion is not included in this method because any soil (and any radioactivity) included in the water being analyzed would inherently be included in the mass and activity values determined by the measurement process.

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**EXAMPLE 1**

**Problem: Calculate the Cow Milk Ingestion DRL for  $^{60}\text{Co}$  in units of areal activity ( $\mu\text{Ci}/\text{m}^2$ )**

The most conservative DIL for  $^{60}\text{Co}$  is  $0.02 \mu\text{Ci}/\text{kg}_{\text{wet}}$  (3 month old, whole body).

Equation 3.3-1 can be used to calculate the DRL.

$$\text{Milk\_DRL}_{\text{area},A,i} = \frac{\text{DIL}_{\text{organ,age},i} * \rho_{\text{milk}}}{\left[ \frac{(\text{CRF} * \text{AFDIR})}{Y} + \frac{\text{ASDIR}}{\rho_{\text{soil}} * d_m} \right] * \text{FDC}_F * \text{TF}_{\text{Milk},A,i} * e^{-\lambda_i t_m}}$$

Assuming:

$$\begin{aligned} \rho_{\text{milk}} &= 1.04 \text{ kg}_{\text{wet}}/\text{l}, \\ \text{CRF} &= 0.5 \text{ (pasture)}, \\ \text{AFDIR}_{\text{cow}} &= 50 \text{ kg}_{\text{wet}}/\text{d}, \\ Y &= 0.7 \text{ kg}_{\text{wet}}/\text{m}^2, \\ \text{ASDIR}_{\text{cow}} &= 0.5 \text{ kg}_{\text{soil}}/\text{d}, \\ \rho_{\text{soil}} &= 1600 \text{ kg}_{\text{soil}}/\text{m}^3, \\ d_m &= 1.0\text{E-}03 \text{ m}, \\ \text{FDC}_F &= 1.0, \\ \text{TF}_{\text{Milk,cow},^{60}\text{Co}} &= 3.0\text{E-}04 \mu\text{Ci}/\text{l per } \mu\text{Ci}/\text{d}, \\ \lambda_{\text{Co}} &= 3.60\text{E-}04 \text{ d}^{-1}, \text{ and} \\ t_m &= 2 \text{ days}. \end{aligned}$$

The  $\text{Milk\_DRL}_{\text{area}}$  for  $^{60}\text{Co}$  for cow milk equals:

$$\text{Milk\_DRL}_{\text{area,cow},^{60}\text{Co}} = \frac{0.02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * 1.04 \frac{\text{kg}_{\text{wet}}}{\text{l}}}{\left[ \left( \frac{0.5 * 50 \frac{\text{kg}_{\text{wet}}}{\text{d}}}{0.7 \frac{\text{kg}_{\text{wet}}}{\text{m}^2}} \right) + \frac{0.5 \frac{\text{kg}_{\text{soil}}}{\text{d}}}{1600 \frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 1.0\text{E-}03 \text{ m}} \right] * 1 * 3.0\text{E-}04 \frac{\mu\text{Ci}}{\mu\text{Ci}/\text{d}} * e^{-3.6\text{E-}04 \text{d}^{-1} * 2\text{d}}} = 1.92 \frac{\mu\text{Ci}}{\text{m}^2}$$

Therefore cows grazing in areas with  $^{60}\text{Co}$  contamination on the ground greater than  $1.92 \mu\text{Ci}/\text{m}^2$  have the potential to produce milk that would equal the DIL. Milk that equals the DIL could produce a dose that equals the PAG when consumed by a 3 month old.

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**EXAMPLE 2**

**Problem: Calculate the Cow Milk Ingestion DRL for  $^{60}\text{Co}$  in units of mass concentration ( $\mu\text{Ci}/\text{kg}_{\text{wet}}$ )**

The most conservative DIL for  $^{60}\text{Co}$  is  $0.02 \mu\text{Ci}/\text{kg}_{\text{wet}}$  (3 month old, whole body).

Equation 3.3-2 can be used to calculate the DRL.

$$\text{Milk\_DRL}_{\text{mass},A,i} = \frac{\text{DIL}_{\text{organ,age},i} * \rho_{\text{milk}}}{\text{AFDIR} * \text{FDC}_F * \text{TF}_{\text{Milk},A,i} * e^{-\lambda_i t_m}}$$

Assuming:

$$\begin{aligned} \rho_{\text{milk}} &= 1.04 \text{ kg}_{\text{wet}}/\text{l}, \\ \text{AFDIR}_{\text{cow}} &= 50 \text{ kg}_{\text{wet}}/\text{d}, \\ \text{FDC}_F &= 1.0, \\ \text{TF}_{\text{Milk,cow},^{60}\text{Co}} &= 3.0\text{E-}04 \mu\text{Ci}/\text{l per } \mu\text{Ci}/\text{d}, \\ \lambda_{\text{Co}} &= 3.60\text{E-}04 \text{ d}^{-1}, \text{ and} \\ t_m &= 2 \text{ days.} \end{aligned}$$

The  $\text{Milk\_DRL}_{\text{mass}}$  for  $^{60}\text{Co}$  for cow milk equals:

$$\text{Milk\_DRL}_{\text{mass,cow},^{60}\text{Co}} = \frac{0.02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * 1.04 \frac{\text{kg}_{\text{wet}}}{\text{l}}}{50 \frac{\text{kg}_{\text{wet}}}{\text{d}} * 1 * 3.0\text{E-}04 \frac{\mu\text{Ci}}{\text{d}} * e^{-3.6\text{E-}04 * 2}} = 1.38 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

Therefore cows that eat forage with  $^{60}\text{Co}$  contamination greater than  $1.38 \mu\text{Ci}/\text{kg}_{\text{wet}}$  have the potential to produce milk that would equal the DIL. Milk that equals the DIL could produce a dose that equals the PAG when consumed by a 3 month old.

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### EXAMPLE 3

**Problem: Calculate the Cow Milk Ingestion DRL for  $^{60}\text{Co}$  in units of water concentration ( $\mu\text{Ci/l}$ )**

The most conservative DIL for  $^{60}\text{Co}$  is  $0.02 \mu\text{Ci/kg}_{\text{wet}}$  (3 month old, whole body).

Equation 3.3-3 can be used to calculate the DRL.

$$\text{Milk\_DRL}_{\text{water},A,i} = \frac{\text{DIL}_{\text{organ,age},i} * \rho_{\text{milk}}}{\text{AWDIR} * \text{FDC}_W * \text{TF}_{\text{Milk},A,i} * e^{-\lambda_i t_m}}$$

Assuming:

$$\begin{aligned} \rho_{\text{milk}} &= 1.04 \text{ kg}_{\text{wet}}/\text{l}, \\ \text{AWDIR}_{\text{cow}} &= 60 \text{ l/d}, \\ \text{FDC}_W &= 1.0, \\ \text{TF}_{\text{Milk,cow},^{60}\text{Co}} &= 3.0\text{E-}04 \mu\text{Ci/l per } \mu\text{Ci/d}, \\ \lambda_{\text{Co}} &= 3.60\text{E-}04 \text{ d}^{-1}, \text{ and} \\ t_m &= 2 \text{ days} \end{aligned}$$

The  $\text{Milk\_DRL}_{\text{water}}$  for  $^{60}\text{Co}$  for cow milk equals:

$$\text{Milk\_DRL}_{\text{water,cow},^{60}\text{Co}} = \frac{0.02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * 1.04 \frac{\text{kg}_{\text{wet}}}{\text{l}}}{60 \frac{\text{l}}{\text{d}} * 1 * 3.0\text{E-}04 \frac{\mu\text{Ci}}{\mu\text{Ci/d}} * e^{-3.6\text{E-}04 * 2}} = 1.15 \frac{\mu\text{Ci}}{\text{l}}$$

Therefore cows that drink water with  $^{60}\text{Co}$  contamination greater than  $1.15 \mu\text{Ci/l}$  have the potential to produce milk that would equal the DIL. Milk that equals the DIL could produce a dose that equals the PAG when consumed by a 3 month old.

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## METHOD 3.4 MEAT INGESTION DERIVED RESPONSE LEVEL

### Application

This method has been developed to calculate Ingestion Derived Response Levels for radioactive material deposited on animal forage/water for the meat pathway.

The Meat Ingestion Derived Response Level:

- 1) Represents:
  - a. Meat\_DRL<sub>area,A,i</sub>: The areal activity ( $\mu\text{Ci}/\text{m}^2$ ), of radionuclide *i* deposited over a grazing area that would result in a grazing animal's (*A*) meat equaling the Derived Intervention Level (DIL) for that radionuclide when the animal is harvested;
  - b. Meat\_DRL<sub>mass,A,i</sub>: The mass concentration ( $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ), of radionuclide *i* in animal feed that would result in the animal's (*A*) meat equaling the Derived Intervention Level (DIL) for that radionuclide when the animal is harvested; or
  - c. Meat\_DRL<sub>water,A,i</sub>: The water concentration ( $\mu\text{Ci}/\text{l}$ ), of radionuclide *i* in an animal's drinking water that would result in the animal's (*A*) meat equaling the Derived Intervention Level (DIL) for that radionuclide when the animal is harvested.
- 2) Is indirectly derived (through the DIL) from the PAG for radiological emergency planning established by the Food and Drug Agency (FDA) (FDA98). A projected or measured concentration value greater than the Meat\_DRL indicates the potential to exceed the PAG.
- 3) Is applied during the first year after an incident and based on the most sensitive population (age group) and target organ to provide a large margin of safety to the public.
- 4) Is used to create data products and define contamination levels to assist decision makers in determining where it may be advisable to conduct sampling to evaluate the potential for implementing protective actions (e.g., sheltering livestock, embargos, special product handling).
- 5) Is calculated using the DIL calculated in Method 3.1

### Discussion

The Meat\_DRL predicts the amount of radioactivity deposited either on an animal's grazing area ( $\mu\text{Ci}/\text{m}^2$ ) or in an animal's feed or water ( $\mu\text{Ci}/\text{kg}_{\text{wet}}$  or  $\mu\text{Ci}/\text{l}$ ) that would cause the animal's meat to equal the DIL.

Sampling efforts should concentrate on the area where the contamination is equal to the Meat\_DRL to determine if the DIL has been exceeded in those areas. Protective actions (e.g., use of stored feed) should be considered in areas where the DIL is exceeded. Meat embargo protective actions should be considered after meat samples indicate that the DIL has actually been exceeded. FDA guidance permits food with radioactivity concentrations below the DIL to move in commerce without restriction. However the FDA and local decision makers have flexibility in whether to apply restrictions in special circumstances.

FRMAC does not have the authority to calculate or use different DILs for radionuclides for which the FDA has provided recommended values unless alternate values are requested by the Advisory Team or local decision makers. FRMAC can calculate DILs for the radionuclides for which the FDA does not provide recommended values, but these values are not automatically approved by the FDA and must receive approval from the Advisory Team or local Decision Makers before they are used.

## Assumptions

The FRMAC radiological assessment calculations use the default assumptions established by the FRMAC Assessment Working Group. The following default assumptions are used in this method:

Meat DRLs:

- 1) Apply to individual radionuclides; there is no sum-of-fraction rule (except for the FDA-listed  $^{103}\text{Ru}$  and  $^{106}\text{Ru}$ ).
- 2) Are based on the most restrictive DIL for each radionuclide based on age group and target organ. See Method 3.1 for DIL calculation assumptions.
- 3) Assume only one intake pathway is present (i.e., if forage/soil is contaminated, drinking water is clean).
- 4) Animal intake rates are assumed to be
  - Cow – 50  $\text{kg}_{\text{wet}}/\text{d}$  for feed, 60 l/d for water, and 0.5  $\text{kg}_{\text{soil}}/\text{d}$  for soil.
  - Goat – 6  $\text{kg}_{\text{wet}}/\text{d}$  for feed, 8 l/d for water, and 0.06  $\text{kg}_{\text{soil}}/\text{d}$  for soil.
- 5) Assume a forage yield of 0.7  $\text{kg}_{\text{wet}}/\text{m}^2$  for pastureland.
- 6) Assume a soil density of 1600  $\text{kg}_{\text{soil}}/\text{m}^3$ .
- 7) Assume a mixing depth of 1.0E-03 m for the first growing season (EPA89) and 0.15 after plowing.
- 8) Assume a half life of 15 days for material weathering off plant material.
- 9) Assume a time to market of 20 days.
- 10) Assume the animal consumes the contaminated feed/water over a period of time sufficient for the animal product intended for human consumption to reach equilibrium.
- 11) Assume that 100% of the contaminated pathway (feed or water) is contaminated.

- 12) Are calculated for food (meat or animal feed) as prepared for consumption. To compare with analytical results it may be necessary to convert to “dry weight,” see Method 4.2.
- 13) Uses Crop Retention Factors for pastureland of:
  - 1.0 for radioiodine and
  - 0.5 for all other radionuclides.
- 14) DRLs for FDA grouped radionuclides (e.g.,  $^{134}\text{Cs}+^{137}\text{Cs}$ ) are adjusted for decay during Grazing Time and Time to Market using the decay constant for the longest-lived group member.

## Inputs

The following information is required to perform the methods described in this section:

- 1) Data – Composition of the deposited radionuclide mixture (radionuclides and concentration). This information may come from predictive analysis (models) or field data (monitoring and/or samples).
- 2) Constants – Crop Retention Factor, Crop Yield, Animal Daily Intake Rates (Feed, Water, Soil), Transfer Factor for each type of Meat and for each radionuclide.
- 3) Other Factors – Decay of radionuclides during the time period under consideration, fraction of animals’ diet contaminated, soil mixing depth.
- 4) Appropriate DIL for each radionuclide – Calculated using Method 3.1.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available and Decision Makers endorse their use.

**NOTE:** Many of the terms in the methods are dependent on variables (e.g., time phase, target organ, PAG, etc.). When critical, these dependencies are shown as subscripts to the appropriate terms. (See Appendix B for the variable list.)

## Outputs

### Final

The final output of this method is the Meat\_DRL value for a radionuclide contaminant for the growing area.

Meat\_DRL<sub>*i*</sub> = Meat Ingestion Derived Response Level, expressed as one of the following:

- a. Meat\_DRL<sub>area,A,*i*</sub>: The areal activity ( $\mu\text{Ci}/\text{m}^2$ ), of radionuclide *i* deposited over a grazing area that would result in a grazing animal’s (*A*) meat equaling the Derived Intervention Level (DIL) for that radionuclide when the animal is harvested;

- b.  $Meat\_DRL_{mass,A,i}$ : The mass concentration ( $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ) of radionuclide  $i$  in animal feed that would result in the animal's (A) meat equaling the Derived Intervention Level (DIL) for that radionuclide when the animal is harvested; or
- c.  $Meat\_DRL_{water,A,i}$ : The water concentration ( $\mu\text{Ci}/\text{l}$ ) of radionuclide  $i$  in an animal's drinking water that would result in the animal's (A) meat equaling the Derived Intervention Level (DIL) for that radionuclide when the animal is harvested.

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

None

## Method 3.4.1 Ingestion DRL for Meat based on areal activity ( $\mu\text{Ci}/\text{m}^2$ ) on forage

This method calculates the areal activity level ( $\mu\text{Ci}/\text{m}^2$ ) of a radionuclide deposited over a grazing area that would result in a grazing animal's meat equaling the DIL for the radionuclide.

### Calculation

Equation 3.4-1 shows this  $Meat\_DRL_{area}$  calculation.

$$Meat\_DRL_{area,A,i} = \frac{DIL_{organ,age,i}}{\left[ \frac{\left( CRF * \left( \frac{1-e^{-\lambda_w t_g}}{\lambda_w * t_g} \right) * AFDIR \right)}{Y} + \frac{ASDIR}{\rho_{soil} * d_m} \right] * FDC_F * TF_{Meat,A,i} * \left( \frac{1-e^{-\lambda_i t_m}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m}}$$

(Eq. 3.4-1)

$$\frac{\mu\text{Ci}}{\text{m}^2} = \frac{\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}}{\left[ \frac{\left( \text{unitless} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \frac{\text{kg}_{\text{wet}}}{\text{d}} \right)}{\frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \frac{\frac{\text{kg}_{\text{soil}}}{\text{d}}}{\frac{\text{kg}_{\text{soil}}}{\text{m}^3} * \text{m}} \right] * \text{unitless} * \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \text{unitless}}$$

where:

- $Meat\_DRL_{area,A,i}$  = Meat Ingestion Derived Response Level – Area, the areal activity of radionuclide  $i$  that would result in a grazing animal's ( $A$ ) meat equaling the DIL for that radionuclide,  $\mu\text{Ci}/\text{m}^2$ ;
- $DIL_{organ, age, i}$  = Derived Intervention Level, the concentration of radionuclide  $i$  in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ;
- $CRF$  = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop, unitless;
- $\lambda_w$  = Decay constant for weathering radioactive material off plants (See Appendix C, Table 11),  $\text{d}^{-1}$ ;
- $t_g$  = Grazing Time, time from deposition or sampling to the end of the grazing period, d;
- $\left( \frac{1 - e^{-\lambda_w t_g}}{\lambda_w * t_g} \right)$  = Integrated average weathering of radioactive material off plants during the time the animal is grazing in the field (the integral of the weathering over the Grazing Time divided by the Grazing Time), unitless;
- $AFDIR$  = Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed,  $\text{kg}_{\text{wet}}/\text{d}$ ;
- $Y$  = Crop Yield, the mass of crop grown per area of land,  $\text{kg}_{\text{wet}}/\text{m}^2$ ;
- $ASDIR$  = Animal Soil Daily Ingestion Rate, the daily rate at which an animal consumes soil,  $\text{kg}_{\text{soil}}/\text{d}$ ;
- $\rho_{\text{soil}}$  = Soil density (See Appendix C, Table 11),  $\text{kg}_{\text{soil}}/\text{m}^3$ ;
- $d_m$  = Mixing Depth (See Appendix C, Table 11), m;
- $FDC_F$  = Fraction of Diet Contaminated (feed), the fraction of the animal's diet that is from contaminated feed, unitless;
- NOTE:** See Appendix C, Table 11 for default  $FDC$  values. If there is convincing local information that the actual  $FDC$  is considerably different, local authorities may decide to use a different  $FDC$ .
- $TF_{Meat,A,i}$  = Transfer Factor for Meat, the fraction of radionuclide  $i$  consumed by an animal ( $A$ ) that is transferred to the meat of the animal,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$  per  $\mu\text{Ci}/\text{d}$ ;
- $\lambda_i$  = Decay constant for radionuclide  $i$ ,  $\text{d}^{-1}$ ;
- $\left( \frac{1 - e^{-\lambda_i t_g}}{\lambda_i * t_g} \right)$  = Integrated average decay of radioactive material during the time the animal is grazing in the field (the integral of radioactive decay over the Grazing Time divided by the Grazing Time), unitless;
- $t_m$  = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d; and
- $e^{-\lambda_i t_m}$  = Radioactive Decay adjustment for radionuclide  $i$  over time  $t_m$ , unitless.

## Method 3.4.2 Ingestion DRL for Meat based on radionuclide concentration ( $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ) in forage mass

This method calculates the mass concentration level ( $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ) of a radionuclide in animal feed that would result in the animal's meat equaling the DIL for the radionuclide.

### Calculation

Equation 3.4-2 shows this  $Meat\_DRL_{mass}$  calculation.

$$Meat\_DRL_{mass,A,i} = \frac{DIL_{organ,age,i}}{AFDIR * FDC_F * TF_{Meat,A,i} * \left( \frac{1 - e^{-\lambda_w t_g}}{\lambda_w * t_g} \right) * \left( \frac{1 - e^{-\lambda_i t_m}}{\lambda_i * t_m} \right) * e^{-\lambda_i t_m}} \quad (\text{Eq. 3.4-2})$$

$$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} = \frac{\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}}{\frac{\text{kg}_{\text{wet}}}{\text{d}} * \text{unitless} * \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \frac{\text{unitless}}{\mu\text{Ci}/\text{d}} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \text{unitless}}$$

where:

$Meat\_DRL_{mass,A,i}$  = Meat Ingestion Derived Response Level – Mass, the mass concentration of radionuclide  $i$  in animal feed that would result in the animal's (A) meat equaling the DIL for that radionuclide when the animal is harvested,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ;

$DIL_{organ, age, i}$  = Derived Intervention Level, the concentration of radionuclide  $i$  in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ;

$AFDIR$  = Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed,  $\text{kg}_{\text{wet}}/\text{d}$ ;

$FDC_F$  = Fraction of Diet Contaminated (feed), the fraction of an animal's diet that is from contaminated feed, unitless;

**NOTE:** See Appendix C, Table 11 for default  $FDC$  values. If there is convincing local information that the actual  $FDC$  is considerably different, local authorities may decide to use a different  $FDC$ .

$TF_{Meat,A,i}$  = Transfer Factor for Meat, the fraction of radionuclide  $i$  consumed by an animal (A) that is transferred to the meat of the animal,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$  per  $\mu\text{Ci}/\text{d}$ ;

$\lambda_w$  = Decay constant for weathering radioactive material off plants (See Appendix C, Table 11),  $\text{d}^{-1}$ ;

$t_g$  = Grazing Time, time from deposition or sampling to the end of the grazing period, d;

$\lambda_i$  = Decay constant for radionuclide  $i$ ,  $d^{-1}$ ;

$\left( \frac{1 - e^{-\lambda_w t_g}}{\lambda_w * t_g} \right)$  = Integrated average weathering of radioactive material off plants during the time the animal is grazing in the field (the integral of the weathering over the Grazing Time divided by the Grazing Time), unitless;

$\left( \frac{1 - e^{-\lambda_i t_g}}{\lambda_i * t_g} \right)$  = Integrated average decay of radioactive material during the time the animal is grazing in the field (the integral of radioactive decay over the Grazing Time divided by the Grazing Time), unitless;

$t_m$  = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d; and

$e^{-\lambda_i t_m}$  = Radioactive Decay adjustment for radionuclide  $i$  over time  $t_m$ , unitless.

**NOTE:** Soil ingestion is not included in this method because any soil (and any radioactivity) included in the fodder being analyzed would inherently be included in the mass and activity values determined by the measurement process.

### Method 3.4.3 Ingestion DRL for Meat based on radionuclide concentration ( $\mu\text{Ci/l}$ ) in water

This method calculates the concentration level ( $\mu\text{Ci/l}$ ) of a radionuclide in an animal's drinking water that would result in the animal's meat equaling the DIL for the radionuclide.

**NOTE:** Because any form of "weathering" that could be applied to this calculation could vary by such a large amount (dependent on water source), and because not including weathering is the conservative approach, no consideration of physical removal of contamination from the drinking water is addressed in this method.

### Calculation

Equation 3.4-3 shows this  $Meat\_DRL_{water}$  calculation.

$$Meat\_DRL_{water,A,i} = \frac{DIL_{organ,age,i}}{AWDIR * FDC_W * TF_{Meat,A,i} * \left( \frac{1 - e^{-\lambda_i t_g}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m}} \quad (\text{Eq. 3.4-3})$$

$$\frac{\mu\text{Ci}}{\text{l}} = \frac{\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}}{\frac{\frac{1}{\text{d}} * \text{unitless} * \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}}{\frac{\mu\text{Ci}}{\text{d}}} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \text{unitless}}$$

where:

$Meat\_DRL_{water,A,i}$  = Meat Ingestion Derived Response Level – Water, the water concentration of radionuclide  $i$  in an animal's drinking water that would result in the animal's ( $A$ ) meat equaling the DIL for that radionuclide when the animal is harvested,  $\mu\text{Ci}/\text{l}$ ;

$DIL_{organ, age, i}$  = Derived Intervention Level, the concentration of radionuclide  $i$  in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ;

$AWDIR$  = Animal Water Daily Ingestion Rate, the daily rate at which an animal consumes water,  $\text{l}/\text{d}$ ;

$FDC_W$  = Fraction of Diet Contaminated (water), the fraction of an animal's diet that is from contaminated water, unitless;

**NOTE:** See Appendix C, Table 11 for default  $FDC$  values. If there is convincing local information that the actual  $FDC$  is considerably different, local authorities may decide to use a different  $FDC$ .

$TF_{Meat,A,i}$  = Transfer Factor for Meat, the fraction of radionuclide  $i$  consumed by an animal ( $A$ ) that is transferred to the meat of the animal,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$  per  $\mu\text{Ci}/\text{d}$ ;

$\lambda_i$  = Decay constant for radionuclide  $i$ ,  $\text{d}^{-1}$ ;

$t_g$  = Grazing Time, time from deposition or sampling to the end of the grazing period,  $\text{d}$ ;

$\left( \frac{1 - e^{-\lambda_i t_g}}{\lambda_i * t_g} \right)$  = Integrated average decay of radioactive material during the time the

animal is grazing in the field (the integral of radioactive decay over the Grazing Time divided by the Grazing Time), unitless;

$t_m$  = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11),  $\text{d}$ ; and

$e^{-\lambda_i t_m}$  = Radioactive Decay adjustment for radionuclide  $i$  over time  $t_m$ , unitless.

**NOTE:** Soil ingestion is not included in this method because any soil (and any radioactivity) included in the water being analyzed would inherently be included in the mass and activity values determined by the measurement process.

## EXAMPLE 1

**Problem:** Calculate the Meat (Beef) Ingestion DRL for  $^{60}\text{Co}$  in units of areal activity ( $\mu\text{Ci}/\text{m}^2$ )

The most conservative DIL for  $^{60}\text{Co}$  is  $0.02 \mu\text{Ci}/\text{kg}_{\text{wet}}$  (3 month old, whole body).

Assuming that the cow will continue to graze on the contaminated field for 90 days after deposition, Equation 3.4-1 can be used to calculate the DRL.

$$Meat\_DRL_{area,A,i} = \frac{DIL_{organ,age,i}}{\left[ \frac{\left( CRF * \left( \frac{1-e^{-\lambda_w t_g}}{\lambda_w * t_g} \right) * AFDIR \right)}{Y} + \frac{ASDIR}{\rho_{soil} * d_m} \right] * FDC_F * TF_{Meat,A,i} * \left( \frac{1-e^{-\lambda_i t_m}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m}}$$

Assuming:

$$\begin{aligned} CRF &= 0.5 \text{ (pasture),} \\ \lambda_w &= 4.62\text{E-}02 \text{ d}^{-1}, \\ t_g &= 90 \text{ d,} \\ AFDIR_{cow} &= 50 \text{ kg}_{\text{wet}}/\text{d,} \\ Y &= 0.7 \text{ kg}_{\text{wet}}/\text{m}^2, \\ ASDIR_{cow} &= 0.5 \text{ kg}_{\text{soil}}/\text{d,} \\ \rho_{soil} &= 1600 \text{ kg}_{\text{soil}}/\text{m}^3, \\ d_m &= 1.0\text{E-}03 \text{ m,} \\ FDC_F &= 1.0, \\ TF_{Meat,cow,^{60}\text{Co}} &= 1.0\text{E-}02 \mu\text{Ci}/\text{kg}_{\text{wet}} \text{ per } \mu\text{Ci}/\text{d,} \\ \lambda_{Co} &= 3.60\text{E-}04 \text{ d}^{-1}, \text{ and} \\ t_m &= 20 \text{ days} \end{aligned}$$

The  $Meat\_DRL_{area}$  for  $^{60}\text{Co}$  for Beef equals:

$$\begin{aligned} Meat\_DRL_{area,cow,^{60}\text{Co}} &= \frac{0.02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}}{\left[ \frac{\left( 0.5 * \frac{1-e^{-4.62\text{E-}02\text{d}^{-1} * 90\text{d}}}{4.62\text{E-}02\text{d}^{-1} * 90\text{d}} * 50 \frac{\text{kg}_{\text{wet}}}{\text{d}} \right)}{0.7 \frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \frac{0.5 \frac{\text{kg}_{\text{soil}}}{\text{d}}}{1600 \frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 1.0\text{E-}03 \text{ m}} \right] * 1 * 1.0\text{E-}02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \frac{1-e^{-3.6\text{E-}04\text{d}^{-1} * 90\text{d}}}{3.6\text{E-}04\text{d}^{-1} * 90\text{d}} * e^{-3.6\text{E-}04 * 20}} \\ &= 0.232 \frac{\mu\text{Ci}}{\text{m}^2} \end{aligned}$$

Therefore cows grazing for 90 days in areas with  $^{60}\text{Co}$  contamination on the ground greater than  $0.232 \mu\text{Ci}/\text{m}^2$  at the start of the grazing period have the potential to produce meat (beef) that would equal the DIL. Meat that equals the DIL could produce a dose that equals the PAG when consumed by a 3 month old.

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**EXAMPLE 2**

**Problem: Calculate the Meat (Beef) Ingestion DRL for  $^{60}\text{Co}$  in units of mass concentration ( $\mu\text{Ci}/\text{kg}_{\text{wet}}$ )**

The most conservative DIL for  $^{60}\text{Co}$  is  $0.02 \mu\text{Ci}/\text{kg}_{\text{wet}}$  (3 month old, whole body).

Assuming that the cow will continue to graze on the contaminated field for 90 days after deposition, Equation 3.4-2 can be used to calculate the DRL.

$$Meat\_DRL_{mass,A,i} = \frac{DIL_{organ,age,i}}{AFDIR * FDC_F * TF_{Meat,A,i} * \left( \frac{1 - e^{-\lambda_w t_g}}{\lambda_w * t_g} \right) * \left( \frac{1 - e^{-\lambda_i t_g}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m}}$$

Assuming:

$$\begin{aligned} AFDIR_{cow} &= 50 \text{ kg}_{\text{wet}}/\text{d}, \\ FDC_F &= 1.0, \\ TF_{Meat,cow,^{60}\text{Co}} &= 1.0\text{E-}02 \mu\text{Ci}/\text{kg}_{\text{wet}} \text{ per } \mu\text{Ci}/\text{d}, \\ \lambda_w &= 4.62\text{E-}02 \text{ d}^{-1}, \\ t_g &= 90 \text{ d}, \\ \lambda_{Co} &= 3.60\text{E-}04 \text{ d}^{-1}, \text{ and} \\ t_m &= 20 \text{ days} \end{aligned}$$

The  $Meat\_DRL_{mass}$  for  $^{60}\text{Co}$  for Beef equals:

$$\begin{aligned} Meat\_DRL_{mass,cow,^{60}\text{Co}} &= \frac{0.02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}}{50 \frac{\text{kg}_{\text{wet}}}{\text{d}} * 1 * 1.0\text{E-}02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}/\text{d}} * \frac{1 - e^{-4.62\text{E-}02 \text{d}^{-1} * 90\text{d}}}{4.62\text{E-}02 \text{d}^{-1} * 90\text{d}} * \frac{1 - e^{-3.6\text{E-}04 \text{d}^{-1} * 90\text{d}}}{3.6\text{E-}04 \text{d}^{-1} * 90\text{d}} * e^{-3.6\text{E-}04 * 20}} \\ &= 0.172 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} \end{aligned}$$

Therefore cows that eat forage for 90 days with  $^{60}\text{Co}$  contamination greater than  $0.172 \mu\text{Ci}/\text{kg}_{\text{wet}}$  at the start of the grazing period have the potential to produce meat (beef) that would equal the DIL. Meat that equals the DIL could produce a dose that equals the PAG when consumed by a 3 month old.

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### EXAMPLE 3

**Problem: Calculate the Meat (Beef) Ingestion DRL for  $^{60}\text{Co}$  in units of water concentration ( $\mu\text{Ci/l}$ )**

The most conservative DIL for  $^{60}\text{Co}$  is  $0.02 \mu\text{Ci/kg}_{\text{wet}}$  (3 month old, whole body).

Assuming that the cow will continue to drink the contaminated water for 90 days after deposition, Equation 3.4-3 can be used to calculate the DRL.

$$\text{Meat}_{\text{DRL}}_{\text{water},A,i} = \frac{\text{DIL}_{\text{organ,age,i}}}{\text{AWDIR} * \text{FDC}_W * \text{TF}_{\text{Meat},A,i} * \left( \frac{1 - e^{-\lambda_i t_g}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m}}$$

Assuming:

$$\begin{aligned} \text{AWDIR}_{\text{cow}} &= 50 \text{ l/d,} \\ \text{FDC}_W &= 1.0, \\ \text{TF}_{\text{Meat,cow},^{60}\text{Co}} &= 1.0\text{E-}02 \mu\text{Ci/kg}_{\text{wet}} \text{ per } \mu\text{Ci/d,} \\ \lambda_{\text{Co}} &= 3.60\text{E-}04 \text{ d}^{-1}, \\ t_g &= 90 \text{ d, and} \\ t_m &= 20 \text{ days} \end{aligned}$$

The  $\text{Meat}_{\text{DRL}}_{\text{water}}$  for  $^{60}\text{Co}$  for Beef equals:

$$\text{Meat}_{\text{DRL}}_{\text{water,cow},^{60}\text{Co}} = \frac{0.02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}}{50 \frac{\text{l}}{\text{d}} * 1 * 1.0\text{E-}02 \frac{\mu\text{Ci}}{\text{d}} * \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \frac{1 - e^{-3.6\text{E-}04\text{d}^{-1} * 90\text{d}}}{3.6\text{E-}04\text{d}^{-1} * 90\text{d}} * e^{-3.6\text{E-}04 * 20}} = 4.1\text{E-}02 \frac{\mu\text{Ci}}{\text{l}}$$

Therefore cows that drink water for 90 days with  $^{60}\text{Co}$  contamination greater than  $4.1\text{E-}02 \mu\text{Ci/l}$  at the start of the drinking period have the potential to produce meat (beef) that would equal the DIL. Meat that equals the DIL could produce a dose that equals the PAG when consumed by a 3 month old.

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## **METHOD 3.5    INGESTION DOSE**

### **Application**

This method has been developed to calculate the Ingestion Dose from the consumption of radioactive material, either in food, milk or water.

The Ingestion Dose:

- 1) Can be applied to the whole body (E) or to a specific organ ( $H_T$ )
- 2) Uses sample results for various food types to calculate the dose that a receptor is projected to receive over a specified time phase (generally 1 year) due to ingestion of the contaminated food.
- 3) Is used to define dose levels to assist decision makers in determining where it may be advisable to implement protective actions (e.g. sheltering livestock, embargos, special product handling).

### **Discussion**

The Ingestion Dose method calculates the expected dose from consuming foods contaminated by radioactive material and is obtained by combining sample results ( $\mu\text{Ci}/\text{kg}$  or  $\mu\text{Ci}/\text{l}$ ) for various food types to produce a total projected dose from the entire diet. Food types generally fall into 4 groups (shown with subgroups):

- 1) Meat/Fish (Beef, Pork, Poultry, Fin Fish, Shell Fish, Other Meat);
- 2) Crop/Produce (Leafy, Exposed, Protected, Other Produce, Breads, Cereals, Other Grains);
- 3) Milk (Fresh Cow's Milk, Other Dairy, Eggs); and
- 4) Beverages (Tap Water, Water Based Drinks, Soups, Other Beverages).

### **Assumptions**

The FRMAC radiological assessment calculations use the default assumptions established by the FRMAC Assessment Working Group. The following default assumptions are used in this method:

- 1) Annual intake for each group and subgroup of foods varies by age group (3 month, 1 yr, 5 yr, 10 yr, 15 yr and adult) (FDA98). If specific intake rates are known, use those instead of defaults.

- 2) Dose calculations are based on samples of foods as prepared for consumption and assume a consumption period of 1 year. To compare with analytical results it may be necessary to convert to “dry weight,” see Method 4.2.
- 3) Inadvertent ingestion of soil is not included in these methods. Activity contained in any soil present in the food would be accounted for in the sample analysis process. Inadvertent Soil Ingestion is discussed in Method 3.7.
- 4) Default calculations utilize the International Commission on Radiological Protection (ICRP) 60+ dosimetry model.

## Inputs

The following information is required to perform the methods described in this section:

- 1) Data – Activity concentration ( $\mu\text{Ci}/\text{kg}$  or  $\mu\text{Ci}/\text{l}$ ) from sample analysis data.
- 2) Constants – Fraction of food contaminated, daily food intake rate, ingestion dose coefficient.
- 3) Other Factors – Decay of radionuclides from sampling time to consumption time (hold time) and over the duration of consumption (default consumption period is 1 year).

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available and Decision Makers endorse their use.

**NOTE:** Many of the terms in the methods are dependent on variables (e.g., time phase, target organ, PAG, etc.). When critical, these dependencies are shown as subscripts to the appropriate terms. (See Appendix B for the variable list.)

## Outputs

### Final

The final output of this method is the Ingestion Dose for a diet including food sources that have been contaminated by a deposition of radioactive material.

$E$  = Committed Effective Dose, the dose to the whole body, from the ingestion of all radionuclides in contaminated food, mrem

$H_T$  = Committed Equivalent Dose, the dose to organ T, from the ingestion of all radionuclides in contaminated food, mrem

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

IngDP = Ingestion Dose Parameter for a specific food type for a specific age group  
(mrem·d/kg<sub>wet</sub>)

### Method 3.5.1 Calculation of Committed Effective Dose

The Ingestion Dose calculation includes contributions from each type of contaminated food at its individual contamination level and appropriate intake rates (averaged over each subgroup). Food contamination levels are decay adjusted for:

- the time between sample evaluation and consumption (hold time) and
- the duration of consumption (default of 1 year).

**NOTE:** Weathering Factor is not included in this calculation because the activities are based on sample results that inherently account for weathering effects.

Equation 3.5-1 represents the final form of the Ingestion Dose calculation:

$$E_{Ing,age} = \sum_{Subgroup} \left( DFIR_{subgroup,age} * FFC_{subgroup} * IngDP_{E,avg,age} \right) \text{ (Eq. 3.5-1)}$$

$$\text{mrem} = \sum_{Subgroup} \left( \frac{\text{kg}_{wet}}{\text{d}} * \text{unitless} * \frac{\text{mrem} \cdot \text{d}}{\text{kg}_{wet}} \right)$$

where:

- $E_{Ing,age}$  = Committed Effective Dose from ingestion, the dose to the whole body, received by a specific age group from ingestion of all radionuclides in all contaminated food types, mrem;
- $DFIR_{subgroup,age}$  = Daily Food Intake Rate for a food subgroup (as prepared for consumption, i.e. wet mass) for a specific age group. (See Appendix C, Table 10), kg<sub>wet</sub>/d;
- $FFC_{subgroup, i}$  = Fraction of Food Subgroup Contaminated, unitless;  
**NOTE:** See Appendix C, Table 11 for default  $FFC$  values. If there is convincing local information that the actual  $FFC$  is considerably different, local authorities may decide to use a different  $FFC$ .
- $IngDP_{E,avg,age}$  = Average Ingestion Dose Parameter for a food subgroup, the average of the individual  $IngDP_{E,f,age}$  for each type of contaminated food in a subgroup for a specific age group, mrem·d/kg<sub>wet</sub>.

**NOTE:** If detailed dietary intake amounts are available, individual food type intakes and fractions contaminated may be used instead of calculating an average for the subgroup, but this method does not assume that information is available.

#### Calculation of IngDP

Equation 3.5-2 shows the calculation of the individual  $IngDP_{E,f,age}$  for each type of contaminated food. These values should be averaged with all other food types in a subgroup to determine the  $IngDP_{E,avg,age}$  for each food subgroup. For example, if the diet includes 3

food types from the “protected” subgroup of the crop/produce group (e.g., corn, carrots, oranges) then sum the IngDPs for each food type and divide by 3 to determine the average Ingestion Dose Parameter for the subgroup.

$$IngDP_{E,f,age} = \sum_i \left( C_{f,i} * IngDC_{E,age,i} * e^{-\lambda_i t_h} * \frac{1 - e^{-\lambda_i t_c}}{\lambda_i} \right) \quad (\text{Eq. 3.5-2})$$

$$\frac{\text{mrem}\cdot\text{d}}{\text{kg}_{\text{wet}}} = \sum_i \left( \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \frac{\text{mrem}}{\mu\text{Ci}} * \text{unitless} * \frac{\text{unitless}}{\text{d}^{-1}} \right)$$

where:

$IngDP_{E,f,age}$  = Ingestion Dose Parameter, the committed effective dose received from ingestion of all radionuclides in a specific food type ( $f$ ) by a specific age group, mrem·d/kg<sub>wet</sub>;

$C_{f,i}$  = Food Contamination, the level of contamination of radionuclide  $i$  in a specific food type ( $f$ ), μCi/kg<sub>wet</sub> or μCi/l;

$IngDC_{E,age,i}$  = Ingestion Dose Coefficient, the ingestion pathway dose coefficient for the whole body ( $E$ ) for a specific age group for radionuclide  $i$ , mrem/μCi;

$\lambda_i$  = Decay constant for radionuclide  $i$ , d<sup>-1</sup>;

$t_h$  = Hold Time, the time elapsed from sample measurement to the beginning of the consumption period, d;

$e^{-\lambda_i t_h}$  = Radioactive Decay adjustment for radionuclide  $i$  over time  $t_h$ , unitless;

$t_c$  = Consumption Time, the length of the consumption period (default 365 days), d;

$\frac{1 - e^{-\lambda_i t_c}}{\lambda_i}$  = Integrated decay over the length of consumption period, d.

### Method 3.5.2 Calculation of Equivalent Dose to an Organ

The preceding calculations assume that the organ of interest is the whole body. The generic approach can be modified to calculate a dose for a specific organ (e.g., skin, thyroid, etc.).

To calculate the dose to a specific organ, replace the IngDC for the whole body with the IngDC for the specific organ when calculating the IngDP.

## EXAMPLE 1

**Problem:** Calculate the Whole Body Ingestion Dose received by an adult from consuming food contaminated with  $^{137}\text{Cs}$  and  $^{60}\text{Co}$  for 1 year beginning 100 days after sampling.

Assume food samples were collected for several food types with results as shown below:

**Table 3.5-E1**

Food Type	$^{60}\text{Co}$ ( $\mu\text{Ci}/\text{kg}_{\text{wet}}$ )	$^{137}\text{Cs}$ ( $\mu\text{Ci}/\text{kg}_{\text{wet}}$ )
Beef	2.50E-03	4.00E-03
Corn	1.50E-03	8.00E-04
Lettuce	1.50E-02	7.00E-03
Milk	2.00E-03 <sup>a</sup>	3.00E-03 <sup>a</sup>
Oranges	6.50E-04	4.00E-05
Water	3.50E-03 <sup>a</sup>	5.00E-04 <sup>a</sup>

<sup>a</sup> Assumes a density of 1.04 kg/l for milk and 1.0 kg/l for water.

### E1.1 Calculating IngDP for each food type using Equation 3.5-2

Table 3.5-E2 shows the values needed to calculate the individual IngDP for each food type.

**Table 3.5-E2**

Radionuclide	IngDC (mrem/ $\mu\text{Ci}$ )	$\lambda$ ( $\text{days}^{-1}$ )	$e^{-\lambda t_h}$	$\frac{1 - e^{-\lambda t_c}}{\lambda}$ (days)
$^{60}\text{Co}$	12.7	3.6E-04	0.965	342
$^{137}\text{Cs}$	50.3	6.33E-05	0.993	361

Time from sampling to start of consumption (hold time ( $t_h$ )): 100 days  
Consumption period ( $t_c$ ): 365 days

Example IngDP calculation for Beef and IngDP values for the other contaminated food types (Table 3.5-E3):

$$\begin{aligned}
 \text{IngDP}_{E,\text{Beef},\text{Adult}} &= 2.5\text{E-}03 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * 12.7 \frac{\text{mrem}}{\mu\text{Ci}} * 0.965 * 342 \text{ d} \\
 &\quad + 4.0\text{E-}03 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * 50.3 \frac{\text{mrem}}{\mu\text{Ci}} * 0.993 * 361 \text{ d} \\
 &= 82.6 \frac{\text{mrem}\cdot\text{d}}{\text{kg}_{\text{wet}}}
 \end{aligned}$$

**Table 3.5-E3**

Food Type	Sub-group	IngDP (mrem·d/kg <sub>wet</sub> )
Beef	Beef	82.6
Corn	Protected Crop	20.7
Lettuce	Leafy Crop	189
Milk	Cow's Milk	62.3
Oranges	Protected Crop	3.45
Water	Tap Water	23.7

## E1.2 Calculating Ingestion Dose using Equation 3.5-1

Obtain the Ingestion Dose for each subgroup by multiplying the IngDP for the subgroup by the associated Daily Food Intake Rate (DFIR) and Fraction of Food Subgroup Contaminated ( $FFC_{\text{subgroup}}$ ), and then add up the subgroup doses to obtain the Committed Effective Dose (E) as shown in Table 3.5-E4.

**Table 3.5-E4**

Food Type	Sub-group	Daily Food Intake Rate (kg <sub>wet</sub> /d) <sup>a</sup>	$FFC_{\text{subgroup}}$	IngDP (mrem·d/kg <sub>wet</sub> )	Subgroup Ingestion Dose (mrem)
Beef	Beef	0.098	1	82.6	8.09
Corn/ Oranges	Protected Crop	0.155	1	12.1 <sup>b</sup>	1.88
Lettuce	Leafy Crop	0.042	1	189	7.94
Milk	Cow's Milk	0.238	1	62.3	14.8
Water	Tap Water	0.679	1	23.7	16.1
E ( $\Sigma$ )					48.8
<sup>a</sup> Assumes a density of 1.04 kg/l for milk and 1.0 kg/l for water. <sup>b</sup> Average value for all the food types in the subgroup. NOTE: When individual food-type DFIRs are known, they may be used and multiplied by the individual food-type IngDP.					

## E1.3 Calculating an Ingestion Dose for an individual organ or for a different age group

To calculate a Committed Equivalent Dose ( $H_T$ ) for a specific organ and/or different age group, use the appropriate IngDC for the organ/age group and calculate as demonstrated above.

## **METHOD 3.6 PROJECTING CONTAMINATION LEVELS IN FOOD**

### **Application**

This method has been developed to project potential contamination levels in food ( $C_f$ ) based on a measured or projected deposition of radioactive material on the ground.

The contamination levels in food:

- 1) Can be used to determine potential doses to individuals consuming the food when results from direct sampling of the food are not available.
- 2) Uses deposition data to project potential contamination levels in crops, milk and meat.
- 3) Is used to define dose levels to assist decision makers in determining where it may be advisable to implement protective actions (e.g. sheltering livestock, embargos, special product handling).

### **Discussion**

This method projects the potential contamination levels in food using projected or measured deposition (areal activity) values ( $\mu\text{Ci}/\text{m}^2$ ). Calculations will be shown for food crops harvested from contaminated ground and for milk and meat from animals grazing on contaminated forage.

### **Assumptions**

The FRMAC radiological assessment calculations use the default assumptions established by the FRMAC Assessment Working Group. The following default assumptions are used in this method:

- 1) All deposition values used are for the time of deposition ( $t=0$ ).
- 2) A time to market of 1 day for fresh produce, 2 days for milk and 20 days for meat.
- 3) A crop yield of  $2 \text{ kg}_{\text{wet}}/\text{m}^2$  for fresh produce.
- 4) Calculations are for food (crops, meat, milk, or animal feed) as prepared for consumption. To compare with analytical results it may be necessary to convert to “dry weight,” see Method 4.2.
- 5) Crop Retention Factors for fresh produce of:
  - 1.0 for radioiodine and
  - 0.2 for all other radionuclides.
- 6) Animal intake rates:
  - Cow –  $50 \text{ kg}_{\text{wet}}/\text{d}$  for feed,  $60 \text{ l}/\text{d}$  for water, and  $0.5 \text{ kg}_{\text{soil}}/\text{d}$  for soil.

- Goat – 6 kg<sub>wet</sub>/d for feed, 8 l/d for water, and 0.06 kg<sub>soil</sub>/d for soil.
- 7) A forage yield of 0.7 kg<sub>wet</sub>/m<sup>2</sup> for pastureland.
  - 8) Crop Retention Factors for pastureland of:
    - 1.0 for radioiodine and
    - 0.5 for all other radionuclides.
  - 9) Assume a soil density of 1600 kg<sub>soil</sub>/m<sup>3</sup>.
  - 10) Assume a mixing depth of 1.0E-03 m for the first growing season (EPA89) and 0.15 m after plowing.
  - 11) The animal consumes the contaminated feed/water over a period of time sufficient for the animal product intended for human consumption to reach equilibrium.

## Inputs

The following information is required to perform the methods described in this section:

- 1) Data – Composition of the deposited radionuclide mixture (radionuclides and concentration). This information may come from predictive analysis (models) or field data (monitoring and/or samples).
- 2) Constants – Crop Retention Factor, Crop Yield, Animal Daily Intake Rates (Feed, Water, Soil), Transfer Factor for milk for each radionuclide, Transfer Factor for meat for each radionuclide.
- 3) Other Factors – Decay of radionuclides during the time period under consideration, fraction of animals' diet contaminated, soil mixing depth.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available and Decision Makers endorse their use.

**NOTE:** Many of the terms in the methods are dependent on variables (e.g., time phase, target organ, PAG, etc.). When critical, these dependencies are shown as subscripts to the appropriate terms. (See Appendix B for the variable list.)

## Outputs

### Final

The final output of this method is the projected contamination levels in foods that have been affected by a deposition of radioactive material.

$C_{crop}$  = Projected Contamination level in a food Crop (fresh produce), the level of activity per mass in a food type harvested from contaminated ground,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ;

- $C_{milk}$  = Projected Contamination level in Milk, the level of activity per volume in milk produced from consuming radioactive material,  $\mu\text{Ci/l}$ ; and
- $C_{meat}$  = Projected Contamination level in Meat, the level of activity per mass in meat produced from consuming radioactive material,  $\mu\text{Ci/kg}_{\text{wet}}$ .

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

Values calculated by this method may be used in Method 3.5 to calculate ingestion dose when food samples are not available.

## Method 3.6.1 Calculation of Contamination in Crops

**NOTE:** Weathering Factor is not included in this calculation because the food supply is constantly being added to from available sources, using the initial (unweathered) deposition provides a conservative evaluation of the potential contamination in food types regardless of when they are placed into the supply.

Equation 3.6-1 shows the calculation for determining the amount of contamination that would be expected in a crop based on the deposition (areal activity) on the ground:

$$C_{crop,i} = \frac{Dp_{i,t_0} * CRF}{Y} * e^{-\lambda_i t_m} \quad (\text{Eq. 3.6-1})$$

$$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} = \frac{\frac{\mu\text{Ci}}{\text{m}^2} * \text{unitless}}{\frac{\text{kg}_{\text{wet}}}{\text{m}^2}} * \text{unitless}$$

where:

- $C_{crop,i}$  = Projected Contamination level in a food Crop (fresh produce), the level of activity of radionuclide  $i$  per mass in a food type harvested from contaminated ground,  $\mu\text{Ci/kg}_{\text{wet}}$ ;
- $Dp_{i,t_0}$  = Initial Deposition, the areal activity of radionuclide  $i$  at the time of deposition  $t_0$ ,  $\mu\text{Ci/m}^2$ ;
- $CRF$  = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop, unitless; and
- $Y$  = Crop Yield, the mass of crop grown per area of land,  $\text{kg}_{\text{wet}}/\text{m}^2$ ; and
- $\lambda_i$  = Decay constant for radionuclide  $i$ ,  $\text{d}^{-1}$ ;
- $t_m$  = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d; and
- $e^{-\lambda_i t_m}$  = Radioactive Decay adjustment for radionuclide  $i$  over time  $t_m$ , unitless.

## Method 3.6.2 Calculation of Contamination in Milk

Equation 3.6-2a shows the calculation for determining the amount of contamination that would be expected in milk based on areal contamination of pastureland and contamination in the drinking water of the animal.

$$C_{milk,i} = \left\{ \begin{aligned} & Dp_{i,t_0} * \left[ \frac{(CRF * AFDIR)}{Y} + \frac{ASDIR}{\rho_{soil} * d_m} \right] * FDC_F \\ & + [AWDIR * FDC_W * C_W] \end{aligned} \right\} * TF_{Milk,A,i} * e^{-\lambda_i t_m} \quad (\text{Eq. 3.6-2a})$$

$$\frac{\mu\text{Ci}}{\text{l}} = \left\{ \begin{aligned} & \frac{\mu\text{Ci}}{\text{m}^2} * \left[ \frac{\left( \text{unitless} * \frac{\text{kg}_{\text{wet}}}{\text{d}} \right)}{\frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \frac{\frac{\text{kg}_{\text{soil}}}{\text{d}}}{\frac{\text{kg}_{\text{soil}}}{\text{m}^3} * \text{m}} \right] * \text{unitless} \\ & + \left[ \frac{1}{\text{d}} * \text{unitless} * \frac{\mu\text{Ci}}{\text{l}} \right] \end{aligned} \right\} * \frac{\mu\text{Ci}/\text{l}}{\mu\text{Ci}/\text{d}} * \text{unitless}$$

where:

- $C_{milk,i}$  = Projected Contamination level in Milk, the level of activity of radionuclide  $i$  per volume in milk produced from animals consuming radioactive material,  $\mu\text{Ci}/\text{l}$ ;
- $CRF$  = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop, unitless;
- $AFDIR$  = Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed,  $\text{kg}_{\text{wet}}/\text{d}$ ;
- $Y$  = Crop Yield, the mass of crop grown per area of land,  $\text{kg}_{\text{wet}}/\text{m}^2$ ;
- $ASDIR$  = Animal Soil Daily Ingestion Rate, the daily rate at which an animal consumes soil,  $\text{kg}_{\text{soil}}/\text{d}$ ;
- $\rho_{soil}$  = Soil density (See Appendix C, Table 11),  $\text{kg}_{\text{soil}}/\text{m}^3$ ;
- $d_m$  = Mixing Depth (See Appendix C, Table 11),  $\text{m}$ ;
- $FDC_F$  = Fraction of the animals' Diet Contaminated (feed), unitless;  
**NOTE:** See Appendix C, Table 11 for default  $FDC$  values. If there is convincing local information that the actual  $FDC$  is considerably different, local authorities may decide to use a different  $FDC$ .
- $Dp_{i,t_0}$  = Initial Deposition, the areal activity of radionuclide  $i$  at the time of deposition  $t_0$ ,  $\mu\text{Ci}/\text{m}^2$ ;
- $AWDIR$  = Animal Water Daily Ingestion Rate, the daily rate at which an animal consumes water,  $\text{l}/\text{d}$ ;
- $FDC_W$  = Fraction of the animals' Diet Contaminated (water), unitless;  
**NOTE:** See Appendix C, Table 11 for default  $FDC$  values. If there is convincing local information that the actual  $FDC$  is considerably different, local authorities may decide to use a different  $FDC$ .

- $C_W$  = Contamination level in drinking water,  $\mu\text{Ci/l}$ ;  
 $TF_{Milk,A,i}$  = Transfer Factor for milk, the fraction of radionuclide  $i$  consumed by an animal ( $A$ ) that is transferred to the milk produced by the animal,  $\mu\text{Ci/l}$  per  $\mu\text{Ci/d}$ ;  
 $\lambda_i$  = Decay constant for radionuclide  $i$ ,  $\text{d}^{-1}$ ;  
 $t_m$  = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11),  $\text{d}$ ; and  
 $e^{-\lambda_i t_m}$  = Radioactive Decay adjustment for radionuclide  $i$  over time  $t_m$ , unitless.

If the contamination level in the soil is known ( $\mu\text{Ci/kg}_{\text{soil}}$ ) the equation can be rewritten as shown in Equation 3.6-2b.

$$C_{milk,i} = \left\{ \frac{(Dp_i * CRF * AFDIR * FDC_F)}{Y} + (ASDIR * C_S) \right\} * TF_{Milk,A,i} * e^{-\lambda_i t_m} + (AWDIR * FDC_W * C_W) \quad (\text{Eq. 3.6-2b})$$

$$\frac{\mu\text{Ci}}{\text{l}} = \left\{ \frac{\left( \frac{\mu\text{Ci}}{\text{m}^2} * \text{unitless} * \frac{\text{kg}_{\text{wet}}}{\text{d}} * \text{unitless} \right) + \left( \frac{\text{kg}_{\text{soil}}}{\text{d}} * \frac{\mu\text{Ci}}{\text{kg}_{\text{soil}}} \right)}{\frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \left( \frac{1}{\text{d}} * \text{unitless} * \frac{\mu\text{Ci}}{\text{l}} \right) \right\} * \frac{\mu\text{Ci}}{\mu\text{Ci/d}} * \text{unitless}$$

where:

$C_S$  = Contamination level in soil,  $\mu\text{Ci/kg}_{\text{soil}}$ ;

### Method 3.6.3 Calculation of Contamination in Meat

Equation 3.6-3a shows the calculation for determining the amount of contamination that would be expected in meat based on areal contamination of pastureland and contamination in the drinking water of the animal.

$$C_{meat,i} = \left\{ Dp_{i,t_0} * \left[ \frac{\left( CRF * \left( \frac{1 - e^{-\lambda_i t_g}}{\lambda_i * t_g} \right) * AFDIR \right)}{Y} + \frac{ASDIR}{\rho_{\text{soil}} * d_m} \right] * FDC_F \right\} * TF_{Meat,A,i} * \left( \frac{1 - e^{-\lambda_i t_g}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m} + [AWDIR * FDC_W * C_W] \quad (\text{Eq. 3.6-3a})$$

$$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} = \left\{ \frac{\mu\text{Ci}}{\text{m}^2} * \left[ \frac{\left( \text{unitless} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \frac{\text{kg}_{\text{wet}}}{\text{d}} \right)}{\frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \frac{\frac{\text{kg}_{\text{soil}}}{\text{d}}}{\frac{\text{kg}_{\text{soil}}}{\text{m}^3} * \text{m}} \right] * \text{unitless} \right. \\ \left. + \left[ \frac{1}{\text{d}} * \text{unitless} * \frac{\mu\text{Ci}}{1} \right] \right\} * \frac{\mu\text{Ci} / \text{kg}_{\text{wet}}}{\mu\text{Ci} / \text{d}} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \text{unitless}$$

where:

- $C_{\text{meat},i}$  = Projected Contamination level in Meat, the level of activity of radionuclide  $i$  per mass in an animal's meat from consuming radioactive material,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ;
- $CRF$  = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop, unitless;
- $t_g$  = Grazing Time, time from deposition or sampling to the end of the grazing period, d;
- $\lambda_w$  = Decay constant for weathering radioactive material off plants (See Appendix C, Table 11),  $\text{d}^{-1}$ ;
- $\left( \frac{1 - e^{-\lambda_w t_g}}{\lambda_w * t_g} \right)$  = Integrated average weathering of radioactive material off plants during the time the animal is grazing in the field (the integral of the weathering over the Grazing Time divided by the Grazing Time), unitless;
- $AFDIR$  = Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed,  $\text{kg}_{\text{wet}}/\text{d}$ ;
- $Y$  = Crop Yield, the mass of crop grown per area of land,  $\text{kg}_{\text{wet}}/\text{m}^2$ ;
- $ASDIR$  = Animal Soil Daily Ingestion Rate, the daily rate at which an animal consumes soil,  $\text{kg}_{\text{soil}}/\text{d}$ ;
- $\rho_{\text{soil}}$  = Soil density (See Appendix C, Table 11),  $\text{kg}_{\text{soil}}/\text{m}^3$ ;
- $d_m$  = Mixing Depth (See Appendix C, Table 11), m;
- $FDC_F$  = Fraction of the animals' Diet Contaminated (feed), unitless;  
**NOTE:** See Appendix C, Table 11 for default  $FDC$  values. If there is convincing local information that the actual  $FDC$  is considerably different, local authorities may decide to use a different  $FDC$ .
- $Dp_{i,t_0}$  = Initial Deposition, the areal activity of radionuclide  $i$  at the time of deposition  $t_0$ ,  $\mu\text{Ci}/\text{m}^2$ ;
- $AWDIR$  = Animal Water Daily Ingestion Rate, the daily rate at which an animal consumes water, l/d;
- $FDC_W$  = Fraction of the animals' Diet Contaminated (water), unitless;  
**NOTE:** See Appendix C, Table 11 for default  $FDC$  values. If there is convincing local information that the actual  $FDC$  is considerably different, local authorities may decide to use a different  $FDC$ .
- $C_W$  = Contamination level in drinking water,  $\mu\text{Ci}/\text{l}$ ;
- $TF_{\text{Meat},A,i}$  = Transfer Factor for Meat, the fraction of radionuclide  $i$  consumed by an animal ( $A$ ) that is transferred to the meat of the animal,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$  per  $\mu\text{Ci}/\text{d}$ ;

$\lambda_i$  = Decay constant for radionuclide  $i$ ,  $d^{-1}$ ;  
 $\left( \frac{1-e^{-\lambda_i t_g}}{\lambda_i * t_g} \right)$  = Integrated average decay of radioactive material during the time the animal is grazing in the field (the integral of radioactive decay over the Grazing Time divided by the Grazing Time), unitless;  
 $t_m$  = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d; and  
 $e^{-\lambda_i t_m}$  = Radioactive Decay adjustment for radionuclide  $i$  over time  $t_m$ , unitless.

If the contamination level in the soil is known ( $\mu\text{Ci}/\text{kg}_{\text{soil}}$ ) the equation can be rewritten as shown in Equation 3.6-3b.

$$C_{\text{meat},i} = \left\{ \frac{\left( Dp_{i,t_0} * CRF * \left( \frac{1-e^{-\lambda_w t_g}}{\lambda_w * t_g} \right) * AFDIR * FDC_F \right)}{Y} + (ASDIR * C_S) \right\} * TF_{\text{Meat},A,i} * \left( \frac{1-e^{-\lambda_i t_g}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m} + (AWDIR * FDC_W * C_W)$$

(Eq. 3.6-3b)

$$\frac{\mu\text{Ci}}{1} = \left\{ \frac{\left( \frac{\mu\text{Ci}}{\text{m}^2} * \text{unitless} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \frac{\text{kg}_{\text{wet}}}{\text{d}} * \text{unitless} \right) + \left( \frac{\text{kg}_{\text{soil}}}{\text{d}} * \frac{\mu\text{Ci}}{\text{kg}_{\text{soil}}} \right)}{\frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \left( \frac{1}{\text{d}} * \text{unitless} * \frac{\mu\text{Ci}}{1} \right) \right\} * \frac{\mu\text{Ci}}{\mu\text{Ci}} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \text{unitless}$$

where:

$C_S$  = Contamination level in soil,  $\mu\text{Ci}/\text{kg}_{\text{soil}}$ ;

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**EXAMPLE 1**

**Problem:** Calculate the projected contamination levels for a lettuce crop from an area with a deposition of  $^{60}\text{Co}$ .

Assuming an initial deposition (areal activity) of  $^{60}\text{Co}$  of  $4.0\text{E-}03 \mu\text{Ci}/\text{m}^2$ , Equation 3.6-1 can be used to predict the contamination level in the lettuce crop.

$$C_{crop,i} = \frac{Dp_{i,t_0} * CRF}{Y} * e^{-\lambda_i t_m}$$

Assuming:

$$\begin{aligned} CRF &= 0.2 \text{ (fresh produce),} \\ Y &= 2.0 \text{ kg}_{\text{wet}}/\text{m}^2 \text{ (fresh produce),} \\ \lambda_{Co} &= 3.60\text{E-}04 \text{ d}^{-1}, \text{ and} \\ t_m &= 1 \text{ day.} \end{aligned}$$

$$C_{lettuce,^{60}Co} = \frac{4.0\text{E-}03 \frac{\mu\text{Ci}}{\text{m}^2} * 0.2}{2.0 \frac{\text{kg}_{\text{wet}}}{\text{m}^2}} * e^{-3.6\text{E-}04 * 1} = 4.0\text{E-}04 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

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**EXAMPLE 2**

**Problem:** Calculate the projected contamination levels for cow's milk from an area with a deposition of  $^{60}\text{Co}$ .

Assume an initial deposition (areal activity) of  $^{60}\text{Co}$  of  $4.0\text{E-}03 \mu\text{Ci}/\text{m}^2$  and a water concentration value of  $3.0\text{E-}05 \mu\text{Ci}/\text{l}$ .

Equation 3.6-2 can be used to calculate the contamination level in the cow's milk.

$$C_{\text{milk},i} = \left\{ \begin{array}{l} Dp_{i,t_0} * \left[ \frac{(CRF * AFDIR)}{Y} + \frac{ASDIR}{\rho_{\text{soil}} * d_m} \right] * FDC_F \\ + [AWDIR * FDC_W * C_W] \end{array} \right\} * TF_{\text{Milk},A,i} * e^{-\lambda_i t_m}$$

Assuming:

$$\begin{aligned} CRF &= 0.5 \text{ (pasture),} \\ AFDIR_{\text{cow}} &= 50 \text{ kg}_{\text{wet}}/\text{d}, \\ Y &= 0.7 \text{ kg}_{\text{wet}}/\text{m}^2 \text{ (pasture),} \\ ASDIR_{\text{cow}} &= 0.5 \text{ kg}_{\text{soil}}/\text{d}, \\ \rho_{\text{soil}} &= 1600 \text{ kg}_{\text{soil}}/\text{m}^3, \\ d_m &= 1.0\text{E-}03 \text{ m,} \\ FDC_F &= 1.0, \\ AWDIR_{\text{cow}} &= 60 \text{ l/d,} \\ FDC_W &= 1.0, \\ TF_{\text{Milk},\text{cow},^{60}\text{Co}} &= 3.0\text{E-}04 \mu\text{Ci/l per } \mu\text{Ci/d,} \\ \lambda_{\text{Co}} &= 3.60\text{E-}04 \text{ d}^{-1}, \text{ and} \\ t_m &= 2 \text{ days.} \end{aligned}$$

$$\begin{aligned} C_{\text{milk},^{60}\text{Co}} &= \left\{ \left[ \frac{\left( \frac{0.5 * 50 \frac{\text{kg}_{\text{wet}}}{\text{d}}}{0.7 \frac{\text{kg}_{\text{wet}}}{\text{m}^2}} \right) + \frac{0.5 \frac{\text{kg}_{\text{soil}}}{\text{d}}}{1600 \frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 1.0\text{E-}03\text{m}}}{1 * 4.0\text{E-}03 \frac{\mu\text{Ci}}{\text{m}^2}} \right] * 3.0\text{E-}04 \frac{\mu\text{Ci}}{\mu\text{Ci/d}} * e^{-3.6\text{E-}04 * 2} \right. \\ &\quad \left. + \left[ 60 \frac{1}{\text{d}} * 1 * 3.0\text{E-}05 \frac{\mu\text{Ci}}{1} \right] \right\} \\ &= 4.4\text{E-}05 \frac{\mu\text{Ci}}{1} \end{aligned}$$

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**EXAMPLE 3**

**Problem: Calculate the projected contamination levels for beef from an area with a deposition of  $^{60}\text{Co}$ .**

Assume an initial deposition (areal activity) of  $^{60}\text{Co}$  of  $4.0\text{E-}03 \mu\text{Ci}/\text{m}^2$  and a water concentration value of  $3.0\text{E-}05 \mu\text{Ci}/\text{l}$ .

Assuming that the cow will continue to graze on the contaminated field for 90 days after deposition, Equation 3.6-3 can be used to calculate the contamination level in the cow's meat.

$$C_{\text{meat},i} = \left\{ DP_{i,t_0} * \left[ \frac{\left( CRF * \left( \frac{1 - e^{-\lambda_w t_g}}{\lambda_w * t_g} \right) * AFDIR \right)}{Y} + \frac{ASDIR}{\rho_{\text{soil}} * d_m} * FDC_F \right] * TF_{\text{Meat},A,i} * \left( \frac{1 - e^{-\lambda_i t_m}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m} \right. \\ \left. + [AWDIR * FDC_W * C_W] \right\}$$

Assuming:

$$\begin{aligned} CRF &= 0.5 \text{ (pasture),} \\ \lambda_w &= 4.62\text{E-}02 \text{ d}^{-1}, \\ t_g &= 90 \text{ d,} \\ AFDIR_{\text{cow}} &= 50 \text{ kg}_{\text{wet}}/\text{d,} \\ Y &= 0.7 \text{ kg}_{\text{wet}}/\text{m}^2 \text{ (pasture),} \\ ASDIR_{\text{cow}} &= 0.5 \text{ kg}_{\text{soil}}/\text{d,} \\ \rho_{\text{soil}} &= 1600 \text{ kg}_{\text{soil}}/\text{m}^3, \\ d_m &= 1.0\text{E-}03 \text{ m,} \\ FDC_F &= 1.0, \\ AWDIR_{\text{cow}} &= 60 \text{ l/d,} \\ FDC_W &= 1.0, \\ TF_{\text{Meat},\text{cow},^{60}\text{Co}} &= 1.0\text{E-}02 \mu\text{Ci}/\text{kg}_{\text{wet}} \text{ per } \mu\text{Ci}/\text{d,} \\ \lambda_{\text{Co}} &= 3.60\text{E-}04 \text{ d}^{-1}, \text{ and} \\ t_m &= 20 \text{ days.} \end{aligned}$$

$$\begin{aligned}
 C_{beef, {}^{60}\text{Co}} &= \left\{ \left[ \frac{\left( 0.5 * \frac{1 - e^{-4.62\text{E-}02\text{d}^{-1} * 90\text{d}}}{4.62\text{E-}02\text{d}^{-1} * 90\text{d}} * 50 \frac{\text{kg}_{\text{wet}}}{\text{d}} \right)}{0.7 \frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \frac{0.5 \frac{\text{kg}_{\text{soil}}}{\text{d}}}{1600 \frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 1.0\text{E-}03\text{m}} \right] * 1 * 4.0\text{E-}03 \frac{\mu\text{Ci}}{\text{m}^2} \right. \\
 &\quad \left. + \left[ 60 \frac{1}{\text{d}} * 1 * 3.0\text{E-}05 \frac{\mu\text{Ci}}{1} \right] \right. \\
 &\quad \left. * 1.0\text{E-}02 \frac{\mu\text{Ci}}{\mu\text{Ci}/\text{d}} * \frac{1 - e^{-3.6\text{E-}04\text{d}^{-1} * 90\text{d}}}{3.6\text{E-}04\text{d}^{-1} * 90\text{d}} * e^{-3.6\text{E-}04 * 20} \right. \\
 &= 3.6\text{E-}04 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}
 \end{aligned}$$

## METHOD 3.7 DOSE FROM INADVERTENT SOIL INGESTION

### Application

This method calculates the Ingestion Dose from the inadvertent consumption of soil that has been contaminated with radioactive material.

The Ingestion Dose Method:

- 1) Can be applied to the whole body (E) or to a specific organ ( $H_T$ )
- 2) Uses monitoring results of areal activity to calculate the dose that a receptor is projected to receive over a specified time phase (generally 1 year) due to ingestion of the contaminated soil.
- 3) Is used to define dose levels to assist decision makers in determining where it may be advisable to implement protective actions.

### Discussion

This method calculates the projected dose from the inadvertent ingestion of soil contaminated by radioactive material and is calculated by evaluating ground monitoring results ( $\mu\text{Ci}/\text{m}^2$ ). Ingestion of contaminated dirt can occur when surface contamination is transferred from a surface to hands, toys, cigarettes, etc.

Generally the contribution of this pathway is minor. However, it can become significant and even dominant in certain special cases. One such case is for long-term residence or outdoor work in areas contaminated with aged plutonium in surface soil.

**If the dose from this pathway exceeds 10% of the appropriate EPA PAG for the Time Phase, it should be included in a decision for protective actions.**

### Assumptions

The FRMAC radiological assessment calculations use the default assumptions established by the FRMAC Assessment Working Group. The following default assumptions are used in this method:

- 1) Default soil intake rates are  $5.0\text{E-}05 \text{ kg}_{\text{soil}}/\text{day}$  for adults and  $1.0\text{E-}04 \text{ kg}_{\text{soil}}/\text{day}$  for children (EPA11). This method uses the conservative value of  $1.0\text{E-}04 \text{ kg}_{\text{soil}}/\text{day}$  for all calculations. If specific intake rates are known, use those instead of defaults.
- 2) Soil density of  $1600 \text{ kg}_{\text{soil}}/\text{m}^3$ .
- 3) Mixing depth of  $1.0\text{E-}03 \text{ m}$  for the surface layer of contaminated soil and  $1.0\text{E-}04 \text{ m}$  for the layer of dust over pavement (EPA89). This method uses the conservative value of  $1.0\text{E-}04 \text{ m}$  for all calculations.

- 4) Default calculations utilize the International Commission on Radiological Protection (ICRP) 60+ dosimetry model.

## Inputs

The following information is required to perform the methods described in this section:

- 1) Data – Areal concentration ( $\mu\text{Ci}/\text{m}^2$ ) from monitoring data.
- 2) Constants – Daily Soil Intake Rate, Ingestion Dose Coefficient.
- 3) Other Factors – Start and end time of period (duration of consumption) under consideration, decay and weathering of radionuclides over the duration of consumption (default consumption period is 1 year).

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available and Decision Makers endorse their use.

**NOTE:** Many of the terms in the methods are dependent on variables (e.g., time phase, target organ, PAG, etc.). When critical, these dependencies are shown as subscripts to the appropriate terms. (See Appendix B for the variable list.)

## Outputs

### Final

The final output of this method is the Ingestion Dose for soils that have been contaminated by a deposition of radioactive material.

$E_{\text{soil}}$  = Committed Effective Dose, the dose to the whole body, from the ingestion of all radionuclides in contaminated soil, mrem

$H_{T,\text{soil}}$  = Committed Equivalent Dose, the dose to organ T from the ingestion of all radionuclides in contaminated soil, mrem

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

None

## Method 3.7.1 Calculation of Committed Effective Dose from Inadvertent Soil Ingestion

Equation 3.7-1 shows the Ingestion Dose calculation:

$$E_{soil,age} = \frac{DSIR}{\rho_{soil} * d_m} * \sum_i \left( e^{-\lambda_i t_1} * WF_{t_1} * IngDC_{E,age,i} * WP_{i,TP} \right) \quad (\text{Eq. 3.7-1})$$

$$\text{mrem} = \frac{\frac{\text{kg}_{soil}}{\text{d}}}{\frac{\text{kg}_{soil}}{\text{m}^3} * \text{m}} * \sum_i \left( \text{unitless} * \text{unitless} * \frac{\text{mrem}}{\mu\text{Ci}} * \frac{\mu\text{Ci} \cdot \text{d}}{\text{m}^2} \right)$$

where:

$E_{soil,age}$  = Committed Effective Dose from inadvertent soil ingestion, the dose to the whole body, received by a specific age group from ingestion of all radionuclides in contaminated soil, mrem;

$DSIR$  = Daily Soil Intake Rate,  $\text{kg}_{soil}/\text{d}$ ;

$\rho_{soil}$  = Soil density (See Appendix C, Table 11),  $\text{kg}_{soil}/\text{m}^3$ ;

$d_m$  = Mixing Depth (See Appendix C, Table 11), m;

$e^{-\lambda_i t_1}$  = Radioactive Decay adjustment for radionuclide  $i$  from  $t_0$  (deposition) to  $t_1$  (start of the time phase), unitless;

$WF_{t_1}$  = Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind) from  $t_0$  (deposition) to  $t_1$  (start of the time phase), unitless;

**NOTE:** See Appendix F, Supplement 2 for details on calculating WF.

$IngDC_{E,age,i}$  = Ingestion Dose Coefficient, the ingestion pathway dose coefficient for the whole body ( $E$ ) for a specific age group for radionuclide  $i$ ,  $\text{mrem}/\mu\text{Ci}$ ; and

$WP_{i,TP}$  = Weathering Parameter, the adjustment for radioactive decay and in-growth and the time-dependent weathering effects that change the amount of a radionuclide available to cause direct exposure or to be ingested over the time phase under consideration ( $TP$ ),  $\text{uCi} \cdot \text{d}/\text{m}^2$ ;  
**NOTE:** See Appendix F, Supplement 2 for details on calculating WP.

## Method 3.7.2 Calculation of Equivalent Dose to an Organ

The preceding calculations assume that the organ of interest is the whole body. The generic approach can be modified to calculate a dose for a specific organ (e.g., skin, thyroid, etc.).

To calculate the dose to a specific organ, replace the IngDC for the whole body with the IngDC for the organ of interest.

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**EXAMPLE 1**

**Problem: Calculate the Whole Body Ingestion Dose received by an adult from inadvertent consumption of soil contaminated with  $^{60}\text{Co}$  and  $^{137}\text{Cs}$  for 1 year, beginning 100 days after deposition.**

Assume monitoring results (at initial deposition) as shown below:

$$^{60}\text{Co} = 2.5\text{E-}03 \mu\text{Ci}/\text{m}^2$$

$$^{137}\text{Cs} = 4.0\text{E-}03 \mu\text{Ci}/\text{m}^2$$

Equation 3.7-1 can be used to calculate the dose:

$$E_{50,\text{soil},\text{age}} = \frac{DSIR}{\rho_{\text{soil}} * d_m} * \sum_i \left( e^{-\lambda t_1} * WF_{t_1} * \text{IngDC}_{E,\text{age},i} * WP_{i,TP} \right)$$

Given:

$$\text{IngDC}_{\text{Co}} = 12.7 \text{ mrem}/\mu\text{Ci}$$

$$\lambda_{\text{Co}} = 3.6\text{E-}04 \text{ d}^{-1}$$

$$\text{IngDC}_{\text{Cs}} = 50.3 \text{ mrem}/\mu\text{Ci}$$

$$\lambda_{\text{Cs}} = 6.33\text{E-}05 \text{ d}^{-1}$$

$$t_1 = 100 \text{ d (Start of Time Phase – used in WP calculation)}$$

$$t_2 = 465 \text{ d (End of Time Phase – used in WP calculation)}$$

$$WF_{100\text{d}} = 0.950$$

Assuming:

$$DSIR = 1.0\text{E-}04 \text{ kg}_{\text{soil}}/\text{d (EPA11)}$$

$$\rho_{\text{soil}} = 1600 \text{ kg}_{\text{soil}}/\text{m}^3$$

$$d_m = 1.0\text{E-}04 \text{ m (EPA89)}$$

Calculating WP as in Appendix F, Supplement 2 yields:

$$WP_{\text{Co}} = 0.725 \text{ uCi}\cdot\text{d}/\text{m}^2$$

$$WP_{\text{Cs}} = 1.26 \text{ uCi}\cdot\text{d}/\text{m}^2$$

$$E_{50,\text{soil},\text{Adult}} = \frac{1.0\text{E-}04 \frac{\text{kg}_{\text{soil}}}{\text{d}}}{1600 \frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 1.0\text{E-}04 \text{ m}} * \left( \begin{array}{l} 0.965 * 0.950 * 12.7 \frac{\text{mrem}}{\mu\text{Ci}} * 0.725 \frac{\mu\text{Ci}\cdot\text{d}}{\text{m}^2} \\ + 0.994 * 0.950 * 50.3 \frac{\text{mrem}}{\mu\text{Ci}} * 1.26 \frac{\mu\text{Ci}\cdot\text{d}}{\text{m}^2} \end{array} \right)$$

$$= 4.27\text{E-}02 \text{ mrem}$$

To calculate a Committed Equivalent Dose ( $H_T$ ) for a specific organ and/or different age group, use the appropriate IngDC for the organ/age group and calculate as demonstrated above.

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## SECTION 4. SUPPLEMENTAL METHODS

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Method 4.1 Determining Resuspension from Samples .....	4.1-1	6/2012
Method 4.2 Comparing Sample Results to Ingestion Pathway Thresholds .....	4.2-1	6/2012
Method 4.3 Normalizing Samples .....	4.3-1	Reserved
Method 4.4 Determining Laboratory Analysis MDA Requirements .....	4.4-1	6/2012
Method 4.5 Using Deposition Velocity .....	4.5-1	6/2012
Method 4.6 Converting “Grab” Air Sample Results to Integrated-Air Values .....	4.6-1	Reserved
Method 4.7 Relating Measured Dose Rates to Areal Activity .....	4.7-1	Reserved

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## **INTRODUCTION TO SUPPLEMENTAL METHODS**

These Methods provide supplemental calculations in support of the primary Methods described in the previous sections. The results of these methods may be used to determine alternate (non-default) input factors that may be used to calculate values that are more applicable to the incident being assessed. These methods may also be used to normalize sample data for comparison to values calculated by other methods.

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## METHOD 4.1 DETERMINING RESUSPENSION FROM SAMPLES

### Application

This method has been developed to calculate a Resuspension Factor based on air and deposition samples.

The Resuspension Factor (*K*):

- 1) Represents the ratio of activity in the air at a particular location to the activity on the ground at that location for a particular radionuclide.

**NOTE:** Resuspension Factors may be different for each radionuclide in a mixture because some chemical/physical forms may be more likely to become airborne than others. Local decision makers should be consulted to determine if radionuclide-specific Resuspension Factors should be used instead of one factor for the entire mixture.

- 2) Is used to calculate the Resuspension Parameter (*KP*) and Deposition Inhalation Dose Parameter (*Dp\_InhDP*) for each radionuclide in a release.

### Discussion

**This calculation is presented as an alternative to the default, time dependent, formula shown in Appendix F, Supplement 2, Equation 2 and may be used only with approval from local decision makers.**

In contrast to direct measurements of air concentration (usually made at occupied locations), air and ground measurements used for determining resuspension factors must be made at or near source locations – i.e., areas of contaminated ground from which activity is being resuspended *into* occupied areas. Although it is possible that such source areas may be near (or may be the same as) occupied areas, it is also possible that the source contamination area is some distance away from the occupied area of interest.

Therefore, the location of resuspension measurements must take into account the geography and weather factors that affect the transfer of activity from the ground to the air that will end up in the occupied areas of interest. In general, resuspension measurements should be made at locations in contaminated areas that are upwind (or may be expected to be upwind) of the occupied areas of interest.

Several ground samples should be taken upwind of each air sampler in order to obtain an average value for the ground in the area covered by the air sampler. The purpose of these

measurements is to obtain the general level of ground activity for comparison to the measured activity on the air filter.

There are several pitfalls to consider when deciding to use a sample based resuspension value:

- 1) It may be difficult to obtain accurate/representative sample-based values.
- 2) Hot particles may significantly skew the air sample activity results.
- 3) Samples are only representative of the resuspension factor for a specific point in time and space.
- 4) Resuspension may change over the time phase of interest as the land use changes.
- 5) Weathering processes and alpha-recoil energy can break apart contaminated particles creating smaller particle sizes over time potentially changing resuspension.
- 6) Sample based resuspension values are sensitive to many factors, including:
  - Air sampler location,
  - Wind direction relative to the air sample location, and
  - Activities being conducted in the sampling area.

## Assumptions

The following default assumptions are used in this method:

None

## Inputs

The following information is required to perform the methods described in this section:

Data: Sampling Results from air and ground monitoring.

## Outputs

### Final

The final output of this method is the resuspension factor for a radionuclide contaminant.

$K_{t,i}$  = Resuspension Factor, the ratio of the activity level in the air to the level on the ground of radionuclide  $i$  at the time of measurement  $t$ ,  $m^{-1}$ .

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

None

## Calculation

Equation 4.1-1 shows the Resuspension Factor calculation.

$$K_i = \frac{\chi_i}{Dp_i} \quad (\text{Eq. 4.1-1})$$

$$m^{-1} = \frac{\mu\text{Ci}/m^3}{\mu\text{Ci}/m^2}$$

where:

- $K_{t,i}$  = Resuspension Factor for radionuclide  $i$  at time  $t$ ,  $m^{-1}$ ;
- $\chi_i$  = Air Concentration of radionuclide  $i$ ,  $\mu\text{Ci}/m^3$ ; and
- $Dp_i$  = Deposition, the areal activity of radionuclide  $i$ ,  $\mu\text{Ci}/m^2$ .

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**EXAMPLE 1****Problem: Calculate the Resuspension Factor from sample results**At a particular sampling location, the average results for  $^{137}\text{Cs}$  are:Air Sampling:  $2.74\text{E-}03 \mu\text{Ci}/\text{m}^3$ Ground Sampling:  $2.74\text{E+}04 \mu\text{Ci}/\text{m}^2$ 

$$K = \frac{2.74\text{E-}03 \frac{\mu\text{Ci}}{\text{m}^3}}{2.74\text{E+}04 \frac{\mu\text{Ci}}{\text{m}^2}} = 1.00\text{E-}07 \text{ m}^{-1}$$

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## **METHOD 4.2    COMPARING SAMPLE RESULTS TO INGESTION PATHWAY THRESHOLDS**

### **Application**

This method provides instructions on how to compare analytical sample results of food and fodder to DILs.

### **Discussion**

DILs are based on the level of radioactive material in food “as prepared for consumption.” The default assumption for this method is that food products are intended to be eaten in a fresh or “wet” condition.

Because many methods of sample analysis require drying the sample material it may be necessary to apply a dry-to-wet conversion factor to the sample results before a direct comparison may be made to the appropriate DIL. Assessment Scientists must determine when it is appropriate to apply the dry-to-wet conversion factor to sample results for comparison to the DIL.

### **Assumptions**

The FRMAC radiological assessment calculations use the default assumptions established by the FDA.

The following default assumptions are used in this method:

- Food products are intended to be eaten in a fresh or “wet” condition. This does not apply to fodder that is to be fed to livestock in a dry form.

### **Inputs**

The following information is required to perform the methods described in this section:

- 1) Data: Sampling Results from food products/fodder in terms of dry mass ( $\mu\text{Ci}/\text{kg}_{\text{dry}}$ ).
- 2) Constants: Mass Conversion Factor for the food product/fodder.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available and Decision Makers endorse their use.

**NOTE:** Many of the terms in the methods are dependent on variables (e.g., time phase, target organ, PAG, etc.). When critical, these dependencies are shown as subscripts to the appropriate terms. (See Appendix B for the variable list.)

## Outputs

### Final

The final output of this method is a sample analysis result in “wet mass” that may be directly compared to a DIL.

$C_{sample,i,wet}$  = Sample Contamination, the level of contamination of radionuclide  $i$  in an analytical sample in terms of wet mass,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ .

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

None.

## Calculation

Equation 4.2-1 shows the wet mass Contamination calculation.

$$C_{sample,i,wet} = C_{sample,i,dry} * MCF_{D-W,subgroup} \quad (\text{Eq. 4.2-1})$$

$$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} = \frac{\mu\text{Ci}}{\text{kg}_{\text{dry}}} * \frac{\text{kg}_{\text{dry}}}{\text{kg}_{\text{wet}}}$$

where:

$C_{sample,i,wet}$  = Sample Contamination, the level of contamination of radionuclide  $i$  in an analytical sample in terms of wet mass,  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ ;

$C_{sample,i,dry}$  = Sample Contamination, the level of contamination of radionuclide  $i$  in an analytical sample in terms of dry mass,  $\mu\text{Ci}/\text{kg}_{\text{dry}}$ ; and

$MCF_{D-W,subgroup}$  = Mass Conversion Factor (dry to wet) – the ratio of dry mass to wet mass for a food subgroup (See Appendix C, Table 9),  $\text{kg}_{\text{dry}}/\text{kg}_{\text{wet}}$ .

**Note:** If the sample results are reported in wet mass, or when the sample is for livestock fodder that will be fed to the animals in a dry form, this calculation is not necessary.

**EXAMPLE 1****Problem: Calculate the wet mass Contamination level from sample results**

A dried sample of an apple crop is found to contain  $6.0\text{E-}02 \mu\text{Ci/kg}$  of  $^{137}\text{Cs}$ . The crop of apples is intended to be consumed as fresh produce (i.e., not dried or dehydrated).

The DIL for  $^{137}\text{Cs}$  is  $3.7\text{E-}02 \mu\text{Ci/kg}$ ; does the sample exceed the DIL?

Because this apple crop's "as prepared for consumption" form will be wet mass, Equation 4.2-1 should be used to calculate the wet mass Concentration.

$$C_{\text{sample},i,\text{wet}} = C_{\text{sample},i,\text{dry}} * MCF_{D-W,\text{subgroup}}$$

Given:

$$MCF_{D-W,\text{apples}} = 0.18 \text{ kg}_{\text{dry}}/\text{kg}_{\text{wet}}$$

$$C_{\text{sample},i,\text{wet}} = 6.0\text{E-}02 \frac{\mu\text{Ci}}{\text{kg}_{\text{dry}}} * 0.18 \frac{\text{kg}_{\text{dry}}}{\text{kg}_{\text{wet}}} = 1.08\text{E-}02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

Since:

$$1.08\text{E-}02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} < 3.7\text{E-}02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

The sample does not exceed the DIL when the apples are evaluated in the "as prepared for consumption" form.

This demonstrates the importance of comparing "wet apples to wet apples" when making decisions about whether a particular food product exceeds the DIL.

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## **METHOD 4.3    NORMALIZING SAMPLES**

**This method is reserved for future development.**

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## METHOD 4.4 DETERMINING DETECTION REQUIREMENTS

This method describes the process for determining detection thresholds (Critical Levels) for a variety of analytical sample types (matrices). When analyzing samples collected during an incident, one of the primary decisions that must be made is what threshold of detection should be used for each sample. Different sample matrices (i.e., water, soil, vegetation) will have different thresholds of detection. The specific questions that the sample data will answer may also affect the thresholds.

**NOTE:** See the FRMAC Laboratory Analysis Manual, Appendix B for details on this process.

FRMAC Assessment will supply Derived Response Levels (DRLs) for each radionuclide in a release mixture that have been determined to be relevant to the incident, radionuclide mixture, and protective action decision being considered to Laboratory Analysis. These DRLs are converted to sample-matrix-specific Analytical Action Levels (AALs) as shown in the following table.

**Table 4.4-1 DRL to AAL Conversions**

Matrix	Source DRL Type	DRL Units	Conversion from DRL to AAL	AAL Units
Air	Deposition DRL "Short Term" <sup>a</sup>	$\mu\text{Ci}/\text{m}^2$	AAL = DRL x Resuspension Factor ( $1\text{E}-06 \text{ m}^{-1}$ Default)	$\mu\text{Ci}/\text{m}^3$
Food	DIL	$\mu\text{Ci}/\text{kg}_{\text{wet}}$	AAL = DIL	$\mu\text{Ci}/\text{kg}_{\text{wet}}$
Forage	Milk_DRL <sub>mass</sub>	$\mu\text{Ci}/\text{kg}_{\text{wet}}$	AAL = Milk_DRL <sub>mass</sub>	$\mu\text{Ci}/\text{kg}_{\text{wet}}$
Milk	DIL	$\mu\text{Ci}/\text{kg}_{\text{wet}}$	AAL = DIL	$\mu\text{Ci}/\text{kg}_{\text{wet}}$
Soil "Short Term"	Deposition DRL "Short Term" <sup>a</sup>	$\mu\text{Ci}/\text{m}^2$	AAL = DRL x Sample Size ( $0.01 \text{ m}^2$ Default)	$\mu\text{Ci}/\text{sample}$
Soil "Long Term"	Deposition DRL "Long Term" <sup>b</sup>	$\mu\text{Ci}/\text{m}^2$	AAL = DRL x Sample Size ( $0.01 \text{ m}^2$ Default)	$\mu\text{Ci}/\text{sample}$
Cow Water	Milk_DRL <sub>water</sub>	$\mu\text{Ci}/\text{l}$	AAL = Milk_DRL <sub>water</sub>	$\mu\text{Ci}/\text{l}$
Drinking Water	EPA Guidelines			pCi/l

<sup>a</sup> Short Term Deposition Derived Response Levels are the minimum (most conservative) of the DRLs for the Early Phase and 1<sup>st</sup> Year Time Phases.

<sup>b</sup> Long Term Deposition Derived Response Levels are the minimum (most conservative) of the DRLs for the Early Phase, 1<sup>st</sup> Year, 2<sup>nd</sup> Year, and 50 Year Time phases as well as the Milk\_DRL<sub>area</sub>

The calculated AAL should then be divided by 10 to determine the initial Critical Level for the radionuclide being evaluated. These values are baseline values that may be modified as the incident progresses upon consultation between the Assessment and Laboratory Analysis Divisions.

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## METHOD 4.5 USING DEPOSITION VELOCITY

### Application

This method provides instructions on how to estimate Integrated Air Activity ( $\tilde{A}_i$ ) values or Deposition ( $Dp_i$ ) values from available data using a Deposition Velocity ( $V_d$ ).

### Discussion

When a plume of radioactive material passes over an area, a certain fraction of that material is deposited on the surface. The rate at which this occurs can be expressed in terms of a deposition velocity.

This method demonstrates how to estimate:

- 1) an Integrated Air Activity value from a measured Deposition value, and
- 2) a Deposition value from a measured Integrated Air Activity value.

### Assumptions

The following default assumptions are used in this method:

- 1) All deposition is assumed to be dry particulates – wet deposition (increases caused by rain or snow) is not included in this method.
- 2) Default Deposition Velocities ( $V_d$ ) of
  - 3.0E-03 m/s, for Particulates
  - 1.0E-02 m/s for Reactive Gasses (e.g., Iodine).
  - 0.0 m/s for Noble Gases which are assumed to remain airborne and are not deposited on the ground.

### Inputs

The following information is required to perform the methods described in this section:

- 1) Data: Integrated Air Activity ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ ), or Deposition ( $\mu\text{Ci}/\text{m}^2$ ).
- 2) Constants: Deposition Velocities for the appropriate particle size.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available and Decision Makers endorse their use.

**NOTE:** Many of the terms in the methods are dependent on variables (e.g., time phase, target organ, PAG, etc.). When critical, these dependencies are shown as subscripts to the appropriate terms. (See Appendix B for the variable list.)

## Outputs

### Final

The final output of this method is either an Integrated Air Activity or a Deposition value for the passage of a plume of radioactive material.

$\tilde{A}_i$  = Integrated air activity of radionuclide  $i$  in a release,  $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ .

$Dp_{i,t_0}$  = Initial Deposition, the areal activity of radionuclide  $i$  at the time of deposition  $t_0$ ,  $\mu\text{Ci}/\text{m}^2$ ;

### Intermediate

The following intermediate values may be referenced in other methods and are called out here for clarity.

None.

## Method 4.5.1 Estimating missing data ( $Dp_i$ or $\tilde{A}_i$ ) from the known value

### Calculation

Equation 4.5-1 shows the calculation of Integrated Air Activity from Deposition.

$$\tilde{A}_i = \frac{Dp_{i,t_0}}{V_d} \quad (\text{Eq. 4.5-1})$$

$$\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} = \frac{\mu\text{Ci}}{\text{m}^2} \bigg/ \frac{\text{m}}{\text{s}}$$

where:

$\tilde{A}_i$  = Integrated air activity of radionuclide  $i$  in a release,  $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ .

$Dp_{i,t_0}$  = Initial Deposition, the areal activity of radionuclide  $i$  at the time of deposition  $t_0$ ,  $\mu\text{Ci}/\text{m}^2$ ; and

$V_d$  = Deposition Velocity, radionuclide-specific default, m/s.

Conversely, Equation 4.5-2 shows the calculation of Deposition from Integrated Air Activity.

$$Dp_i = \tilde{A}_i * V_d \quad (\text{Eq. 4.5-2})$$

$$\frac{\mu\text{Ci}}{\text{m}^2} = \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * \frac{\text{m}}{\text{s}}$$

## Method 4.5.2 Estimating a deposition velocity ( $V_d$ ) for a mixture containing multiple particle sizes

### Calculation

If the details of the particle size distribution are known and their corresponding deposition velocities, it is possible to estimate a weighted average deposition velocity using Equation 4.5-3.

$$\bar{V}_d = \sum (V_{d_{PS}} * F_{PS}) \quad (\text{Eq. 4.5-3})$$

$$\frac{\text{m}}{\text{s}} = \frac{\text{m}}{\text{s}} * \text{unitless}$$

where:

- $\bar{V}_d$  = Weighted Average Deposition Velocity, m/s;
- $V_{d,PS}$  = Deposition Velocity for a specific particle size, m/s; and,
- $F_{PS}$  = Fraction of the mixture of a specific particle size, unitless.

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**EXAMPLE 1**

**Problem:** Calculate the ground deposition of a radionuclide from the Integrated Air Activity.

An air sampler has reported an integrated air activity of  $10 \mu\text{Ci}\cdot\text{s}/\text{m}^3$  of Sr-90. What is the Sr-90 deposition value expected in the area of the air sampler?

$$Dp_i = \tilde{A}_i * V_d$$

Given that the default deposition velocity is  $3.0\text{E-}03 \text{ m/s}$ :

$$Dp_i = 10 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * 3.0\text{E-}03 \frac{\text{m}}{\text{s}} = 3.0\text{E-}02 \frac{\mu\text{Ci}}{\text{m}^2}$$

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**EXAMPLE 2**

**Problem: Calculate the Weighted Average Deposition Velocity for a mix of particle sizes.**

$$\bar{V}_d = \sum (V_{d_{PS}} * F_{PS})$$

A plume contains the following particle size mixture:

Particle Size	% of mixture
1 micron	50
10 micron	40
100 micron	10

What is the weighted average deposition velocity for the mixture if you assume the following deposition velocities for individual particle sizes?

Particle Size	V <sub>d</sub> (m/s)
1 micron	1.0E-03
10 micron	3.0E-03
100 micron	2.4E-01

$$\bar{V}_d = \sum \left( \begin{array}{l} 1.0\text{E-}03 \frac{\text{m}}{\text{s}} * 0.5 + \\ 3.0\text{E-}03 \frac{\text{m}}{\text{s}} * 0.4 + \\ 2.4\text{E-}01 \frac{\text{m}}{\text{s}} * 0.1 \end{array} \right) = 2.6\text{E-}02 \frac{\text{m}}{\text{s}}$$

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**METHOD 4.6    CONVERTING “GRAB” AIR SAMPLE RESULTS TO  
INTEGRATED-AIR VALUES**

**This Method is reserved for future development.**

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**METHOD 4.7    RELATING MEASURED DOSE RATES TO AREAL  
ACTIVITY**

**This method is reserved for future development.**

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## GLOSSARY

<b>Acute Dose</b>	The dose delivered over a period of 30 days.
<b>Acute Dose Coefficient</b>	The Effective or Equivalent Dose received over 30 days per unit intake (mrem/ $\mu$ Ci).
<b>Areal Activity</b>	The amount of radioactive material per area (e.g., $\mu$ Ci/m <sup>2</sup> ).
<b>Chronic Dose</b>	The dose delivered over a period of 50-70 years.
<b>Chronic Dose Coefficient</b>	The Effective or Equivalent Dose received over 50-70 years per unit intake (mrem/ $\mu$ Ci).
<b>Committed Effective Dose (E)</b>	The sum of the committed equivalent doses following intake (inhalation or ingestion) of a radionuclide to each organ multiplied by a tissue weighting factor.
<b>Committed Equivalent Dose (H<sub>T</sub>)</b>	The equivalent dose to a specific organ following intake (inhalation or ingestion). It does not include contributions from external dose.
<b>DCFPK (Dose Coefficient Package)</b>	An electronic database containing dose coefficients from ICRP Dosimetry Models.
<b>Deposition</b>	The contamination on the surface of the ground.
<b>Derived Intervention Level (DIL)</b>	The concentration of a radionuclide in food that could lead to an individual receiving a dose equal to the PAG.
<b>Derived Response Level (DRL)</b>	A calculated value (e.g., dose rate or radionuclide concentration) that corresponds to an early health effect threshold, a PAG, or a DIL. DRLs can be used to relate environmental measurements or laboratory analysis to the potential for early health effects or need for protective actions. Used to facilitate prompt assessments.
<b>Early Phase</b>	The period at the beginning of a nuclear incident when immediate decisions for effective use of protective actions are required, and must be based primarily on predictions of radiological conditions in the environment. This phase may last from hours to days. For the purpose of dose projection, it is assumed to last for four days.
<b>Effective Dose (E)</b>	The sum of the equivalent dose from each organ multiplied by a tissue weighting factor.
<b>Equivalent Dose (H<sub>T</sub>)</b>	The dose to an organ multiplied by the radiation weighting factor.
<b>Emergency Worker Guidance</b>	Guidance on the external dose and Committed Effective Dose incurred by workers (other than a pregnant woman) while performing emergency services.
<b>External Dose</b>	The dose of radiation received by an individual from a source of ionizing radiation outside the body.
<b>Groundshine</b>	External radiation from radioactive materials deposited on the ground.
<b>ICRP 60+</b>	ICRP Publication 60 and the collection of ICRP documents relating to the ICRP 60 dosimetry model published subsequently.

<b>Intermediate Phase</b>	The period beginning after the incident source and releases have been brought under control and reliable environmental measurements are available for use as a basis for decisions on additional protective actions and extending until these protective actions have terminated. This phase may overlap the early phase and late phase and may last from weeks to many months. For the purposes of dose projection, it is assumed to last for one year.
<b>Late Phase</b>	The period beginning when recovery actions designed to reduce radiation levels in the environment to permanently acceptable levels are commenced, and ending when all recovery actions have been completed. This phase may extend from months to years.
<b>Mixture</b>	The nuclide ratio (relative abundance) of the radionuclides in a release.
<b>Pathways</b>	The paths radionuclides follow from the source through the environment, including vegetation and animals, to reach an individual or a population.
<b>Protective Action Guide (PAG)</b>	The projected dose, from an accidental release of radioactive material, where specific actions to reduce or avoid dose are warranted.
<b>Quality Factor (QF)</b>	The principal modifying factor that represents the biological effectiveness of different radiation types with respect to induction of stochastic effects. It is used to calculate the dose equivalent from the absorbed dose. The absorbed dose, expressed in rad or Gy, is multiplied by the appropriate quality factor to obtain the dose equivalent.
<b>Relative Biological Effectiveness (RBE)</b>	The RBE of a given type of ionizing radiation is a factor used to compare the biological effectiveness of absorbed radiation doses (i.e., rads) due to one type of ionizing radiation with that of other types of ionizing radiation; more specifically, it is the experimentally determined ratio of an absorbed dose of a radiation in question to the absorbed dose of a reference radiation required to produce an identical biological effect in a particular experimental organism or tissue.
<b>Resuspension</b>	Reintroduction to the breathing zone of material originally deposited onto surfaces.
<b>Submersion</b>	To be surrounded or engulfed by the radioactive cloud.
<b>Total Effective Dose (TED)</b>	The sum of the effective dose (for external exposures) and the committed effective dose.
<b>Total Equivalent Dose – Organ (TEDO)</b>	The sum of the equivalent dose (for external exposure) and the committed equivalent dose to a specific organ.
<b>Transfer Factor</b>	The ratio of the concentration of an element in an organism of interest, such as plants and food products, to the concentration in the source medium, such as soil, plant forage or water.
<b>Turn-Back Guidance</b>	Guidance given to emergency workers indicating when they should seek areas of lower exposure rate or potential. This guidance is usually implemented via a DRL expressed as an integrated dose reading on a self-reading dosimeter, an exposure rate, or a deposition concentration indicating that the emergency worker should leave the area where further exposure is possible.

**Weathering** Reduction of dose from deposited radionuclides (external and resuspension) over time due to movement of contamination below the surface or binding on surface materials.

**Weighting Factors** The fraction of the overall health risk resulting from uniform whole body irradiation attributable to a specific organ.

Organ	Weighting Factor
Gonads	0.20
Red bone marrow	0.12
Colon	0.12
Lungs	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surfaces	0.01
Remainder <sup>1</sup>	0.05
Whole body <sup>2</sup>	1.00

Source: ICRP90, Table 2.

<sup>1</sup> "Remainder" means the following additional tissues and organs and their masses, in grams, following parenthetically: adrenals (14), brain (1400), extrathoracic airways (15), small intestine (640), kidneys (310), muscle (28,000), pancreas (100), spleen (180), thymus (20), and uterus (80). The equivalent dose to the remainder tissues ( $H_{\text{remainder}}$ ) is normally calculated as the mass-weighted mean dose to the preceding ten organs and tissues. In those cases in which the most highly irradiated remainder tissue or organ receives the highest equivalent dose of all the organs, a weighting factor of 0.025 (half of remainder) is applied to that tissue or organ and 0.025 (half of remainder) to the mass-weighted equivalent dose in the rest of the remainder tissues and organs to give the remainder equivalent dose.

<sup>2</sup> For the case of uniform external irradiation of the whole body, a tissue weighting factor ( $w_T$ ) equal to 1 may be used in determination of the effective dose.

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TERM	UNITS	DEFINITION	METHODS
$2Path\_DRL_{\bar{A}}$	$\frac{\mu Ci}{m^2}$	Two-Pathway Air Derived Response Level, the integrated air activity ( $\bar{A}$ ) of radionuclide $i$ at which the total dose from <i>all radionuclides</i> in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.	1.1, 1.3, 1.4
$2Path\_DRL_{Dp}$	$\frac{\mu Ci}{m^2}$	Two-Pathway Deposition Derived Response Level, the areal activity, at time $t_n$ , of radionuclide $i$ at which the total dose from <i>all radionuclides</i> in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.	1.1, 1.3, 1.4
$2Path\_DRL_{DR}$	$\frac{mrem}{hr}$	Two-Pathway Dose Rate Derived Response Level, the external dose rate, at time $t_n$ , at which the total dose from <i>all radionuclides</i> in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.	1.2, 1.5
$2Path\_DRL_{XR}$	$\frac{mR}{hr}$	Two-Pathway Exposure Rate Derived Response Level, the external exposure rate, at time $t_n$ , at which the total dose from <i>all radionuclides</i> in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.	1.2, 1.5
$2Path\_DRL_{\alpha, \bar{A}}$	$\frac{\mu Ci_{\alpha} \cdot s}{m^3}$	Two-Pathway Air Alpha Derived Response Level, the integrated air alpha activity of the mixture at which the total dose from <i>all radionuclides</i> in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.	1.3
$2Path\_DRL_{\alpha, Dp}$	$\frac{\mu Ci_{\alpha}}{m^2}$	Two-Pathway Deposition Alpha Derived Response Level, the areal alpha activity of the mixture, at time $t_n$ , at which the total dose from <i>all radionuclides</i> in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.	1.3
$2Path\_DRL_{\beta, \bar{A}}$	$\frac{\mu Ci_{\beta} \cdot s}{m^3}$	Two-Pathway Air Beta Derived Response Level, the integrated air beta activity of the mixture at which the total dose from <i>all radionuclides</i> in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.	1.4
$2Path\_DRL_{\beta, Dp}$	$\frac{\mu Ci_{\beta}}{m^2}$	Two-Pathway Deposition Beta Derived Response Level, the areal beta activity of the mixture, at time $t_n$ , at which the total dose from <i>all radionuclides</i> in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.	1.4

TERM	UNITS	DEFINITION	METHODS
<i>2Path_MTDP</i>	mrem	Two-Pathway Mixture Total Dose Parameter, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration, from the radionuclide mixture.	1.1, 1.2
<i>2Path_PPD</i>	mrem	Two-Pathway Projected Public Dose, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration, from the radionuclide mixture.	1.5
<i>4Path_DRL<sub><math>\bar{A}</math></sub></i>	$\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3}$	Four-Pathway Air Derived Response Level, the integrated air activity ( $\bar{A}$ ) of radionuclide <i>i</i> at which the total dose from <i>all radionuclides</i> in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.	1.1, 1.3, 1.4
<i>4Path_DRL<sub>DP</sub></i>	$\frac{\mu\text{Ci}}{\text{m}^2}$	Four-Pathway Deposition Derived Response Level, the areal activity, at time $t_n$ , of radionuclide <i>i</i> at which the total dose from <i>all radionuclides</i> in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.	1.1, 1.3, 1.4
<i>4Path_DRL<sub>DR</sub></i>	$\frac{\text{mrem}}{\text{hr}}$	Four-Pathway Dose Rate Derived Response Level, the external dose rate, at time $t_n$ , at which the total dose from <i>all radionuclides</i> in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.	1.2, 1.5
<i>4Path_DRL<sub>XR</sub></i>	$\frac{\text{mR}}{\text{hr}}$	Four-Pathway Exposure Rate Derived Response Level, the external exposure rate, at time $t_n$ , at which the total dose from <i>all radionuclides</i> in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.	1.2, 1.5
<i>4Path_DRL<sub><math>\alpha, \bar{A}</math></sub></i>	$\frac{\mu\text{Ci}_{\alpha}\cdot\text{s}}{\text{m}^3}$	Four-Pathway Air Alpha Derived Response Level, the integrated air alpha activity of the mixture at which the total dose from <i>all radionuclides</i> in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.	1.3
<i>4Path_DRL<sub><math>\alpha, DP</math></sub></i>	$\frac{\mu\text{Ci}_{\alpha}}{\text{m}^2}$	Four-Pathway Deposition Alpha Derived Response Level, the areal alpha activity of the mixture, at time $t_n$ , at which the total dose from <i>all radionuclides</i> in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.	1.3

TERM	UNITS	DEFINITION	METHODS
$4Path\_DRL_{\beta,\tilde{A}}$	$\frac{\mu Ci_{\beta} \cdot s}{m^3}$	Four-Pathway Air Beta Derived Response Level, the integrated air beta activity of the mixture at which the total dose from <i>all radionuclides</i> in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.	1.4
$4Path\_DRL_{\beta,Dp}$	$\frac{\mu Ci_{\beta}}{m^2}$	Four-Pathway Deposition Beta Derived Response Level, the areal beta activity of the mixture, at time $t_n$ , at which the total dose from <i>all radionuclides</i> in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.	1.4
$4Path\_MTDP$	mrem	Four-Pathway Mixture Total Dose Parameter, the sum of the external dose from submersion and groundshine and the committed dose from inhalation of plume-borne and resuspended material, over the time phase under consideration, from the radionuclide mixture.	1.1, 1.2
$4Path\_PPD$	mrem	Four-Pathway Projected Public Dose, the sum of the external dose from submersion and groundshine and the committed dose from inhalation of plume-borne and resuspended material, over the time phase under consideration, from the radionuclide mixture.	1.5
$\tilde{A}_i$	$\frac{\mu Ci \cdot s}{m^3}$	Integrated air activity of radionuclide $i$ in a release.	1.1, 4.5
$AFDIR$	$\frac{kg_{wet}}{d}$	Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed (forage or stored).	3.3, 3.4, 3.6, Appendix C
$APF$	unitless	Assigned Protection Factor, the level of respiratory protection that a respirator is expected to provide. (Default of 1 when no respirators are used.) <b>NOTE:</b> Consult Health and Safety personnel for appropriate values for APF.	2.2
$ASDIR$	$\frac{kg_{soil}}{d}$	Animal Soil Daily Ingestion Rate, the daily rate at which an animal consumes soil.	3.3, 3.4, 3.6, Appendix C
$AWDIR$	$\frac{L}{d}$	Animal Water Daily Ingestion Rate, the daily rate at which an animal consumes water.	3.3, 3.4, 3.6, Appendix C
$BR_{AA}$	$\frac{m^3}{s}$	Activity-Averaged Breathing Rate, the average volume of air breathed per unit time by an adult male (ICRP94, Table B.16B).	1.1

TERM	UNITS	DEFINITION	METHODS
$BR_{LE}$	$\frac{m^3}{s}$	Light Exercise Breathing Rate, the volume of air breathed per unit time by an adult male during light exercise (ICRP94, Table 6).	1.1, 2.2
$\chi$	$\frac{\mu Ci}{m^3}$	Air concentration of radionuclide $i$ .	4.1
$C_{crop}$	$\frac{\mu Ci}{kg_{wet}}$	Projected Contamination level in a food crop (fresh produce), the level of activity of radionuclide $i$ per mass in a food type harvested from contaminated ground.	3.6
$C_f$	$\frac{\mu Ci}{kg_{wet}}$	Food Contamination, the level of contamination of radionuclide $i$ in a specific food type (f). (May also be expressed in $\mu Ci/L$ .)	3.5
$C_{meat}$	$\frac{\mu Ci}{kg_{wet}}$	Projected Contamination level in meat, the level of activity of radionuclide $i$ per mass in an animal's meat from consuming radioactive material.	3.6
$C_{milk}$	$\frac{\mu Ci}{L}$	Projected Contamination level in milk, the level of activity of radionuclide $i$ per volume in milk produced from animals consuming radioactive material.	3.6
$C_S$	$\frac{\mu Ci}{kg_{soil}}$	Measured Contamination level of radionuclide $i$ in soil.	3.6
$C_{sample,dry}$	$\frac{\mu Ci}{kg_{dry}}$	Sample Contamination, the level of contamination of radionuclide $i$ in a sample in terms of dry mass.	4.2
$C_{sample,wet}$	$\frac{\mu Ci}{kg_{wet}}$	Sample Contamination, the level of contamination of radionuclide $i$ in a sample in terms of wet mass.	4.2
$C_w$	$\frac{\mu Ci}{L}$	Measured Contamination level of radionuclide $i$ in drinking water.	3.6
$CRF$	unitless	Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop.	3.2, 3.3, 3.4, 3.6
$Crop\_DRL_{mat}$	$\frac{\mu Ci}{m^2}$	Ingestion Derived Response Level for mature Crop/Produce, the areal activity of radionuclide $i$ that would cause the crop/produce growing in that area to equal the applicable DIL at the time of contamination.	3.2

TERM	UNITS	DEFINITION	METHODS
$Crop\_DRL_{imm}$	$\frac{\mu\text{Ci}}{\text{m}^2}$	Ingestion Derived Response Level for immature Crop/Produce, the areal activity of radionuclide $i$ that would cause the crop/produce growing in that area to equal the applicable DIL at the time of harvest.	3.2
$DFIR$	$\frac{\text{kg}_{\text{wet}}}{\text{d}}$	Daily Food Intake Rate, the daily intake rate (as prepared for consumption, i.e. wet mass) for a specific age group.	3.1, 3.5
$DFIR_{\text{subgroup}}$	$\frac{\text{kg}_{\text{wet}}}{\text{d}}$	Daily Food Intake Rate for a food subgroup (as prepared for consumption, i.e. wet mass) for a specific age group.	3.5
$DIL$	$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$	Derived Intervention Level, the concentration of radionuclide $i$ in food at which the ingestion dose to the most sensitive population (age group) and target organ would equal the applicable ingestion PAG.	3.1, 3.2, 3.3, 3.4
$d_m$	m	Mixing Depth (See Appendix C, Table 11).	3.2, 3.3, 3.4, 3.6, 3.7, Appendix C
$Dp_i$	$\frac{\mu\text{Ci}}{\text{m}^2}$	Deposition, the activity of radionuclide $i$ per unit area of ground (areal activity).	1.1, 1.2, 3.6, 4.1, 4.5
$Dp\_ExDC$	$\frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}\cdot\text{hr}}$	Deposition External Dose Coefficient, the external dose rate from radionuclide $i$ per unit activity deposited on the ground. <i>Units may either be in seconds or hours, depending on the Method.</i>	1.1, 1.2, Appendix C
$Dp\_ExDP$	mrem	Deposition External Dose Parameter, the external dose from groundshine from radionuclide $i$ , over the time phase under consideration.	1.1, 2.2, Appendix C
$Dp\_InhDP$	mrem	Deposition Inhalation Dose Parameter, the committed dose from radionuclide $i$ deposited on the ground from the inhalation of the resuspended fraction of the radionuclide over the time phase under consideration.	1.1, 2.2, Appendix C
$Dp\_MExDF$	$\frac{\text{mrem}}{\text{hr}}$	Deposition Mixture External Dose Factor, the external dose rate at time $t_n$ from a radionuclide mixture deposited on the ground.	1.2
$Dp\_TDP$	mrem	Deposition Total Dose Parameter, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration, from the deposition of radionuclide $i$ .	1.1, 1.5, Appendix C

TERM	UNITS	DEFINITION	METHODS
$DSIR$	$\frac{\text{kg}_{\text{soil}}}{\text{d}}$	Daily Soil Intake Rate, the amount of soil inadvertently ingested by humans in a day.	3.7
$E_{Ing}$	mrem	Committed Effective Dose from ingestion, the dose to the whole body from ingestion of all radionuclides in all contaminated food types.	3.5
$E_{soil}$	mrem	Committed Effective Dose from inadvertent soil ingestion, the dose to the whole body from the ingestion of all radionuclides in contaminated soil.	3.7
$EDI$	d	Effective Days of Intake, the number of days required for radionuclide $i$ to decay to <1% of its initial activity (maximum of 365).	3.1
$ExDR$	$\frac{\text{mrem}}{\text{hr}}$	External dose rate, the external dose rate from materials deposited on the ground.	1.5
$ExDR_a$	$\frac{\text{mrem}}{\text{hr}}$	External dose rate at time $t_a$ (hours after detonation).	1.7
$ExDR_b$	$\frac{\text{mrem}}{\text{hr}}$	External dose rate at time $t_b$ (hours after detonation).	1.7
$ExDR_r$	$\frac{\text{mrem}}{\text{hr}}$	Reference external dose rate at 1 hour after nuclear detonation.	1.7
$ExDR_{r,PAG}$	$\frac{\text{mrem}}{\text{hr}}$	Reference external dose rate at 1 hour after nuclear detonation which would produce a dose equal to the PAG over the time phase under consideration.	1.7
$ExDR_t$	$\frac{\text{mrem}}{\text{hr}}$	External dose rate at time $t$ (hours after detonation).	1.7
$ExTDCF$	$\frac{\text{mrem}_{\text{inh+external}}}{\text{mrem}_{\text{external}}}$	External to Total Dose Conversion Factor, the ratio of the total dose (external + inhalation) to the external dose for a deposition of radioactive material over the time phase under consideration. <b>NOTE:</b> This value is used to convert a measurement from a self-reading dosimeter into a dose which includes the dose from inhalation of resuspended material.	2.2
$FDC$	unitless	Fraction of Diet Contaminated, the fraction of a human's diet that is contaminated with radionuclide $i$ . FDC is age and radionuclide dependent.	3.1, Appendix C

TERM	UNITS	DEFINITION	METHODS
$FDC_F$	unitless	Fraction of Diet Contaminated (feed), the fraction of the animal's diet that is from feed contaminated by radionuclide $i$	3.3, 3.4, 3.6, Appendix C
$FDC_W$	unitless	Fraction of Diet Contaminated (water), the fraction of an animal's diet that is from water contaminated by radionuclide $i$ .	3.3, 3.4, 3.6, Appendix C
$FFC_{subgroup}$	unitless	Fraction of Food Subgroup contaminated by radionuclide $i$ .	3.5, Appendix C
$F_{PS}$	unitless	Fraction of the mixture of a specific particle size.	4.5
$GRF$	unitless	Ground Roughness Factor, a constant (0.82) that compensates for the fact that the external exposure is not coming from an infinite flat plane (An02).	1.1, 1.2
$H_T$	mrem	Committed Equivalent Dose, the dose to organ $T$ from the ingestion of all radionuclides in contaminated food.	3.5
$H_{T,soil}$	mrem	Committed Equivalent Dose from inadvertent soil ingestion, the dose to organ $T$ from the ingestion of soil.	3.7
$IngDC$	$\frac{\text{mrem}}{\mu\text{Ci}}$	Ingestion Dose Coefficient, the ingestion pathway dose coefficient for the target organ for a specific age group for radionuclide $i$ .	3.1, 3.5, 3.7
$IngDP$	$\frac{\text{mrem}\cdot\text{d}}{\text{kg}_{\text{wet}}}$	Ingestion Dose Parameter, the committed effective dose received from ingestion of all radionuclides in a specific food type ( $f$ ) by a specific age group.	3.5
$IngDP_{avg}$	$\frac{\text{mrem}\cdot\text{d}}{\text{kg}_{\text{wet}}}$	Average Ingestion Dose Parameter for a food subgroup, the average of the individual $IngDPs$ for each type of contaminated food in a subgroup for a specific age group.	3.5
$InhDC$	$\frac{\text{mrem}}{\mu\text{Ci}}$	Inhalation Dose Coefficient, the committed dose coefficient for inhalation of radionuclide $i$ .	1.1, Appendix C
$K_t$	$\text{m}^{-1}$	Resuspension Factor, the fraction of radioactive material transferred from the surface to the breathing zone at given time $t$ after initial deposition.	4.1, Appendix F
$KIPF$	unitless	Potassium Iodide Protection Factor, default of 1 for all non-iodine isotopes or when no KI is administered. <b>NOTE:</b> Consult Health and Safety personnel for appropriate values for KIPF.	2.2

TERM	UNITS	DEFINITION	METHODS
$KP$	$\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3}$	Resuspension Parameter, value that adjusts the airborne radioactivity level of radionuclide $i$ over the time phase under consideration for radioactive decay and in-growth and the resuspension factor.	1.1, Appendix F
$\lambda_i$	$\text{s}^{-1}$ or $\text{d}^{-1}$	Decay constant for radionuclide $i$ .	3.2, 3.3, 3.4, 3.5, 3.6, 3.7, Appendix C, Appendix F
$\lambda_w$	$\text{d}^{-1}$	Decay constant for weathering radioactive material off plants.	3.2, 3.4, 3.6, Appendix C
$MCF_{D-W}$	$\frac{\text{kg}_{\text{dry}}}{\text{kg}_{\text{wet}}}$	Mass Conversion Factor (dry to wet), the ratio of dry mass to wet mass for a food type or subgroup.	3.2, 4.2 Appendix C
$Meat\_DRL_{\text{area}}$	$\frac{\mu\text{Ci}}{\text{m}^2}$	Meat Ingestion Derived Response Level - Area, the areal activity of radionuclide $i$ deposited over a grazing area that would result in a grazing animal's meat equaling the DIL for that radionuclide when the animal is harvested.	3.4
$Meat\_DRL_{\text{mass}}$	$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$	Meat Ingestion Derived Response Level - Mass, the mass concentration of radionuclide $i$ in animal feed that would result in the animal's meat equaling the DIL for that radionuclide when the animal is harvested.	3.4
$Meat\_DRL_{\text{water}}$	$\frac{\mu\text{Ci}}{\text{L}}$	Meat Ingestion Derived Response Level - Water, the water concentration of radionuclide $i$ in an animal's drinking water that would result in the animal's meat equaling the DIL for that radionuclide when the animal is harvested.	3.4
$Milk\_DRL_{\text{area}}$	$\frac{\mu\text{Ci}}{\text{m}^2}$	Milk Ingestion Derived Response Level - Area, the areal activity of radionuclide $i$ deposited over a grazing area that would result in the grazing animal's milk equaling the DIL for that radionuclide.	3.3
$Milk\_DRL_{\text{mass}}$	$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$	Milk Ingestion Derived Response Level - Mass, the mass concentration of radionuclide $i$ in animal feed that would result in the grazing animal's milk equaling the DIL for that radionuclide.	3.3
$Milk\_DRL_{\text{water}}$	$\frac{\mu\text{Ci}}{\text{L}}$	Milk Ingestion Derived Response Level - Water, the water concentration of radionuclide $i$ in an animal's drinking water that would result in the grazing animal's milk equaling the DIL for that radionuclide.	3.3

TERM	UNITS	DEFINITION	METHODS
$NF\_DRL$	$\frac{\text{mrem}}{\text{hr}}$	Nuclear Fallout Derived Response Level, the external dose rate, at time $t_n$ , at which the external dose from <i>all radionuclides</i> in a fallout deposition mixture would equal the PAG for the time phase under consideration.	1.7
$Pl\_ExDC_i$	$\frac{\text{mrem}\cdot\text{m}^3}{\mu\text{Ci}\cdot\text{s}}$	Plume External Dose Coefficient, the external dose rate from submersion in radionuclide $i$ in the plume.	1.1, Appendix C
$Pl\_ExDP_{i,TP}$	mrem	Plume External Dose Parameter, the external dose from submersion from plume-borne radionuclide $i$ .	1.1, Appendix C
$Pl\_InhDP_{i,TP}$	mrem	Plume Inhalation Dose Parameter, the committed dose from inhalation of plume-borne radionuclide $i$ .	1.1, Appendix C
$Pl\_TDP_{i,TP}$	mrem	Plume Total Dose Parameter, the sum of the external dose from submersion in, and the committed dose from inhalation of, plume-borne radionuclide $i$ .	1.1, 1.5, Appendix C
$\rho_{milk}$	$\frac{\text{kg}_{\text{wet}}}{\text{L}}$	Milk density.	3.3, Appendix C
$\rho_{soil}$	$\frac{\text{kg}_{\text{soil}}}{\text{m}^3}$	Soil Density.	3.2, 3.3, 3.4, 3.6, 3.7, Appendix C
$ST$	hr	Stay Time	2.1
$t_0$	NA	Release Time. The time the release begins. This time is usually assumed to correspond to the time of deposition.	1.1, 1.2, 3.6, 3.7, 4.5, Appendix F
$t_1$	s or hr	Start Time. The start of the time phase (integration period) under consideration.	1.1, 1.7, 3.7, Appendix F
$t_2$	s or hr	End Time. The end of the time phase (integration period) under consideration.	1.1, 1.7, 2.7, Appendix F
$t_a, t_b$	hr	Time after a nuclear detonation at which a measurement is made.	1.7
$t_c$	d	Consumption Time, the length of the food consumption period.	3.5
$t_f$	d	Field Time, the time the crop spends growing in the field from deposition or sampling to harvest, d;	3.2
$t_g$	d	Grazing Time, time from deposition or sampling to the end of the grazing period.	3.4, 3.6

TERM	UNITS	DEFINITION	METHODS
$t_h$	d	Hold Time, the time elapsed from sample measurement to the beginning of the food consumption period.	3.5
$t_m$	d	Time to Market, the number of days from harvest to food consumption. See Appendix C, Table 11.	3.2, 3.3, 3.4, 3.6, Appendix C
$t_n$	s, hr, d	Evaluation Time, the point in time, relative to the start of the release, at which the measurement, prediction or evaluation is performed.	1.1, 1.2, 1.3, 1.4, 1.5, 1.7
$TBL_{DR}$	$\frac{\text{mrem}}{\text{hr}}$	Dose Rate Turn-Back Limit, the Integrated Dose Turn-Back Limit divided by the Stay Time in the contaminated area.	2.1
$TBL_{XR}$	$\frac{\text{mR}}{\text{hr}}$	Exposure Rate Turn-Back Limit, the Integrated Exposure Turn-Back Limit divided by the Stay Time in the contaminated area.	2.1
$TBL_{D_{TP}}$	$\text{mrem}_{\text{external}}$	Turn-Back Limit for Integrated External Dose, the integrated external dose, as recorded by the self-reading dosimeter, received from a radionuclide mixture deposited on the ground over the time phase under consideration, which would result in the worker receiving their dose limit.	2.2
$TBL_{X_{TP}}$	mR	Turn-Back Limit for Integrated External Exposure, the integrated external exposure, as recorded by a self-reading exposure meter, received from a radionuclide mixture deposited on the ground over the time phase under consideration, which would result in the worker receiving their dose limit.	2.2
$TF_{crop}$	$\frac{\mu\text{Ci}/\text{kg}_{\text{dry}}}{\mu\text{Ci}/\text{kg}_{\text{soil}}}$	Transfer Factor for a food crop, the fraction of radionuclide $i$ deposited on the growing medium that is transferred to the plant during the growing season. <b>NOTE:</b> Transfer Factors for plants are in terms of edible dry plants (PNNL03).	3.2
$TF_{Meat}$	$\frac{\mu\text{Ci}/\text{kg}_{\text{wet}}}{\mu\text{Ci}/\text{d}}$	Transfer Factor for meat, the fraction of radionuclide $i$ consumed by an animal ( $A$ ) that is transferred to the meat of the animal.	3.4, 3.6
$TF_{Milk}$	$\frac{\mu\text{Ci}/\text{L}}{\mu\text{Ci}/\text{d}}$	Transfer Factor for milk, the fraction of radionuclide $i$ consumed by an animal ( $A$ ) that is transferred to the milk produced by the animal.	3.3, 3.6
$V_d$	m/s	Deposition velocity for a specific particle size.	4.5
$\bar{V}_d$	m/s	Weighted average deposition velocity.	4.5

TERM	UNITS	DEFINITION	METHODS
$WF$	unitless	Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind).	1.1, 1.2, 3.7, Appendix F
$WP$	$\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^2}$	Weathering Parameter, the adjustment for radioactive decay and in-growth and the time-dependent weathering effects that change the amount of a radionuclide available to cause direct exposure or to be ingested over the time phase under consideration.	1.1, 3.7, Appendix F
$x$	unitless	Power function exponent, the value that represents the decay of fallout radioactivity at a given location. Default =1.2.	1.7
$XDCF_A$	$\frac{\text{mrem}}{\text{mR}}$	Exposure to Dose Conversion Factor (acute), the constant used to convert external exposure (mR) to midline (bone marrow) dose (mrem), 0.7.	1.2, 2.1, 2.2
$XDCF_C$	$\frac{\text{mrem}}{\text{mR}}$	Exposure to Dose Conversion Factor (chronic), the constant used to convert external exposure (mR) to deep tissue (1 cm) dose (mrem), 1.0.	1.2, 2.1, 2.2
$Y$	$\frac{\text{kg}_{\text{wet}}}{\text{m}^2}$	Crop Yield, the mass of crop grown per area of land.	3.2, 3.3, 3.4, 3.6, Appendix C
$Y_\alpha$	$\frac{\mu\text{Ci}_\alpha}{\mu\text{Ci}_{\text{nt}}}$	Yield, the alpha activity per total (nuclear transformation) activity of radionuclide $i$ .	1.3
$Y_\beta$	$\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}_{\text{nt}}}$	Yield, the beta activity per total (nuclear transformation) activity of radionuclide $i$ .	1.4

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Table 1 – Radiological Data <sup>1</sup>

Parent Radionuclide	$t_{1/2}$ (d)	$\lambda$ (d <sup>-1</sup> )	Dp_ExDF <sup>2,3</sup> (Groundshine) (mrem·m <sup>2</sup> /μCi·hr)	Pl_ExDC <sup>2</sup> (Submersion) (mrem·m <sup>3</sup> /μCi·hr)	InhDC <sup>2</sup> (Inhalation) (mrem/μCi)
Am-241	1.6E+05	4.4E-06	2.4E-04	9.0E-03	3.6E+05
Ba-140	1.3E+01	5.4E-02	2.9E-02	1.8E+00	2.7E+01
Ce-141	3.3E+01	2.1E-02	7.6E-04	4.2E-02	1.4E+01
Ce-144	2.8E+02	2.4E-03	2.0E-03	4.3E-02	2.0E+02
Cf-252	9.6E+02	7.2E-04	4.7E-03	3.0E-01	1.4E+05
Cm-242	1.6E+02	4.3E-03	7.3E-06	5.2E-05	2.2E+04
Cm-244	6.6E+03	1.0E-04	6.4E-06	5.3E-05	2.1E+05
Co-60	1.9E+03	3.6E-04	2.5E-02	1.6E+00	1.1E+02
Cs-134	7.5E+02	9.2E-04	1.6E-02	9.4E-01	7.6E+01
Cs-136	1.3E+01	5.3E-02	2.2E-02	1.3E+00	1.0E+01
Cs-137	1.1E+04	6.3E-05	6.0E-03	3.4E-01	1.5E+02
Gd-153	2.4E+02	2.9E-03	1.0E-03	4.1E-02	8.8E+00
I-129	5.7E+09	1.2E-10	2.2E-04	3.8E-03	1.3E+02
I-131	8.0E+00	8.6E-02	4.0E-03	2.3E-01	2.7E+01
I-132	9.6E-02	7.2E+00	2.4E-02	1.4E+00	4.2E-01
I-133	8.7E-01	8.0E-01	6.8E-03	3.7E-01	5.4E+00
I-134	3.7E-02	1.9E+01	2.7E-02	1.6E+00	2.1E-01
I-135	2.8E-01	2.5E+00	1.7E-02	1.1E+00	1.2E+00
Ir-192	7.4E+01	9.4E-03	8.5E-03	4.8E-01	2.5E+01
La-140	1.7E+00	4.1E-01	2.4E-02	1.5E+00	4.2E+00
Mo-99	2.8E+00	2.5E-01	3.1E-03	1.6E-01	3.7E+00
Nb-95	3.5E+01	2.0E-02	7.9E-03	4.7E-01	6.5E+00
Np-237	7.8E+08	8.9E-10	6.5E-03	3.3E-01	1.3E+06
Np-239	2.4E+00	2.9E-01	1.8E-03	9.8E-02	3.8E+00
Pm-147	9.6E+02	7.2E-04	3.1E-07	1.2E-04	2.6E+01
Pu-238	3.2E+04	2.2E-05	6.5E-06	4.5E-05	4.0E+05
Pu-239	8.8E+06	7.9E-08	3.4E-06	5.0E-05	4.4E+05
Pu-241	5.3E+03	1.3E-04	4.9E-08	2.5E-06	8.5E+03
Ra-226	5.8E+05	1.2E-06	1.9E-02	1.1E+00	7.3E+04
Ru-103	3.9E+01	1.8E-02	5.2E-03	2.9E-01	1.1E+01
Ru-106	3.7E+02	1.9E-03	3.8E-03	1.4E-01	2.4E+02
Sb-127	3.8E+00	1.8E-01	7.5E-03	4.2E-01	7.4E+00
Sb-129	1.8E-01	3.9E+00	1.7E-02	9.5E-01	1.1E+00
Se-75	1.2E+02	5.8E-03	3.9E-03	2.2E-01	5.0E+00
Sr-89	5.1E+01	1.4E-02	7.5E-04	5.9E-03	2.9E+01
Sr-90	1.1E+04	6.5E-05	1.2E-03	1.2E-02	5.9E+02
Sr-91	4.0E-01	1.8E+00	1.2E-02	6.4E-01	1.5E+00
Te-129m	3.4E+01	2.1E-02	1.5E-03	4.7E-02	2.9E+01
Te-131m	1.3E+00	5.5E-01	1.6E-02	9.5E-01	4.0E+00
Te-132	3.3E+00	2.1E-01	2.7E-02	1.6E+00	8.0E+00
Tm-170	1.3E+02	5.4E-03	2.7E-04	4.3E-03	3.4E+01
Y-91	5.9E+01	1.2E-02	8.1E-04	8.0E-03	3.3E+01
Yb-169	3.2E+01	2.2E-02	3.2E-03	1.6E-01	1.1E+01
Zr-95	6.4E+01	1.1E-02	2.5E-02	1.5E+00	3.6E+01

<sup>1</sup> Values generated using DCFPAK Version 2.0.  
<sup>2</sup> Values include dose contributions from all daughters that are considered to be in equilibrium (i.e., half-life shorter than ultimate parent (e.g., Cs-137 includes contribution from Ba-137m)).  
<sup>3</sup> Deposition External Dose Factor - Values include adjustment of Deposition External Dose Coefficient for ground roughness (0.82).

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**Table 2-1 Dose Limits for Workers Performing Emergency Services**

<b>TED<sup>a</sup> (rem)</b>	<b>Lens of Eye (rem)</b>	<b>Other Organ, Thyroid, Skin (rem)</b>	<b>Activity</b>	<b>Condition</b>
5	15	50	All.	
10	30	100	Protecting valuable property.	Lower dose not practicable.
25	75	250	Lifesaving or protection of large populations.	Lower dose not practicable.
>25	>75	>250	Lifesaving or protection of large populations.	Only on a voluntary basis by persons fully aware of the risks involved (see Table 3).

Source: EPA92, Table 2-2

<sup>a</sup> Sum of external Effective Dose and Committed Effective Dose to non-pregnant adults from exposure and intake during an emergency situation. These limits apply to all doses from an incident, except those received in unrestricted areas as members of the public during the Intermediate Phase of the incident.

**Table 2-2 PAGs**

<b>Time Phase</b>	<b>Protective Action</b>	<b>Limit (rem)</b>	<b>Comments</b>
Early	Evacuation or Sheltering	TED 1-5 <sup>a</sup> Thyroid 5-25 Skin 50-250	Evacuation should normally be initiated at 1 rem. Sheltering may be the preferred protective action when it provides protection equal to or greater than evacuation.
		Administration of stable iodine	Equivalent Dose to the thyroid from radioiodine. Requires approval of state medical officials.
	5		Pregnant or Lactating Women, Children 0-18 yrs
	10		Adults 18-40 yrs
	500	Adults over 40 yrs	
1 <sup>st</sup> Year	Relocation <sup>b</sup>	2 <sup>a</sup>	Or 100 rem skin dose.
	Apply dose reduction techniques	<2	Should be taken to reduce doses to ALARA. (Scrubbing and/or flushing hard surfaces, soaking or plowing soil, minor removal of soil from areas of concentration, limiting outdoor time, etc.)
2 <sup>nd</sup> Year	Relocation <sup>b</sup>	0.5 <sup>a</sup>	Any single year after the 1 <sup>st</sup> .
50 Years	Relocation <sup>b</sup>	5 <sup>a</sup>	Total for 50 years.
Ingestion	See Table 2-3	0.5 CED 5 H <sub>T</sub>	Due to ingestion of contaminated food in one year. Whichever is more limiting (Whole Body or Organ).

Source: EPA92, FDA98, FDA01

<sup>a</sup> The sum of the Effective Dose resulting from exposure to external sources and the Committed Effective Dose incurred from all significant inhalation pathways during the time phase.

<sup>b</sup> Persons previously evacuated from areas outside the relocation zone defined by this PAG may return to occupy their residences. Cases involving relocation of persons at high risk from such action (e.g., patients under intensive care) should be evaluated individually.

**Table 2-3 Default Time Phases**

<b>Time Phase</b>	<b>Start</b>	<b>End</b>
Early	0	96 hours
1 <sup>st</sup> Year	0	Day 365
2 <sup>nd</sup> Year	Day 365	Day 730
50 Years	0	Year 50

For example: To calculate a value for the 1<sup>st</sup> Year, set start and end to 0 (beginning of day 1) and 365 (end of day 365) days, respectively, and for the 2<sup>nd</sup> Year, set start and end to 365 (beginning of day 366) and 730 (end of day 730) days, respectively.

**Table 2-4 Ingestion Protective Actions**

<b>Animals</b>	Move to shelter and/or corral, provide protected feed and water.
<b>All foods</b>	Isolate by temporary embargo until survey and initial sampling is completed. Determine whether condemnation or other disposition is appropriate.
<b>Milk</b>	Hold for decay or divert to other products involving adequate decay during processing (e.g., cheese, butter, dry milk solids, or evaporated milk).
<b>Fruits and Vegetables</b>	Wash, brush, scrub or peel to remove surface contamination. Preserve by canning, freezing, dehydration, or storage to permit decay.
<b>Grains</b>	Process by milling and polishing to remove surface contamination.

No actions are to be implemented that place personnel in jeopardy from an imminent release, or that may interfere with them taking shelter, or cause them to leave shelter during a release.

The blending of contaminated food with uncontaminated food is not permitted.

The FDA has developed guidance (FDA98) on the protective actions that should be considered if the ingestion of contaminated food may result in doses that meet or exceed the PAG. Specific protective actions to be implemented following an accident are not provided in these recommendations because there are such a wide variety of actions that could be taken. The protective actions would be determined by state and local officials with assistance from the growers, producers, and manufacturers.

**Table 3-1 Whole-Body**

Whole-Body Absorbed Dose (rad)	Early Fatalities <sup>a, b</sup> (percent)	Whole-Body Absorbed Dose (rad)	Prodromal Effects <sup>a, c</sup> (percent affected)
140	5	50	2
200	15	100	15
300	50	150	50
400	85	200	85
460	95	250	98

Source: EPA92, Table 2-3

<sup>a</sup> Risks will be lower for protracted exposure periods.

<sup>b</sup> Supportive medical treatment may increase the dose where these frequencies occur by approximately 50 percent.

<sup>c</sup> Forewarning symptoms of more serious health effects associated with large doses of radiation.

**Table 3-2 Organs**

Organ	Dose Threshold (rad)	Early Health Effects
Bone Marrow (hematopoietic syndrome)	50	Marrow depression
Small Intestine (gastrointestinal syndrome)	50 100 800	Vomiting Diarrhea Lethality
Skin	200	Transient erythema
Thyroid	300	Hypothyroidism
Lung <sup>a</sup>	600	Pneumonitis
Bone	1000	Osteonecrosis

Source Me95

<sup>a</sup> The lung dose includes an RBE of 10 applied to the high Linear Energy Transfer (alpha) dose conversion factors.

**Table 3-3 Cancer Risk to Average Individuals from 25 rem Effective Dose**

Age at Exposure (years)	Approximate Risk of Premature Death (deaths per 1,000 persons exposed)	Average Years of Life Lost if Premature Death Occurs (years)
20 to 30	9.1	24
30 to 40	7.2	19
40 to 50	5.3	15
50 to 60	3.5	11

Source: EPA92, Table 2-4

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**Table 4 – Dose Parameters and DRLs**

This series of Tables contains the Dose Parameters and DRLs for the Assessment Working Group’s list of radionuclides. Values are provided for the 4 standard Time Phases (Early, 1<sup>st</sup> Year, 2<sup>nd</sup> Year and 50 Year.) All values calculated using DCFPAK Version 2.0.

These values are **only appropriate** when all of the following are true:

- the organ of interest is the Whole Body relating to a PAG for an Effective Dose,
- mixture of interest contains only 1 radionuclide (and any included daughters),  
**NOTE:** Contributions from daughter radionuclides with half-lives less than the “root” parent are included with the parent radionuclide.
- default time phases shown in Table 2-3 are used, and
- Evaluation Time ( $t_n$ ) is equal to the time of Deposition ( $t_0$ ).

The terms contained in this series of Tables are defined below and on the next page:

Dose Parameters		
$Dp\_ExDP$	$\frac{mrem \cdot m^2}{\mu Ci}$	Deposition External Dose Parameter, the external dose from groundshine, over the time phase under consideration ( $TP$ ), <u>per unit activity</u> of radionuclide $i$ .
$Dp\_InhDP$	$\frac{mrem \cdot m^2}{\mu Ci}$	Deposition Inhalation Dose Parameter, the committed dose, over the time phase under consideration ( $TP$ ), <u>per unit activity</u> of radionuclide $i$ deposited on the ground from the inhalation of the resuspended fraction of the radionuclide.
$DP\_TDP$	$\frac{mrem \cdot m^2}{\mu Ci}$	Deposition Total Dose Parameter, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration ( $TP$ ), <u>per unit activity</u> of radionuclide $i$ deposited on the ground.
$Pl\_ExDP$	$\frac{mrem \cdot m^3}{\mu Ci \cdot s}$	Plume External Dose Parameter, the external dose from submersion, over the time phase under consideration ( $TP$ ), <u>per unit activity</u> of plume-borne radionuclide $i$ .
$Pl\_InhDP$	$\frac{mrem \cdot m^3}{\mu Ci \cdot s}$	Plume Inhalation Dose Parameter, the committed dose, over the time phase under consideration ( $TP$ ), from inhalation <u>per unit activity</u> of plume-borne radionuclide $i$ .
$Pl\_TDP$	$\frac{mrem \cdot m^3}{\mu Ci \cdot s}$	Plume Total Dose Parameter, the sum of the external dose from submersion and the committed dose from inhalation of the plume-borne material, over the time phase under consideration ( $TP$ ), <u>per unit activity</u> of plume-borne radionuclide $i$ .
<b>Note:</b>		
Dose Parameters are expressed in different units than those found in the Methods Sections. The values in the Methods are calculated using the TOTAL amount of each radionuclide present in a release while the values shown here have been normalized to a “unit activity” for each radionuclide. For example, the $Dp\_ExDP$ would have units of mrem in Method 1.1 and mrem <u>per <math>\mu Ci/m^2</math></u> ( $mrem \cdot m^2/\mu Ci$ ) in these Tables.		
The values in the following tables account for the contributions of included daughter radionuclides at their appropriate equilibrium concentration (e.g., Ba-140 includes the contribution of 1 “unit” of Ba-140 and 1.15 “units” of La-140.)		

DRLs		
$4Path\_DRL_{Dp}$	$\frac{\mu Ci}{m^2}$	Four-Pathway Deposition Derived Response Level, the areal activity, at time $t_n$ , of radionuclide $i$ at which the total dose from <i>all radionuclides</i> in a release (considering plume and ground dose pathways) would equal the Protective Action Guide (PAG) over the time phase under consideration.
$4Path\_DRL_{\tilde{A}}$	$\frac{\mu Ci \cdot s}{m^3}$	Four-Pathway Air Derived Response Level, the integrated air activity ( $\tilde{A}$ ) of radionuclide $i$ at which the total dose from <i>all radionuclides</i> in a release (considering plume and ground dose pathways) would equal the Protective Action Guide (PAG) over the time phase under consideration.
$4Path\_DRL_{DR}$	$\frac{mrem}{hr}$	Four-Pathway Dose Rate Derived Response Level, the external dose rate, at time $t_n$ , at which the total dose from all radionuclides in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.
$2Path\_DRL_{Dp}$	$\frac{\mu Ci}{m^2}$	Two-Pathway Deposition Derived Response Level, the areal activity ( $Dp$ ), at time $t_n$ , of radionuclide $i$ at which the total dose from <i>all radionuclides</i> in a release (considering only ground dose pathways) would equal the Protective Action Guide (PAG) over the time phase under consideration.
$2Path\_DRL_{\tilde{A}}$	$\frac{\mu Ci \cdot s}{m^3}$	Two-Pathway Air Derived Response Level, the integrated air activity ( $\tilde{A}$ ) of radionuclide $i$ at which the total dose from <i>all radionuclides</i> in a release (considering only ground dose pathways) would equal the Protective Action Guide (PAG) over the time phase under consideration.
$2Path\_DRL_{DR}$	$\frac{mrem}{hr}$	Two-Pathway Dose Rate Derived Response Level, the external dose rate, at time $t_n$ , at which the total dose from all radionuclides in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.
<b>Note:</b>		
DRLs in these tables were calculated assuming a deposition velocity of 3.0E-03 m/s, except for isotopes of iodine, for which 1.0E-02 m/s was used.		

Table 4-1 Plume Dose Parameters..... C-11

Table 4-2a Early Phase Deposition Dose Parameters ..... C-13

Table 4-2b Early Phase DRLs ..... C-14

Table 4-3a First Year Deposition Dose Parameters..... C-15

Table 4-3b First Year DRLs..... C-16

Table 4-4a Second Year Deposition Dose Parameters ..... C-17

Table 4-4b Second Year DRLs ..... C-18

Table 4-5a Fifty Year Deposition Dose Parameters ..... C-19

Table 4-5b Fifty Year DRLs ..... C-20

Table 4-1 Plume Dose Parameters <sup>a</sup>

Parent Radionuclide	PI_ExDP (mrem·m <sup>3</sup> /μCi·s)	PI_InhDP (mrem·m <sup>3</sup> /μCi·s)	PI_TDP (mrem·m <sup>3</sup> /μCi·s)
Am-241	2.49E-06	1.49E+02	1.49E+02
Ba-140	5.03E-04	1.10E-02	1.15E-02
Ce-141	1.16E-05	5.79E-03	5.80E-03
Ce-144	1.20E-05	8.14E-02	8.14E-02
Cf-252	8.25E-05	5.71E+01	5.71E+01
Cm-242	1.44E-08	9.14E+00	9.14E+00
Cm-244	1.48E-08	8.80E+01	8.80E+01
Co-60	4.40E-04	4.74E-02	4.78E-02
Cs-134	2.62E-04	3.15E-02	3.17E-02
Cs-136	3.63E-04	4.29E-03	4.65E-03
Cs-137	9.45E-05	6.05E-02	6.06E-02
Gd-153	1.15E-05	3.70E-03	3.72E-03
I-129	1.06E-06	5.54E-02	5.54E-02
I-131	6.29E-05	1.14E-02	1.15E-02
I-132	3.85E-04	1.76E-04	5.61E-04
I-133	1.03E-04	2.27E-03	2.37E-03
I-134	4.48E-04	8.63E-05	5.34E-04
I-135	2.91E-04	4.98E-04	7.90E-04
Ir-192	1.34E-04	1.02E-02	1.04E-02
La-140	4.11E-04	1.76E-03	2.17E-03
Mo-99	4.44E-05	1.56E-03	1.61E-03
Nb-95	1.29E-04	2.70E-03	2.83E-03
Np-237	9.22E-05	5.20E+02	5.20E+02
Np-239	2.72E-05	1.59E-03	1.62E-03
Pm-147	3.21E-08	1.08E-02	1.08E-02
Pu-238	1.24E-08	1.67E+02	1.67E+02
Pu-239	1.40E-08	1.84E+02	1.84E+02
Pu-241	7.07E-10	3.53E+00	3.53E+00
Ra-226	3.07E-04	3.04E+01	3.04E+01
Ru-103	8.18E-05	4.56E-03	4.64E-03
Ru-106	3.96E-05	1.02E-01	1.02E-01
Sb-127	1.17E-04	3.10E-03	3.22E-03
Sb-129	2.64E-04	4.50E-04	7.15E-04
Se-75	6.14E-05	2.07E-03	2.13E-03
Sr-89	1.62E-06	1.23E-02	1.23E-02
Sr-90	3.29E-06	2.45E-01	2.45E-01
Sr-91	1.78E-04	6.41E-04	8.19E-04
Te-129m	1.30E-05	1.23E-02	1.23E-02
Te-131m	2.64E-04	1.66E-03	1.92E-03
Te-132	4.31E-04	3.35E-03	3.78E-03
Tm-170	1.20E-06	1.43E-02	1.43E-02
Y-91	2.22E-06	1.38E-02	1.38E-02
Yb-169	4.40E-05	4.60E-03	4.64E-03
Zr-95	4.10E-04	1.50E-02	1.54E-02

**Note:**

<sup>a</sup> Plume Dose Parameters (External, Inhalation, and Total) are the same for all Time Phases that include the entirety of the plume (e.g., Early Phase, 1<sup>st</sup> Year, 50 Year) and are zero for Time Phases that do not include plume passage (e.g., 2<sup>nd</sup> Year).

Table 4-2a Early Phase Deposition Dose Parameters

Parent Radionuclide	Dp_ExDP (mrem·m <sup>2</sup> /μCi)	Dp_InhDP (mrem·m <sup>2</sup> /μCi)	Dp_TDP (mrem·m <sup>2</sup> /μCi)
Am-241	2.3E-02	2.8E+02	2.8E+02
Ba-140	2.5E+00	1.9E-02	2.5E+00
Ce-141	7.0E-02	1.0E-02	8.0E-02
Ce-144	1.9E-01	1.5E-01	3.4E-01
Cf-252	4.5E-01	1.1E+02	1.1E+02
Cm-242	6.9E-04	1.7E+01	1.7E+01
Cm-244	6.1E-04	1.6E+02	1.6E+02
Co-60	2.4E+00	8.8E-02	2.5E+00
Cs-134	1.5E+00	5.8E-02	1.6E+00
Cs-136	1.9E+00	7.2E-03	1.9E+00
Cs-137	5.8E-01	1.1E-01	6.9E-01
Gd-153	9.6E-02	6.8E-03	1.0E-01
I-129	2.1E-02	1.0E-01	1.2E-01
I-131	3.2E-01	1.8E-02	3.4E-01
I-132	7.9E-02	1.3E-05	7.9E-02
I-133	2.0E-01	1.3E-03	2.0E-01
I-134	3.4E-02	2.4E-06	3.4E-02
I-135	1.9E-01	1.0E-04	1.9E-01
Ir-192	8.0E-01	1.9E-02	8.2E-01
La-140	1.1E+00	1.7E-03	1.1E+00
Mo-99	1.9E-01	1.9E-03	1.9E-01
Nb-95	7.3E-01	4.8E-03	7.4E-01
Np-237	6.2E-01	9.6E+02	9.7E+02
Np-239	1.0E-01	1.8E-03	1.0E-01
Pm-147	2.9E-05	2.0E-02	2.0E-02
Pu-238	6.3E-04	3.1E+02	3.1E+02
Pu-239	3.2E-04	3.4E+02	3.4E+02
Pu-241	4.9E-06	6.6E+00	6.6E+00
Ra-226	1.8E+00	5.6E+01	5.8E+01
Ru-103	4.8E-01	8.2E-03	4.9E-01
Ru-106	3.6E-01	1.9E-01	5.5E-01
Sb-127	5.2E-01	4.2E-03	5.2E-01
Sb-129	1.0E-01	8.6E-05	1.0E-01
Se-75	3.7E-01	3.8E-03	3.7E-01
Sr-89	7.0E-02	2.2E-02	9.2E-02
Sr-90	1.2E-01	4.5E-01	5.7E-01
Sr-91	1.6E-01	3.4E-04	1.6E-01
Te-129m	1.3E-01	2.2E-02	1.6E-01
Te-131m	6.5E-01	3.0E-03	6.5E-01
Te-132	1.7E+00	4.3E-03	1.7E+00
Tm-170	2.6E-02	2.6E-02	5.2E-02
Y-91	7.6E-02	2.5E-02	1.0E-01
Yb-169	3.0E-01	8.2E-03	3.0E-01
Zr-95	2.4E+00	2.7E-02	2.4E+00

Table 4-2b Early Phase DRLs

Parent Radionuclide	4Path_DRL <sub>DP</sub> ( $\mu\text{Ci}/\text{m}^2$ )	4Path_DRL <sub>A</sub> ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )	4Path_DRL <sub>DR</sub> (mrem/hr)	2Path_DRL <sub>DP</sub> ( $\mu\text{Ci}/\text{m}^2$ )	2Path_DRL <sub>A</sub> ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )	2Path_DRL <sub>DR</sub> (mrem/hr)
Am-241	2.0E-02	6.7E+00	4.8E-06	3.6E+00	1.2E+03	8.6E-04
Ba-140	1.6E+02	5.2E+04	4.6E+00	4.0E+02	1.3E+05	1.2E+01
Ce-141	5.0E+02	1.7E+05	3.8E-01	1.2E+04	4.1E+06	9.5E+00
Ce-144	3.6E+01	1.2E+04	7.1E-02	3.0E+03	9.9E+05	5.8E+00
Cf-252	5.2E-02	1.7E+01	2.5E-04	9.4E+00	3.1E+03	4.4E-02
Cm-242	3.3E-01	1.1E+02	2.4E-06	5.9E+01	2.0E+04	4.3E-04
Cm-244	3.4E-02	1.1E+01	2.2E-07	6.1E+00	2.0E+03	3.9E-05
Co-60	5.4E+01	1.8E+04	1.4E+00	4.0E+02	1.3E+05	1.0E+01
Cs-134	8.2E+01	2.7E+04	1.3E+00	6.2E+02	2.1E+05	1.0E+01
Cs-136	2.9E+02	9.7E+04	6.3E+00	5.3E+02	1.8E+05	1.2E+01
Cs-137	4.8E+01	1.6E+04	2.9E-01	1.5E+03	4.8E+05	8.7E+00
Gd-153	7.5E+02	2.5E+05	7.5E-01	9.7E+03	3.2E+06	9.8E+00
I-129	1.8E+02	1.8E+04	3.8E-02	8.1E+03	8.1E+05	1.8E+00
I-131	6.7E+02	6.7E+04	2.7E+00	2.9E+03	2.9E+05	1.2E+01
I-132	7.4E+03	7.4E+05	1.8E+02	1.3E+04	1.3E+06	3.0E+02
I-133	2.3E+03	2.3E+05	1.6E+01	5.0E+03	5.0E+05	3.4E+01
I-134	1.1E+04	1.1E+06	3.1E+02	2.9E+04	2.9E+06	7.9E+02
I-135	3.8E+03	3.8E+05	6.3E+01	5.4E+03	5.4E+05	9.0E+01
Ir-192	2.3E+02	7.8E+04	2.0E+00	1.2E+03	4.1E+05	1.0E+01
La-140	5.5E+02	1.8E+05	1.3E+01	9.1E+02	3.0E+05	2.1E+01
Mo-99	1.4E+03	4.6E+05	4.3E+00	5.2E+03	1.7E+06	1.6E+01
Nb-95	6.0E+02	2.0E+05	4.7E+00	1.4E+03	4.5E+05	1.1E+01
Np-237	5.7E-03	1.9E+00	3.7E-05	1.0E+00	3.5E+02	6.7E-03
Np-239	1.6E+03	5.2E+05	2.8E+00	9.8E+03	3.3E+06	1.7E+01
Pm-147	2.8E+02	9.2E+04	8.5E-05	5.0E+04	1.7E+07	1.5E-02
Pu-238	1.8E-02	6.0E+00	1.2E-07	3.2E+00	1.1E+03	2.1E-05
Pu-239	1.6E-02	5.4E+00	5.4E-08	2.9E+00	9.8E+02	9.8E-06
Pu-241	8.4E-01	2.8E+02	4.1E-08	1.5E+02	5.1E+04	7.4E-06
Ra-226	9.8E-02	3.3E+01	1.8E-03	1.7E+01	5.7E+03	3.2E-01
Ru-103	4.9E+02	1.6E+05	2.5E+00	2.0E+03	6.8E+05	1.1E+01
Ru-106	2.9E+01	9.7E+03	1.1E-01	1.8E+03	6.1E+05	6.9E+00
Sb-127	6.3E+02	2.1E+05	4.7E+00	1.9E+03	6.4E+05	1.5E+01
Sb-129	2.9E+03	9.8E+05	4.8E+01	9.7E+03	3.2E+06	1.6E+02
Se-75	9.2E+02	3.1E+05	3.6E+00	2.7E+03	8.9E+05	1.0E+01
Sr-89	2.4E+02	8.0E+04	1.8E-01	1.1E+04	3.6E+06	8.1E+00
Sr-90	1.2E+01	4.1E+03	1.5E-02	1.8E+03	5.8E+05	2.1E+00
Sr-91	2.3E+03	7.7E+05	2.7E+01	6.3E+03	2.1E+06	7.3E+01
Te-129m	2.4E+02	7.8E+04	3.4E-01	6.4E+03	2.1E+06	9.3E+00
Te-131m	7.7E+02	2.6E+05	1.2E+01	1.5E+03	5.1E+05	2.5E+01
Te-132	3.3E+02	1.1E+05	9.0E+00	5.7E+02	1.9E+05	1.5E+01
Tm-170	2.1E+02	6.9E+04	5.6E-02	1.9E+04	6.4E+06	5.2E+00
Y-91	2.1E+02	7.1E+04	1.7E-01	9.9E+03	3.3E+06	8.0E+00
Yb-169	5.4E+02	1.8E+05	1.7E+00	3.3E+03	1.1E+06	1.1E+01
Zr-95	1.3E+02	4.4E+04	3.3E+00	4.2E+02	1.4E+05	1.1E+01

Table 4-3a First Year Deposition Dose Parameters

Parent Radionuclide	Dp_ExDP (mrem·m <sup>2</sup> /μCi)	Dp_InhDP (mrem·m <sup>2</sup> /μCi)	Dp_TDP (mrem·m <sup>2</sup> /μCi)
Am-241	1.9E+00	1.1E+03	1.1E+03
Ba-140	1.3E+01	4.7E-02	1.3E+01
Ce-141	8.4E-01	3.4E-02	8.7E-01
Ce-144	1.0E+01	6.0E-01	1.1E+01
Cf-252	3.3E+01	4.3E+02	4.7E+02
Cm-242	3.0E-02	6.6E+01	6.6E+01
Cm-244	5.0E-02	6.8E+02	6.8E+02
Co-60	1.9E+02	3.6E-01	1.9E+02
Cs-134	1.1E+02	2.4E-01	1.1E+02
Cs-136	9.8E+00	1.9E-02	9.8E+00
Cs-137	4.8E+01	4.7E-01	4.8E+01
Gd-153	5.1E+00	2.7E-02	5.1E+00
I-129	1.7E+00	4.3E-01	2.2E+00
I-131	1.1E+00	3.9E-02	1.1E+00
I-132	7.9E-02	1.3E-05	7.9E-02
I-133	2.2E-01	1.4E-03	2.2E-01
I-134	3.4E-02	2.4E-06	3.4E-02
I-135	1.9E-01	1.0E-04	1.9E-01
Ir-192	2.0E+01	6.9E-02	2.0E+01
La-140	1.4E+00	1.9E-03	1.4E+00
Mo-99	3.0E-01	2.6E-03	3.0E-01
Nb-95	9.4E+00	1.6E-02	9.4E+00
Np-237	5.2E+01	4.0E+03	4.1E+03
Np-239	1.4E-01	2.6E-03	1.5E-01
Pm-147	2.2E-03	8.2E-02	8.4E-02
Pu-238	5.2E-02	1.3E+03	1.3E+03
Pu-239	2.7E-02	1.4E+03	1.4E+03
Pu-241	1.8E-03	2.7E+01	2.7E+01
Ra-226	1.5E+02	2.3E+02	3.8E+02
Ru-103	6.8E+00	2.8E-02	6.9E+00
Ru-106	2.2E+01	7.6E-01	2.3E+01
Sb-127	1.0E+00	7.1E-03	1.0E+00
Sb-129	1.0E-01	1.5E-04	1.1E-01
Se-75	1.3E+01	1.5E-02	1.3E+01
Sr-89	1.3E+00	7.8E-02	1.3E+00
Sr-90	9.7E+00	1.9E+00	1.2E+01
Sr-91	1.7E-01	8.0E-04	1.7E-01
Te-129m	1.7E+00	7.2E-02	1.7E+00
Te-131m	8.6E-01	6.8E-03	8.7E-01
Te-132	3.0E+00	6.3E-03	3.0E+00
Tm-170	9.8E-01	1.0E-01	1.1E+00
Y-91	1.6E+00	9.0E-02	1.6E+00
Yb-169	3.5E+00	2.7E-02	3.5E+00
Zr-95	5.3E+01	9.9E-02	5.3E+01

Table 4-3b First Year DRLs

Parent Radionuclide	4Path_DRL <sub>DP</sub> ( $\mu\text{Ci}/\text{m}^2$ )	4Path_DRL <sub>A</sub> ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )	4Path_DRL <sub>DR</sub> (mrem/hr)	2Path_DRL <sub>DP</sub> ( $\mu\text{Ci}/\text{m}^2$ )	2Path_DRL <sub>A</sub> ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )	2Path_DRL <sub>DR</sub> (mrem/hr)
Am-241	3.9E-02	1.3E+01	9.4E-06	1.7E+00	5.8E+02	4.2E-04
Ba-140	1.2E+02	4.0E+04	3.5E+00	1.6E+02	5.2E+04	4.6E+00
Ce-141	7.1E+02	2.4E+05	5.4E-01	2.3E+03	7.7E+05	1.8E+00
Ce-144	5.2E+01	1.7E+04	1.0E-01	1.8E+02	6.0E+04	3.5E-01
Cf-252	1.0E-01	3.4E+01	4.8E-04	4.3E+00	1.4E+03	2.0E-02
Cm-242	6.4E-01	2.1E+02	4.7E-06	3.0E+01	1.0E+04	2.2E-04
Cm-244	6.7E-02	2.2E+01	4.3E-07	3.0E+00	9.9E+02	1.9E-05
Co-60	9.7E+00	3.2E+03	2.4E-01	1.1E+01	3.5E+03	2.6E-01
Cs-134	1.6E+01	5.5E+03	2.7E-01	1.8E+01	6.0E+03	2.9E-01
Cs-136	1.8E+02	5.9E+04	3.8E+00	2.0E+02	6.8E+04	4.4E+00
Cs-137	2.9E+01	9.8E+03	1.8E-01	4.2E+01	1.4E+04	2.5E-01
Gd-153	3.2E+02	1.1E+05	3.2E-01	3.9E+02	1.3E+05	3.9E-01
I-129	2.6E+02	2.6E+04	5.6E-02	9.2E+02	9.2E+04	2.0E-01
I-131	8.7E+02	8.7E+04	3.5E+00	1.8E+03	1.8E+05	7.0E+00
I-132	1.5E+04	1.5E+06	3.5E+02	2.5E+04	2.5E+06	6.0E+02
I-133	4.4E+03	4.4E+05	3.0E+01	9.1E+03	9.1E+05	6.2E+01
I-134	2.3E+04	2.3E+06	6.2E+02	5.8E+04	5.8E+06	1.6E+03
I-135	7.5E+03	7.5E+05	1.3E+02	1.1E+04	1.1E+06	1.8E+02
Ir-192	8.5E+01	2.8E+04	7.2E-01	9.9E+01	3.3E+04	8.4E-01
La-140	9.6E+02	3.2E+05	2.2E+01	1.5E+03	4.9E+05	3.4E+01
Mo-99	2.4E+03	8.0E+05	7.5E+00	6.7E+03	2.2E+06	2.1E+01
Nb-95	1.9E+02	6.4E+04	1.5E+00	2.1E+02	7.1E+04	1.7E+00
Np-237	1.1E-02	3.8E+00	7.3E-05	4.9E-01	1.6E+02	3.2E-03
Np-239	2.9E+03	9.7E+05	5.2E+00	1.4E+04	4.5E+06	2.4E+01
Pm-147	5.4E+02	1.8E+05	1.7E-04	2.4E+04	7.9E+06	7.3E-03
Pu-238	3.5E-02	1.2E+01	2.3E-07	1.6E+00	5.2E+02	1.0E-05
Pu-239	3.2E-02	1.1E+01	1.1E-07	1.4E+00	4.7E+02	4.7E-06
Pu-241	1.7E+00	5.5E+02	8.1E-08	7.3E+01	2.4E+04	3.6E-06
Ra-226	1.9E-01	6.3E+01	3.6E-03	5.2E+00	1.7E+03	9.7E-02
Ru-103	2.4E+02	7.9E+04	1.2E+00	2.9E+02	9.7E+04	1.5E+00
Ru-106	3.5E+01	1.2E+04	1.3E-01	8.7E+01	2.9E+04	3.3E-01
Sb-127	9.6E+02	3.2E+05	7.2E+00	2.0E+03	6.6E+05	1.5E+01
Sb-129	5.8E+03	1.9E+06	9.6E+01	1.9E+04	6.3E+06	3.1E+02
Se-75	1.4E+02	4.7E+04	5.5E-01	1.5E+02	5.0E+04	5.8E-01
Sr-89	3.7E+02	1.2E+05	2.8E-01	1.5E+03	5.0E+05	1.1E+00
Sr-90	2.1E+01	7.2E+03	2.6E-02	1.7E+02	5.8E+04	2.1E-01
Sr-91	4.5E+03	1.5E+06	5.2E+01	1.2E+04	3.9E+06	1.4E+02
Te-129m	3.4E+02	1.1E+05	5.0E-01	1.2E+03	3.9E+05	1.7E+00
Te-131m	1.3E+03	4.4E+05	2.1E+01	2.3E+03	7.6E+05	3.7E+01
Te-132	4.7E+02	1.6E+05	1.3E+01	6.6E+02	2.2E+05	1.8E+01
Tm-170	3.4E+02	1.1E+05	9.3E-02	1.8E+03	6.2E+05	5.0E-01
Y-91	3.2E+02	1.1E+05	2.6E-01	1.2E+03	4.0E+05	9.8E-01
Yb-169	4.0E+02	1.3E+05	1.3E+00	5.7E+02	1.9E+05	1.8E+00
Zr-95	3.5E+01	1.2E+04	8.7E-01	3.8E+01	1.3E+04	9.6E-01

Table 4-4a Second Year Deposition Dose Parameters

Parent Radionuclide	Dp_ExDP (mrem·m <sup>2</sup> /μCi)	Dp_InhDP (mrem·m <sup>2</sup> /μCi)	Dp_TDP (mrem·m <sup>2</sup> /μCi)
Am-241	1.6E+00	6.9E+00	8.5E+00
Ba-140	2.4E-08	7.9E-14	2.4E-08
Ce-141	2.9E-04	1.8E-08	2.9E-04
Ce-144	3.7E+00	1.1E-03	3.7E+00
Cf-252	2.2E+01	1.8E+00	2.4E+01
Cm-242	5.7E-03	8.4E-02	9.0E-02
Cm-244	4.2E-02	3.9E+00	3.9E+00
Co-60	1.4E+02	1.8E-03	1.4E+02
Cs-134	6.8E+01	9.0E-04	6.8E+01
Cs-136	3.2E-08	5.4E-14	3.2E-08
Cs-137	4.0E+01	2.7E-03	4.0E+01
Gd-153	1.5E+00	4.0E-05	1.5E+00
I-129	1.5E+00	2.6E-03	1.5E+00
I-131	8.0E-13	4.6E-19	8.0E-13
I-132	NA	NA	NA
I-133	1.4E-23	3.8E-134	1.4E-23
I-134	NA	NA	NA
I-135	1.3E-12	2.0E-13	1.5E-12
Ir-192	5.6E-01	5.1E-06	5.6E-01
La-140	2.5E-66	1.7E-72	2.5E-66
Mo-99	1.9E-10	3.7E-11	2.3E-10
Nb-95	5.9E-03	1.6E-08	5.9E-03
Np-237	4.5E+01	2.4E+01	6.9E+01
Np-239	6.2E-09	2.3E-06	2.3E-06
Pm-147	1.4E-03	3.4E-04	1.8E-03
Pu-238	4.5E-02	7.6E+00	7.7E+00
Pu-239	2.3E-02	8.5E+00	8.5E+00
Pu-241	4.1E-03	1.7E-01	1.7E-01
Ra-226	1.3E+02	1.4E+00	1.3E+02
Ru-103	9.1E-03	6.5E-08	9.1E-03
Ru-106	9.6E+00	1.8E-03	9.6E+00
Sb-127	3.6E-04	2.0E-07	3.6E-04
Sb-129	9.0E-07	6.2E-11	9.0E-07
Se-75	1.4E+00	5.4E-06	1.4E+00
Sr-89	7.1E-03	9.2E-07	7.1E-03
Sr-90	8.1E+00	1.1E-02	8.2E+00
Sr-91	1.3E-04	1.7E-08	1.3E-04
Te-129m	7.4E-04	5.1E-08	7.4E-04
Te-131m	1.4E-13	8.5E-20	1.4E-13
Te-132	3.9E-34	4.3E-40	3.9E-34
Tm-170	1.2E-01	4.5E-05	1.2E-01
Y-91	1.7E-02	2.3E-06	1.7E-02
Yb-169	1.1E-03	1.3E-08	1.1E-03
Zr-95	8.5E-01	3.9E-06	8.5E-01

Table 4-4b Second Year DRLs

Parent Radionuclide	4Path_DRL <sub>DP</sub> ( $\mu\text{Ci}/\text{m}^2$ )	4Path_DRL <sub>A</sub> ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )	4Path_DRL <sub>DR</sub> (mrem/hr)	2Path_DRL <sub>DP</sub> ( $\mu\text{Ci}/\text{m}^2$ )	2Path_DRL <sub>A</sub> ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )	2Path_DRL <sub>DR</sub> (mrem/hr)
Am-241	5.9E+01	2.0E+04	1.4E-02	5.9E+01	2.0E+04	1.4E-02
Ba-140	2.1E+10	6.9E+12	6.0E+08	2.1E+10	6.9E+12	6.0E+08
Ce-141	1.7E+06	5.8E+08	1.3E+03	1.7E+06	5.8E+08	1.3E+03
Ce-144	1.4E+02	4.5E+04	2.6E-01	1.4E+02	4.5E+04	2.6E-01
Cf-252	2.1E+01	7.0E+03	9.9E-02	2.1E+01	7.0E+03	9.9E-02
Cm-242	5.6E+03	1.9E+06	4.1E-02	5.6E+03	1.9E+06	4.1E-02
Cm-244	1.3E+02	4.3E+04	8.2E-04	1.3E+02	4.3E+04	8.2E-04
Co-60	3.5E+00	1.2E+03	8.8E-02	3.5E+00	1.2E+03	8.8E-02
Cs-134	7.3E+00	2.4E+03	1.2E-01	7.3E+00	2.4E+03	1.2E-01
Cs-136	1.6E+10	5.2E+12	3.4E+08	1.6E+10	5.2E+12	3.4E+08
Cs-137	1.2E+01	4.2E+03	7.5E-02	1.2E+01	4.2E+03	7.5E-02
Gd-153	3.3E+02	1.1E+05	3.3E-01	3.3E+02	1.1E+05	3.3E-01
I-129	3.3E+02	3.3E+04	7.2E-02	3.3E+02	3.3E+04	7.2E-02
I-131	6.2E+14	6.2E+16	2.5E+12	6.2E+14	6.2E+16	2.5E+12
I-132	NA	NA	NA	NA	NA	NA
I-133	3.7E+25	3.7E+27	2.5E+23	3.7E+25	3.7E+27	2.5E+23
I-134	NA	NA	NA	NA	NA	NA
I-135	3.4E+14	3.4E+16	5.7E+12	3.4E+14	3.4E+16	5.7E+12
Ir-192	9.0E+02	3.0E+05	7.6E+00	9.0E+02	3.0E+05	7.6E+00
La-140	2.0E+68	6.6E+70	4.7E+66	2.0E+68	6.6E+70	4.7E+66
Mo-99	2.2E+12	7.3E+14	6.9E+09	2.2E+12	7.3E+14	6.9E+09
Nb-95	8.5E+04	2.8E+07	6.8E+02	8.5E+04	2.8E+07	6.8E+02
Np-237	7.2E+00	2.4E+03	4.7E-02	7.2E+00	2.4E+03	4.7E-02
Np-239	2.2E+08	7.3E+10	3.9E+05	2.2E+08	7.3E+10	3.9E+05
Pm-147	2.8E+05	9.4E+07	8.6E-02	2.8E+05	9.4E+07	8.6E-02
Pu-238	6.5E+01	2.2E+04	4.3E-04	6.5E+01	2.2E+04	4.3E-04
Pu-239	5.9E+01	2.0E+04	2.0E-04	5.9E+01	2.0E+04	2.0E-04
Pu-241	2.9E+03	9.7E+05	1.4E-04	2.9E+03	9.7E+05	1.4E-04
Ra-226	3.8E+00	1.3E+03	7.2E-02	3.8E+00	1.3E+03	7.2E-02
Ru-103	5.5E+04	1.8E+07	2.8E+02	5.5E+04	1.8E+07	2.8E+02
Ru-106	5.2E+01	1.7E+04	2.0E-01	5.2E+01	1.7E+04	2.0E-01
Sb-127	1.4E+06	4.7E+08	1.1E+04	1.4E+06	4.7E+08	1.1E+04
Sb-129	5.6E+08	1.9E+11	9.2E+06	5.6E+08	1.9E+11	9.2E+06
Se-75	3.6E+02	1.2E+05	1.4E+00	3.6E+02	1.2E+05	1.4E+00
Sr-89	7.1E+04	2.4E+07	5.3E+01	7.1E+04	2.4E+07	5.3E+01
Sr-90	6.1E+01	2.0E+04	7.5E-02	6.1E+01	2.0E+04	7.5E-02
Sr-91	4.0E+06	1.3E+09	4.6E+04	4.0E+06	1.3E+09	4.6E+04
Te-129m	6.8E+05	2.3E+08	9.9E+02	6.8E+05	2.3E+08	9.9E+02
Te-131m	3.6E+15	1.2E+18	5.7E+13	3.6E+15	1.2E+18	5.7E+13
Te-132	1.3E+36	4.3E+38	3.4E+34	1.3E+36	4.3E+38	3.4E+34
Tm-170	4.3E+03	1.4E+06	1.2E+00	4.3E+03	1.4E+06	1.2E+00
Y-91	2.9E+04	9.6E+06	2.3E+01	2.9E+04	9.6E+06	2.3E+01
Yb-169	4.7E+05	1.6E+08	1.5E+03	4.7E+05	1.6E+08	1.5E+03
Zr-95	5.9E+02	2.0E+05	1.5E+01	5.9E+02	2.0E+05	1.5E+01

Table 4-5a Fifty Year Deposition Dose Parameters

Parent Radionuclide	Dp_ExDP (mrem·m <sup>2</sup> /μCi)	Dp_InhDP (mrem·m <sup>2</sup> /μCi)	Dp_TDP (mrem·m <sup>2</sup> /μCi)
Am-241	4.5E+01	1.2E+03	1.2E+03
Ba-140	1.3E+01	4.7E-02	1.3E+01
Ce-141	8.4E-01	3.4E-02	8.7E-01
Ce-144	1.6E+01	6.0E-01	1.7E+01
Cf-252	1.1E+02	4.4E+02	5.5E+02
Cm-242	4.3E-02	6.6E+01	6.6E+01
Cm-244	6.4E-01	6.8E+02	6.8E+02
Co-60	1.1E+03	3.7E-01	1.1E+03
Cs-134	3.1E+02	2.4E-01	3.1E+02
Cs-136	9.8E+00	1.9E-02	9.8E+00
Cs-137	7.6E+02	4.7E-01	7.6E+02
Gd-153	7.3E+00	2.7E-02	7.4E+00
I-129	4.3E+01	4.3E-01	4.3E+01
I-131	1.1E+00	3.9E-02	1.1E+00
I-132	7.9E-02	1.3E-05	7.9E-02
I-133	2.2E-01	1.4E-03	2.2E-01
I-134	3.4E-02	2.4E-06	3.4E-02
I-135	1.9E-01	1.0E-04	1.9E-01
Ir-192	2.1E+01	6.9E-02	2.1E+01
La-140	1.4E+00	1.9E-03	1.4E+00
Mo-99	3.0E-01	2.6E-03	3.0E-01
Nb-95	9.4E+00	1.6E-02	9.4E+00
Np-237	1.3E+03	4.0E+03	5.3E+03
Np-239	1.4E-01	2.6E-03	1.5E-01
Pm-147	7.3E-03	8.2E-02	9.0E-02
Pu-238	1.1E+00	1.3E+03	1.3E+03
Pu-239	6.6E-01	1.4E+03	1.4E+03
Pu-241	8.5E-01	2.8E+01	2.8E+01
Ra-226	3.6E+03	2.4E+02	3.9E+03
Ru-103	6.9E+00	2.8E-02	6.9E+00
Ru-106	4.0E+01	7.6E-01	4.1E+01
Sb-127	1.0E+00	7.1E-03	1.0E+00
Sb-129	1.0E-01	1.5E-04	1.1E-01
Se-75	1.5E+01	1.5E-02	1.5E+01
Sr-89	1.3E+00	7.8E-02	1.3E+00
Sr-90	1.5E+02	1.9E+00	1.5E+02
Sr-91	1.7E-01	8.0E-04	1.7E-01
Te-129m	1.7E+00	7.2E-02	1.7E+00
Te-131m	8.6E-01	6.8E-03	8.7E-01
Te-132	3.0E+00	6.3E-03	3.0E+00
Tm-170	1.1E+00	1.0E-01	1.2E+00
Y-91	1.6E+00	9.0E-02	1.7E+00
Yb-169	3.5E+00	2.7E-02	3.5E+00
Zr-95	5.3E+01	9.9E-02	5.4E+01

Table 4-5b Fifty Year DRLs

Parent Radionuclide	4Path_DRL <sub>DP</sub> ( $\mu\text{Ci}/\text{m}^2$ )	4Path_DRL <sub>A</sub> ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )	4Path_DRL <sub>DR</sub> (mrem/hr)	2Path_DRL <sub>DP</sub> ( $\mu\text{Ci}/\text{m}^2$ )	2Path_DRL <sub>A</sub> ( $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ )	2Path_DRL <sub>DR</sub> (mrem/hr)
Am-241	9.8E-02	3.3E+01	2.3E-05	4.2E+00	1.4E+03	9.9E-04
Ba-140	3.0E+02	1.0E+05	8.8E+00	3.9E+02	1.3E+05	1.1E+01
Ce-141	1.8E+03	5.9E+05	1.4E+00	5.7E+03	1.9E+06	4.4E+00
Ce-144	1.1E+02	3.8E+04	2.2E-01	2.9E+02	9.8E+04	5.7E-01
Cf-252	2.6E-01	8.5E+01	1.2E-03	9.1E+00	3.0E+03	4.3E-02
Cm-242	1.6E+00	5.4E+02	1.2E-05	7.5E+01	2.5E+04	5.5E-04
Cm-244	1.7E-01	5.6E+01	1.1E-06	7.3E+00	2.4E+03	4.7E-05
Co-60	4.7E+00	1.6E+03	1.2E-01	4.7E+00	1.6E+03	1.2E-01
Cs-134	1.5E+01	5.1E+03	2.5E-01	1.6E+01	5.3E+03	2.6E-01
Cs-136	4.4E+02	1.5E+05	9.6E+00	5.1E+02	1.7E+05	1.1E+01
Cs-137	6.4E+00	2.1E+03	3.8E-02	6.6E+00	2.2E+03	3.9E-02
Gd-153	5.8E+02	1.9E+05	5.9E-01	6.8E+02	2.3E+05	6.8E-01
I-129	1.0E+02	1.0E+04	2.2E-02	1.2E+02	1.2E+04	2.5E-02
I-131	2.2E+03	2.2E+05	8.7E+00	4.4E+03	4.4E+05	1.7E+01
I-132	3.7E+04	3.7E+06	8.8E+02	6.3E+04	6.3E+06	1.5E+03
I-133	1.1E+04	1.1E+06	7.5E+01	2.3E+04	2.3E+06	1.6E+02
I-134	5.7E+04	5.7E+06	1.5E+03	1.5E+05	1.5E+07	4.0E+03
I-135	1.9E+04	1.9E+06	3.2E+02	2.7E+04	2.7E+06	4.5E+02
Ir-192	2.1E+02	6.9E+04	1.8E+00	2.4E+02	8.1E+04	2.0E+00
La-140	2.4E+03	8.0E+05	5.6E+01	3.7E+03	1.2E+06	8.6E+01
Mo-99	6.0E+03	2.0E+06	1.9E+01	1.7E+04	5.5E+06	5.2E+01
Nb-95	4.8E+02	1.6E+05	3.8E+00	5.3E+02	1.8E+05	4.2E+00
Np-237	2.8E-02	9.3E+00	1.8E-04	9.4E-01	3.1E+02	6.1E-03
Np-239	7.3E+03	2.4E+06	1.3E+01	3.4E+04	1.1E+07	6.0E+01
Pm-147	1.4E+03	4.5E+05	4.2E-04	5.6E+04	1.9E+07	1.7E-02
Pu-238	8.8E-02	2.9E+01	5.8E-07	3.9E+00	1.3E+03	2.5E-05
Pu-239	8.0E-02	2.7E+01	2.7E-07	3.5E+00	1.2E+03	1.2E-05
Pu-241	4.1E+00	1.4E+03	2.0E-07	1.8E+02	5.9E+04	8.6E-06
Ra-226	3.6E-01	1.2E+02	6.7E-03	1.3E+00	4.3E+02	2.4E-02
Ru-103	5.9E+02	2.0E+05	3.1E+00	7.3E+02	2.4E+05	3.8E+00
Ru-106	6.7E+01	2.2E+04	2.5E-01	1.2E+02	4.1E+04	4.7E-01
Sb-127	2.4E+03	8.0E+05	1.8E+01	4.9E+03	1.6E+06	3.7E+01
Sb-129	1.5E+04	4.9E+06	2.4E+02	4.8E+04	1.6E+07	7.9E+02
Se-75	3.2E+02	1.1E+05	1.2E+00	3.4E+02	1.1E+05	1.3E+00
Sr-89	9.2E+02	3.1E+05	6.9E-01	3.7E+03	1.2E+06	2.8E+00
Sr-90	2.1E+01	7.1E+03	2.6E-02	3.2E+01	1.1E+04	3.9E-02
Sr-91	1.1E+04	3.8E+06	1.3E+02	2.9E+04	9.8E+06	3.4E+02
Te-129m	8.6E+02	2.9E+05	1.3E+00	2.9E+03	9.6E+05	4.2E+00
Te-131m	3.3E+03	1.1E+06	5.3E+01	5.7E+03	1.9E+06	9.2E+01
Te-132	1.2E+03	3.9E+05	3.1E+01	1.7E+03	5.5E+05	4.4E+01
Tm-170	8.3E+02	2.8E+05	2.3E-01	4.1E+03	1.4E+06	1.1E+00
Y-91	8.0E+02	2.7E+05	6.5E-01	3.0E+03	1.0E+06	2.4E+00
Yb-169	9.9E+02	3.3E+05	3.2E+00	1.4E+03	4.7E+05	4.6E+00
Zr-95	8.5E+01	2.8E+04	2.2E+00	9.3E+01	3.1E+04	2.4E+00

This Table is RESERVED for the future inclusion of Skin Dose Data.

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Shielding/Protection Factors are the ratio of the exterior dose to the interior dose at the location in question. For example, a Factor of 20 would reduce an exterior dose of 100 rem to 5 rem.

**Table 6-1 Gamma Cloud Source Shielding Factors**

Structure or Location	Shielding Factor <sup>a</sup>
Outside	1.0
Vehicles	1.0
Wood frame house <sup>b</sup> (no basement)	1.1
Basement of wood frame house	1.67
Masonry house (no basement)	1.67
Basement of masonry house	2.5
Large office or industrial building	5

<sup>a</sup> EGG75

<sup>b</sup> A wood frame house with brick or stone veneer is approximately equivalent to a masonry house for shielding purposes.

**Table 6-2 Surface Deposition Shielding Factors for Vehicles**

Vehicle	Representative Shielding Factor <sup>a</sup>
Cars on fully contaminated road	2
Cars on fully decontaminated 50-foot road	4
Trains	2.5

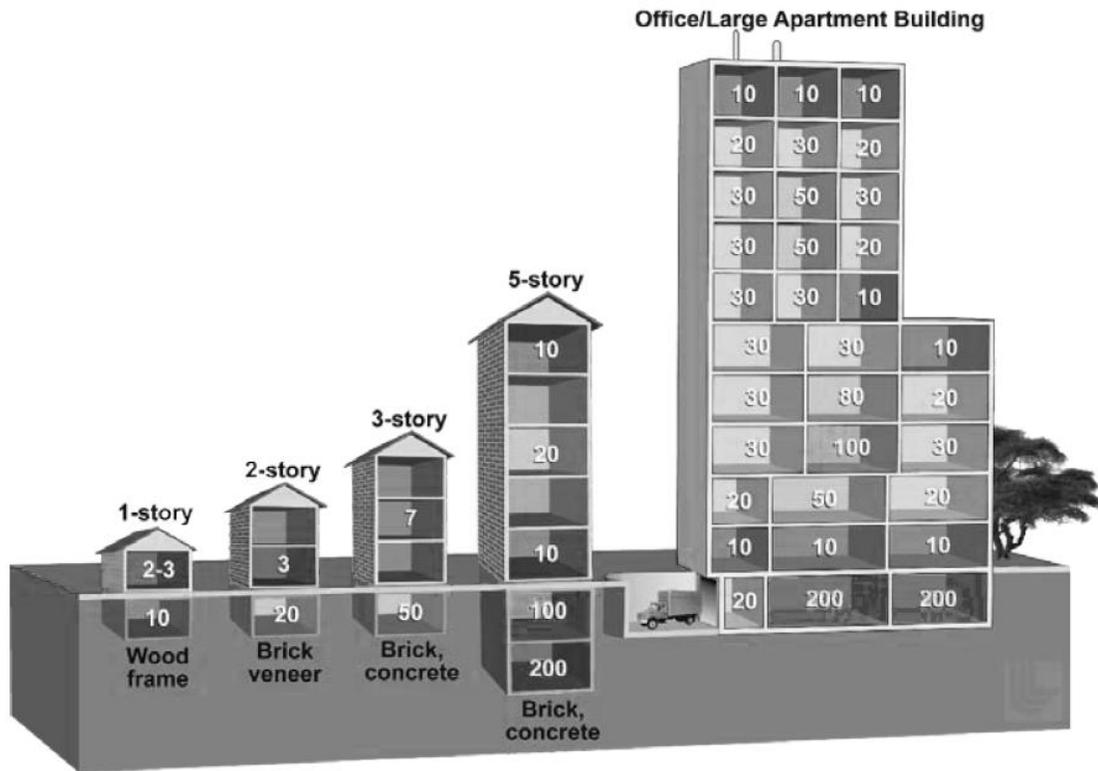
<sup>a</sup> EGG75

**Table 6-3 Fallout Protection Factors for Buildings <sup>a</sup>**

Structure	Basement	1st Floor	2nd Floor	3rd Floor
Vinyl-sided 2-story home	22-46	2-4	2-3	N/A
Brick-sided 2-story home	31-62	3-8	3-5	N/A
Brick-walled urban row home	N/A	12-70	12-70	5-30
Vinyl-sided 3-storey apt building	N/A	3-7	2-6	3-5
Brick-sided 3-story apt building	N/A	4-11	4-9	4-8
3-story office (brick-sided concrete walls)	N/A	8-126	4-43	3-7

<sup>a</sup> LLNL11

**Figure 6-1 Approximate Protection Factors for locations in different Building Types**



Source: LLNL11

**Table 7 – Breathing Rates by Age Group**

This table lists the breathing rates for all age groups from ICRP Publication 66 (ICRP94).

Age Group	Activity								Total Volume m <sup>3</sup> /day	Activity Avg. Rate m <sup>3</sup> /hr
	Sleeping		Sitting		Light Exercise		Heavy Exercise			
	Rate m <sup>3</sup> /hr	Time hr/day								
<b>Newborn (3 month)</b>	0.09	17.0	NA	NA	0.19	7.0	NA	NA	<b>2.86</b>	<b>0.12</b>
<b>Infant (1 year)</b>	0.15	14.0	0.22	3.33	0.35	6.67	NA	NA	<b>5.20</b>	<b>0.22</b>
<b>5 yr old</b>	0.24	12.0	0.32	4.0	0.57	8.0	NA	NA	<b>8.76</b>	<b>0.37</b>
<b>10 yr old</b>	0.31	10.0	0.38	4.67	1.12	9.33	NA	NA	<b>15.28</b>	<b>0.64</b>
<b>15 yr old (m)</b>	0.42	10.0	0.48	5.5	1.38	7.5	2.92	1.0	<b>20.10</b>	<b>0.84</b>
<b>15 yr old (f)</b>	0.35	10.0	0.4	7.0	1.3	6.75	2.57	0.25	<b>15.72</b>	<b>0.66</b>
<b>Adult (m) (Sedentary)</b>	0.45	8.5	0.54	5.5	1.5	9.75	3.0	0.25	<b>22.18</b>	<b>0.92</b>
<b>Adult (f) (Sedentary)</b>	0.32	8.5	0.39	5.5	1.25	9.75	2.7	0.25	<b>17.68</b>	<b>0.74</b>

See ICRP94, Tables 8, B.16A, and B.16B for methods to calculate breathing rates.

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**Table 8 – Ingestion Pathway – DILs, DRLs, and Transfer Factors**

This table includes an abbreviated list of radionuclides compared to the list tabulated in other sections of this appendix. Parent radionuclides with a half life less than 6 hours are excluded from ingestion pathway analysis because it is unlikely that a quantity that is sufficient to cause an ingestion concern could be dispersed. Noble Gases are excluded from ingestion pathway analysis because Ingestion Dose Coefficients are currently not available.

Daughter radionuclides in transient (or secular) equilibrium are excluded from independent ingestion pathway analysis because their contribution to dose is included in the dose coefficient of the ultimate parent. Daughter radionuclides with a half life greater than 6 hours **are included in the list below separately from the parent radionuclide** because it may be possible to disperse a quantity of these radionuclides that is sufficient to cause an ingestion concern before significant decay occurs without the parent radionuclide being present.

Radionuclide (units)	FDA Listed	DIL <sup>a</sup> (μCi/kg <sub>wet</sub> )	Mature Crop DRL <sup>b</sup> (μCi/m <sup>2</sup> )	Leafy TF (kg <sub>soil</sub> /kg <sub>dry</sub> )	Fruit TF (kg <sub>soil</sub> /kg <sub>dry</sub> )	Root TF (kg <sub>soil</sub> /kg <sub>dry</sub> )	Grain TF (kg <sub>soil</sub> /kg <sub>dry</sub> )	Milk_DRL <sup>c</sup> (area) (μCi/m <sup>2</sup> )	Milk_DRL <sup>c</sup> (mass) (μCi/kg <sub>wet</sub> )	Milk_DRL <sup>c</sup> (water) (μCi/l)	Milk TF <sup>c</sup> (d/l)	Meat TF <sup>d</sup> (d/kg <sub>wet</sub> )
Am-241	Y <sup>e</sup>	5.4E-05	5.4E-04	4.7E-04	2.5E-04	3.5E-04	2.2E-05	1.0E+00	7.5E-01	6.2E-01	1.5E-06	4.0E-05
Ba-140	Y	1.9E-01	2.0E+00	1.5E-01	1.5E-02	1.5E-02	1.5E-02	1.2E+01	9.0E+00	7.5E+00	4.8E-04	2.0E-04
Ce-141	Y	1.9E-01	2.0E+00	2.0E-02	2.0E-02	2.0E-02	2.0E-02	1.9E+02	1.4E+02	1.2E+02	3.0E-05	2.0E-05
Ce-144	Y	1.4E-02	1.4E-01	2.0E-02	2.0E-02	2.0E-02	2.0E-02	1.3E+01	9.4E+00	7.8E+00	3.0E-05	2.0E-05
Cf-252		1.0E-04	1.0E-03	4.7E-04 <sup>f</sup>	2.5E-04	3.5E-04	2.2E-05	1.9E+00	1.4E+00	1.2E+00	1.5E-06	4.0E-05
Cm-242	Y	5.1E-04	5.2E-03	7.7E-04	1.5E-05	4.3E-04	2.1E-05	7.4E-01	5.4E-01	4.5E-01	2.0E-05	4.0E-05
Cm-244	Y	5.4E-05	5.4E-04	7.7E-04	1.5E-05	4.3E-04	2.1E-05	7.7E-02	5.6E-02	4.7E-02	2.0E-05	4.0E-05
Co-60		2.0E-02	2.0E-01	2.3E-01	7.0E-03	6.7E-02	3.7E-03	1.9E+00	1.4E+00	1.2E+00	3.0E-04	1.0E-02
Cs-134	Y <sup>g</sup>	2.5E-02	2.5E-01	4.6E-01	2.2E-01	1.3E-01	2.6E-02	9.1E-02	6.6E-02	5.5E-02	7.9E-03	5.0E-02
Cs-136		3.1E-01	3.3E+00	4.6E-01	2.2E-01	1.3E-01	2.6E-02	1.3E+00	9.2E-01	7.6E-01	7.9E-03	5.0E-02
Cs-137	Y <sup>g</sup>	3.7E-02	3.7E-01	4.6E-01	2.2E-01	1.3E-01	2.6E-02	1.3E-01	9.7E-02	8.0E-02	7.9E-03	5.0E-02
Gd-153		3.6E-01	3.6E+00	2.0E-02	2.0E-02	2.0E-02	2.0E-02	3.5E+02	2.5E+02	2.1E+02	3.0E-05	2.0E-05
I-129	Y	1.5E-03	3.0E-03	4.0E-02	4.0E-02	4.0E-02	4.0E-02	2.4E-03	3.5E-03	2.9E-03	9.0E-03	4.0E-02
I-131	Y	4.6E-03	1.0E-02	4.0E-02	4.0E-02	4.0E-02	4.0E-02	8.8E-03	1.3E-02	1.0E-02	9.0E-03	4.0E-02
I-133	Y	1.9E-01	8.4E-01	4.0E-02	4.0E-02	4.0E-02	4.0E-02	1.5E+00	2.2E+00	1.8E+00	9.0E-03	4.0E-02
I-135		3.2E+00	8.0E+01	4.0E-02	4.0E-02	4.0E-02	4.0E-02	7.9E+02	1.1E+03	9.5E+02	9.0E-03	4.0E-02
Ir-192		7.9E-02	8.0E-01	5.5E-02	1.5E-02	1.5E-02	1.5E-02	1.2E+03	8.4E+02	7.0E+02	2.0E-06	1.5E-03
La-140		1.8E+00	2.7E+01	5.2E-03	4.0E-03	3.5E-04	4.0E-03	5.9E+03	4.3E+03	3.6E+03	2.0E-05	2.0E-03
Mo-99		4.0E+00	5.1E+01	8.0E-01	5.0E-02	8.0E-01	8.0E-01	1.1E+02	8.0E+01	6.7E+01	1.7E-03	1.0E-03

Radionuclide (units)	FDA Listed	DIL <sup>a</sup> (μCi/kg <sub>wet</sub> )	Mature Crop DRL <sup>b</sup> (μCi/m <sup>2</sup> )	Leafy TF (kg <sub>soil</sub> /kg <sub>dry</sub> )	Fruit TF (kg <sub>soil</sub> /kg <sub>dry</sub> )	Root TF (kg <sub>soil</sub> /kg <sub>dry</sub> )	Grain TF (kg <sub>soil</sub> /kg <sub>dry</sub> )	Milk_DRL <sup>c</sup> (area) (μCi/m <sup>2</sup> )	Milk_DRL <sup>c</sup> (mass) (μCi/kg <sub>wet</sub> )	Milk_DRL <sup>c</sup> (water) (μCi/l)	Milk TF <sup>c</sup> (d/l)	Meat TF <sup>d</sup> (d/kg <sub>wet</sub> )
Nb-95	Y	3.2E-01	3.3E+00	2.5E-02	2.5E-02	2.5E-02	2.5E-02	2.3E+04	1.7E+04	1.4E+04	4.1E-07	3.0E-07
Nb-95m		2.3E+00	2.8E+01	2.5E-02	2.5E-02	2.5E-02	2.5E-02	2.3E+05	1.7E+05	1.4E+05	4.1E-07	3.0E-07
Np-237	Y	1.1E-04	1.1E-03	3.2E-02	1.0E-02	1.3E-02	2.7E-03	6.2E-01	4.5E-01	3.7E-01	5.0E-06	1.0E-03
Np-239	Y	7.6E-01	1.0E+01	3.2E-02	1.0E-02	1.3E-02	2.7E-03	7.8E+03	5.7E+03	4.7E+03	5.0E-06	1.0E-03
Pa-233		1.9E-01	2.0E+00	4.7E-04	2.5E-04	3.5E-04	2.2E-05	1.2E+03	8.4E+02	7.0E+02	5.0E-06	4.0E-05
Pm-147		3.0E-01	3.0E+00	2.0E-02	2.0E-02	2.0E-02	2.0E-02	2.8E+02	2.1E+02	1.7E+02	3.0E-05	2.0E-05
Pu-238	Y <sup>e</sup>	6.8E-05	6.8E-04	6.0E-05	4.5E-05	1.1E-03	8.6E-06	1.8E+00	1.3E+00	1.1E+00	1.1E-06	1.0E-05
Pu-239	Y <sup>e</sup>	6.0E-05	5.9E-04	6.0E-05	4.5E-05	1.1E-03	8.6E-06	1.5E+00	1.1E+00	9.3E-01	1.1E-06	1.0E-05
Pu-241	Y	3.2E-03	3.3E-02	6.0E-05	4.5E-05	1.1E-03	8.6E-06	8.4E+01	6.2E+01	5.1E+01	1.1E-06	1.0E-05
Ra-226		5.5E-05	5.5E-04	4.9E-02	6.1E-03	2.0E-03	1.2E-03	1.2E-03	8.8E-04	7.3E-04	1.3E-03	9.0E-04
Ru-103	Y <sup>h</sup>	1.8E-01	1.9E+00	4.0E-02	4.0E-02	4.0E-02	5.0E-03	1.6E+03	1.2E+03	1.0E+03	3.3E-06	5.0E-02
Ru-106	Y <sup>h</sup>	1.2E-02	1.2E-01	4.0E-02	4.0E-02	4.0E-02	5.0E-03	1.1E+02	7.7E+01	6.4E+01	3.3E-06	5.0E-02
Sb-127		8.5E-01	1.0E+01	1.3E-04	8.0E-05	5.6E-04	3.0E-02	1.4E+03	1.0E+03	8.5E+02	2.5E-05	1.0E-03
Se-75		5.5E-02	5.5E-01	2.5E-01	5.0E-02	5.0E-02	2.5E-01	4.0E-01	2.9E-01	2.4E-01	4.0E-03	1.5E-02
Sr-89	Y	3.8E-02	3.8E-01	3.0E+00	2.0E-01	5.0E-01	2.1E-01	4.0E-01	2.9E-01	2.4E-01	2.8E-03	8.0E-03
Sr-90	Y	4.3E-03	4.3E-02	3.0E+00	2.0E-01	5.0E-01	2.1E-01	4.4E-02	3.2E-02	2.7E-02	2.8E-03	8.0E-03
Sr-91		2.9E+01	1.7E+03	3.0E+00	2.0E-01	5.0E-01	2.1E-01	9.8E+03	7.1E+03	5.9E+03	2.8E-03	8.0E-03
Tc-99m		1.2E+03	1.8E+05	2.1E+02	1.5E+00	2.4E-01	7.3E-01	5.9E+07	4.3E+07	3.6E+07	1.4E-04	1.0E-04
Te-127		1.0E+02	6.0E+03	2.5E-02	4.0E-03	4.0E-03	4.0E-03	2.2E+05	1.6E+05	1.4E+05	4.5E-04	7.0E-03
Te-129m		4.0E-02	4.1E-01	2.5E-02	4.0E-03	4.0E-03	4.0E-03	2.7E+00	1.9E+00	1.6E+00	4.5E-04	7.0E-03
Te-131m		1.8E+00	3.2E+01	2.5E-02	4.0E-03	4.0E-03	4.0E-03	3.5E+02	2.6E+02	2.1E+02	4.5E-04	7.0E-03
Te-132	Y	1.2E-01	1.5E+00	2.5E-02	4.0E-03	4.0E-03	4.0E-03	1.2E+01	8.4E+00	7.0E+00	4.5E-04	7.0E-03
Tm-170 <sup>i</sup>		5.6E-02	5.7E-01	2.0E-02	2.0E-02	2.0E-02	2.0E-02	1.1E-01	7.9E-02	6.6E-02	3.0E-05	2.0E-05
U-237		9.2E-01	1.0E+01	8.3E-03	4.0E-03	1.2E-02	1.3E-03	8.0E+01	5.8E+01	4.9E+01	4.0E-04	3.0E-04
Y-90		6.2E-01	8.0E+00	1.0E-02	1.0E-02	1.0E-02	1.0E-02	1.5E+03	1.1E+03	9.0E+02	2.0E-05	1.0E-03
Y-91	Y	3.2E-02	3.3E-01	1.0E-02	1.0E-02	1.0E-02	1.0E-02	4.7E+01	3.5E+01	2.9E+01	2.0E-05	1.0E-03
Yb-169 <sup>j</sup>		2.4E-01	2.5E+00	2.0E-02	2.0E-02	2.0E-02	2.0E-02	4.8E-01	3.5E-01	2.9E-01	3.0E-05	2.0E-05
Zr-95	Y	1.1E-01	1.1E+00	1.0E-03	1.0E-03	1.0E-03	1.0E-03	5.7E+03	4.2E+03	3.5E+03	5.5E-07	1.0E-06

**Notes:**

- <sup>a</sup> Calculated DILs are based on the ICRP 60+ dosimetry model for the most sensitive organ of the most sensitive age group. Fraction of Diet Contaminated is assumed to be 0.3 except for <sup>132</sup>Te, <sup>131</sup>I, <sup>133</sup>I and <sup>239</sup>Np in the diet of an Infant, where it is assumed to be 1.0. (See Volume 1, Method 4.1.)
- <sup>b</sup> Assumes Crops are ready to harvest. (See Volume 1, Method 4.2 for assumptions and default inputs.)
- <sup>c</sup> Values for Cow's Milk. See Volume 1, Method 4.3. Transfer Factors from PNNL-13421.
- <sup>d</sup> Values for Beef. See Volume 1, Method 4.4. Transfer Factors from PNNL-13421.
- <sup>e</sup> These radionuclides are grouped for evaluation purposes. When more than one of these nuclides is present the TOTAL amount of the radionuclides is compared to a group DIL of 5.4E-05  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ .
- <sup>f</sup> Two values for Cf are reported in the reference. The most conservative is in the table, the other is 2.5E-04.
- <sup>g</sup> These radionuclides are grouped for evaluation purposes. When more than one of these nuclides is present the TOTAL amount of the radionuclides is compared to a group DIL of 3.2E-02  $\mu\text{Ci}/\text{kg}_{\text{wet}}$ .
- <sup>h</sup> <sup>103</sup>Ru and <sup>106</sup>Ru DIL is based on Sum of Fractions (<sup>103</sup>Ru /0.18) + (<sup>106</sup>Ru /0.012) <1. For the purposes of this table, we are assuming only ONE isotope is present.
- <sup>i</sup> No specific Transfer Factors listed in PNNL-13421. Lanthanides are assigned the Ce value per Section 1.3 of the document.

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**Table 9-1 Dry-to-Wet Mass <sup>a</sup>**

<b>Plant Type</b>	<b>Mass Conversion Factor kg<sub>dry</sub>/kg<sub>wet</sub></b>
Leafy vegetables	0.2
Other/root vegetables	0.25
Fruit	0.18
Grain	0.91
Animal Feed	
Forage	0.22
Stored hay	0.22
Stored grain	0.91

<sup>a</sup> Values from PNNL03, Table 2.1.

Inverse values for converting from wet to dry:

**Table 9-2 Wet-to-Dry Mass**

<b>Plant Type</b>	<b>Mass Conversion Factor kg<sub>wet</sub>/kg<sub>dry</sub></b>
Leafy vegetables	5
Other/root vegetables	4
Fruit	5.56
Grain	1.1
Animal Feed	
Forage	4.55
Stored hay	4.55
Stored grain	1.1

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**Table 10 – Daily Food Intake Rates**

This table lists the average DFIR for populations of various ages in the United States.

Food Category	Daily Consumption (kg/day)					
	3 months	1 year	5 years	10 years	15 years	Adult
<b>Total Dairy</b>	<b>5.7E-01</b>	<b>4.9E-01</b>	<b>4.6E-01</b>	<b>5.0E-01</b>	<b>4.8E-01</b>	<b>2.9E-01</b>
Fresh Cow's Milk	2.7E-01	3.2E-01	4.1E-01	4.5E-01	4.3E-01	2.4E-01
Other	3.0E-01	1.7E-01	4.4E-02	5.0E-02	5.3E-02	5.2E-02
<b>Fresh Eggs</b>	<b>4.9E-03</b>	<b>1.2E-02</b>	<b>1.8E-02</b>	<b>1.8E-02</b>	<b>2.2E-02</b>	<b>2.9E-02</b>
<b>Total Meat</b>	<b>4.5E-02</b>	<b>6.9E-02</b>	<b>1.1E-01</b>	<b>1.4E-01</b>	<b>1.7E-01</b>	<b>1.9E-01</b>
Beef	1.8E-02	3.0E-02	5.3E-02	7.3E-02	9.1E-02	9.8E-02
Pork	5.8E-03	9.7E-03	1.6E-02	2.0E-02	2.6E-02	3.1E-02
Poultry	1.8E-02	1.9E-02	2.2E-02	2.7E-02	3.2E-02	3.3E-02
Other	2.6E-03	1.0E-02	2.0E-02	2.4E-02	2.7E-02	2.7E-02
<b>Total Fish</b>	<b>9.0E-04</b>	<b>3.8E-03</b>	<b>8.8E-03</b>	<b>1.2E-02</b>	<b>1.5E-02</b>	<b>1.9E-02</b>
Fin Fish	6.0E-04	3.5E-03	8.2E-03	1.1E-02	1.3E-02	1.6E-02
Shellfish	3.0E-04	3.0E-04	6.0E-04	1.1E-03	1.7E-03	3.0E-03
<b>Total Produce</b>	<b>1.6E-01</b>	<b>1.6E-01</b>	<b>1.9E-01</b>	<b>2.4E-01</b>	<b>2.6E-01</b>	<b>2.9E-01</b>
Leafy	3.2E-03	6.2E-03	1.5E-02	2.3E-02	2.9E-02	4.2E-02
Exposed	7.6E-02	6.6E-02	6.2E-02	7.3E-02	7.4E-02	8.3E-02
Protected	5.1E-02	7.3E-02	1.1E-01	1.4E-01	1.5E-01	1.5E-01
Other	2.6E-02	1.5E-02	6.2E-03	7.8E-03	7.2E-03	6.5E-03
<b>Total Grains</b>	<b>5.6E-02</b>	<b>1.1E-01</b>	<b>1.9E-01</b>	<b>2.3E-01</b>	<b>2.5E-01</b>	<b>2.1E-01</b>
Breads	1.6E-02	6.0E-02	1.3E-01	1.7E-01	1.9E-01	1.6E-01
Cereals	3.8E-02	3.8E-02	3.9E-02	3.8E-02	3.3E-02	2.6E-02
Other	1.8E-03	8.3E-03	1.9E-02	2.4E-02	2.7E-02	2.5E-02
<b>Total Beverages</b>	<b>3.1E-01</b>	<b>5.2E-01</b>	<b>8.0E-01</b>	<b>9.4E-01</b>	<b>1.1</b>	<b>1.5</b>
Tap Water	1.7E-01	3.0E-01	4.8E-01	5.7E-01	6.4E-01	6.8E-01
Water-Based Drinks	8.3E-03	5.3E-02	1.1E-01	1.3E-01	1.7E-01	4.7E-01
Soups	1.0E-02	2.7E-02	4.0E-02	3.6E-02	3.5E-02	4.4E-02
Other	1.2E-01	1.4E-01	1.8E-01	2.1E-01	2.9E-01	3.3E-01
<b>Miscellaneous</b>	<b>5.5E-03</b>	<b>1.6E-02</b>	<b>3.1E-02</b>	<b>3.9E-02</b>	<b>3.9E-02</b>	<b>3.4E-02</b>
<b>Total Daily Intake (kg/d)</b>	<b>1.1</b>	<b>1.4</b>	<b>1.8</b>	<b>2.1</b>	<b>2.4</b>	<b>2.6</b>
<b>Total Annual Intake (kg/yr)</b>	<b>420</b>	<b>510</b>	<b>660</b>	<b>780</b>	<b>870</b>	<b>940</b>

Sources: EPA84, FDA98 (Rounded to 2 significant figures.)

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**Table 11 – Ingestion Pathway Default Assumptions**

The parameters in this table can vary depending on several environmental factors. The FRMAC Assessment Working Group has determined that these values are reasonable over a wide variety of conditions and should be used as the defaults for the methods in this Manual.

Parameter	Description	Value <sup>a</sup>
Animal Feed Daily Ingestion Rate (AFDIR)	Milk Cow	50 kg/d
	Beef Cow	50 kg/d
	Goat	6 kg/d
Animal Soil Daily Ingestion Rate (ASDIR)	Milk Cow	0.5 kg/d <sup>b</sup>
	Beef Cow	0.5 kg/d <sup>b</sup>
	Goat	0.06 kg/d <sup>b,c</sup>
Animal Water Daily Ingestion Rate (AWDIR)	Milk Cow	60 l/d
	Beef Cow	50 l/d
	Goat	8 l/d
Consumption Time	Time contaminated food is consumed.	365 d
Crop Retention Factor (CRF)	Pastureland	0.5 <sup>d</sup>
	Pastureland, Iodines	1.0
	Fresh produce, particulates	0.2
	Fresh produce, Iodines	1.0
	Crops planted AFTER deposition	0.0
Crop Weathering Decay Constant	Corresponds to a 15 day half life.	4.62E-02 d <sup>-1e</sup>
Crop Yield (Y)	Produce	2.0 kg/m <sup>2</sup>
	Pastureland	0.7 kg/m <sup>2</sup>
Density of Milk ( $\rho_{\text{milk}}$ )		1.04 kg/L <sup>f</sup>
Density of Soil ( $\rho_{\text{soil}}$ )		1600 kg/m <sup>3f</sup>
Fraction of Diet Contaminated (FDC)	I-131, I-133, Te-132, and Np-239 in the diet of an infant (3 mo and 1 yr old).	1.0 <sup>g</sup>
	All other Radionuclide/Age Group combinations.	0.3 <sup>g</sup>
Fraction of Diet Contaminated (Feed) or (Water)	Cow Feed (FDC <sub>F</sub> ) Cow Water (FDC <sub>W</sub> )	1.0
Fraction of Subgroup Contaminated (FFC <sub>subgroup</sub> )		1.0 <sup>f</sup>
Mixing Depth ( $d_m$ )	Paved	1.0E-04 <sup>h</sup>
	Unpaved (First Growing Season)	1.0E-03 <sup>h</sup>
	After Plowing (plow depth)	0.15
Daily Soil Intake Rate (DSIR)	Adult	5.0E-05 kg/d <sup>i</sup>
	Child	1.0E-04 kg/d <sup>i</sup>
Time to Market ( $t_m$ )	Crop/Produce	1 d
	Milk	2 d
	Meat	20 d

**Notes:**

- <sup>a</sup> All values from NRC77 unless otherwise indicated.
- <sup>b</sup> ANL01
- <sup>c</sup> Goat value estimated based on ratio of Feed to Soil for Cows (100:1).
- <sup>d</sup> Ng77 (Appendix B, page 113)
- <sup>e</sup> NCRP07 (Page 165)
- <sup>f</sup> FRMAC Assumption
- <sup>g</sup> FDA98 (Appendix E, page 2)
- <sup>h</sup> EPA89
- <sup>i</sup> EPA11 (Table ES-1)

This section reserved for potential inclusion of Worksheets in the future.

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**SI PREFIXES**

E	exa	$10^{18}$
P	peta	$10^{15}$
T	tera	$10^{12}$
G	giga	$10^9$

M	mega	$10^6$
k	kilo	$10^3$
c	centi	$10^{-2}$
m	milli	$10^{-3}$

$\mu$	micro	$10^{-6}$
n	nano	$10^{-9}$
p	pico	$10^{-12}$

**RADIATION**

Absorbed Dose:	100 rad = 1 Gy
Dose Equivalent:	100 rem = 1 Sv
Activity:	1 Ci = 3.7E+10 dps = 37 GBq 1 Bq = 1 dps = 27 pCi
Specific Activity:	1 $\mu$ Ci/kg = 1000 pCi/g
Areal Activity:	1 $\mu$ Ci/m <sup>2</sup> = 1 Ci/km <sup>2</sup> = 100 pCi/cm <sup>2</sup>
Volumetric Activity:	1 Ci/m <sup>3</sup> = 1 mCi/L = 1 $\mu$ Ci/cm <sup>3</sup>
Dose Conversion:	1 Sv/Bq = 3.7E+12 rem/Ci
Dose Rate Conversion:	1 (mrem/yr)/( $\mu$ Ci/m <sup>2</sup> ) = 0.114 (rem/hr)/(Ci/m <sup>2</sup> )

**TIME**

	s	min	hr	d	yr
1 s =	1	1.67E-02	2.78E-04	1.16E-05	3.17E-08
1 m =	60	1	1.67E-02	6.94E-04	1.90E-06
1 hr =	3600	60	1	4.17E-02	8760
1 d =	8.64E+04	1.44E+03	24	1	2.74E-03
1 yr =	3.15E+07	5.26E+05	8760	365	1

**TEMPERATURE & PRESSURE**

$^{\circ}\text{K} = ^{\circ}\text{C} + 273$ $^{\circ}\text{F} = (^{\circ}\text{C} \times 1.8) + 32$ $^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$		lb/in <sup>2</sup>	atm	bar	kPa	mm (Hg)
	1 lb/in <sup>2</sup> =	1	6.80E-02	6.89E-02	6.89	51.7
	1 atm =	14.7	1	1.01	101	760
	1 bar =	14.5	0.99	1	100	752
	1 kPa =	0.145	9.90E-03	0.01	1	7.52
	1 mm (Hg) =	1.93E-02	1.32E-03	1.33E-03	0.133	1

**LENGTH**

		in	ft	yd	mile (s)	mile (n)	cm	m	km
1 in	=	1	8.33E-02	2.78E-02	1.58E-05	1.37E-05	2.54	2.54E-02	2.54E-06
1 ft	=	12	1	0.333	1.89E-04	1.65E-04	30.5	0.305	3.05E-04
1 yd	=	36	3	1	5.68E-04	4.94E-04	91.4	0.914	9.14E-04
1 mile (statute)	=	6.34E+04	5.28E+03	1.76E+03	1	0.869	1.61E+05	1.61E+03	1.61
1 mile (nautical)	=	7.29E+04	6.08E+03	2.03E+03	1.15	1	1.85E+05	1.85E+03	1.85
1 cm	=	0.394	3.28E-02	1.09E-02	6.21E-06	5.40E-06	1	1.0E-02	1.0E-05
1 m	=	39.4	3.28	1.09	6.21E-04	5.40E-04	100	1	1.0E-03
1 km	=	3.94E+04	3.28E+03	1.09E+03	0.621	0.540	1.0E+05	1.0E+03	1

**AREA**

		in <sup>2</sup>	ft <sup>2</sup>	yd <sup>2</sup>	acre	mi <sup>2</sup> (s)	cm <sup>2</sup>	m <sup>2</sup>	ha	km <sup>2</sup>
1 in <sup>2</sup>	=	1	6.94E-03	7.72E-04	1.59E-07	2.49E-10	6.45	6.45E-04	6.45E-08	6.45E-10
1 ft <sup>2</sup>	=	144	1	0.111	2.30E-05	3.59E-08	929	9.29E-02	9.29E-06	9.29E-08
1 yd <sup>2</sup>	=	1.30E+03	9	1	2.07E-04	3.23E-07	8.36E+03	0.836	8.36E-05	8.36E-07
1 acre	=	6.27E+06	4.36E+04	4.84E+03	1	1.56E-03	4.05E+07	4.05E+03	0.405	4.05E-03
1 mi <sup>2</sup> (statute)	=	4.01E+09	2.79E+07	3.10E+06	640	1	2.59E+10	2.59E+06	259	2.59
1 cm <sup>2</sup>	=	0.155	1.08E-03	1.20E-04	2.47E-08	3.86E-11	1	1.0E-04	1.0E-09	1.0E-10
1 m <sup>2</sup>	=	1.55E+03	10.8	1.20	2.47E-04	3.86E-07	1.0E+04	1	1.0E-04	1.0E-06
1 ha	=	1.55E+07	1.08E+05	1.20E+04	2.47	3.86E-03	1.0E+08	1.0E+04	1	0.01
1 km <sup>2</sup>	=	1.55E+09	1.08E+07	1.20E+06	247	0.386	1.0E+10	1.0E+06	100	1

**VOLUME**

		in <sup>3</sup>	fl oz	ft <sup>3</sup>	qt	gal	bu	mL	L
1 in <sup>3</sup>	=	1	0.554	5.79E-04	1.73E-02	6.92E-02	4.65E-04	16.4	1.64E-02
1 fl oz	=	1.80	1	1.04E-03	3.13E-02	7.81E-03	8.39E-04	29.6	2.96E-02
1 ft <sup>3</sup>	=	1.73E+03	957	1	29.9	7.48	0.802	2.83E+04	28.3
1 qt	=	57.8	32	3.34E-02	1	0.25	2.69E-02	9.47E+02	0.947
1 gal	=	231	128	0.134	4	1	0.107	3.79E+03	3.79
1 bu	=	2.15E+03	1.19E+03	1.24	37.2	9.31	1	3.52E+04	35.2
1 mL	=	6.10E-02	3.38E-02	3.53E-05	1.06E-03	2.64E-04	2.84E-05	1	1.0E-03
1 L	=	61.0	33.8	3.53E-02	1.06	0.264	2.84E-02	1.0E+03	1

**NOTE: 1 Bushel (bu) = 8 dry gallons**

**VELOCITY**

		ft/s	m/s	km/h	mile/h	knot
1 ft/s	=	1	0.305	1.10	0.682	0.592
1 m/s	=	3.28	1	3.6	2.24	1.94
1 km/h	=	0.911	0.278	1	0.621	0.540
1 mile/h	=	1.47	0.447	1.61	1	0.869
1 knot	=	1.69	0.514	1.85	1.15	1

**FLOW RATE**

		gal/min	ft <sup>3</sup> /min	L/s	m <sup>3</sup> /hr
1 gal/min	=	1	0.134	6.32E-02	0.227
1 ft <sup>3</sup> /min	=	7.48	1	0.472	1.70
1 L/s	=	15.8	2.12	1	3.60
1 m <sup>3</sup> /hr	=	4.40	0.589	0.278	1

**WEIGHT**

		oz	lb	ton (US)	kg	ton (metric)
oz	=	1	6.25E-02	3.13E-05	2.84E-02	2.84E-05
lb	=	16	1	5.0E-04	0.454	4.54E-04
ton (US)	=	3.2E+04	2.0E+03	1	907	0.907
kg	=	35.2	2.20	1.10E-03	1	1.0E-03
ton (metric)	=	3.52E+04	2.20E+03	1.10	1.0E+03	1

**DENSITY**

		lb/in <sup>3</sup>	lb/ft <sup>3</sup>	g/cm <sup>3</sup>	kg/m <sup>3</sup>
1 lb/in <sup>3</sup>	=	1	5.79E-04	27.7	2.77E+04
1 lb/ft <sup>3</sup>	=	1.73E+03	1	1.60E-02	16.0
1 g/cm <sup>3</sup>	=	3.61E-02	62.4	1	1.0E+03
1 kg/m <sup>3</sup>	=	3.61E-05	6.24E-02	1.0E-03	1

**Misc**Water Density = (1 g/cm<sup>3</sup> at 4°C)Air Density = (0.001293 g/cm<sup>3</sup> at STP)1 ft<sup>3</sup> = 7.48 gal = 62.4 lb1 ft<sup>3</sup> = 0.0807 lb

1 gal = 8.33 lb

1 m<sup>3</sup> = 1.29 kg

Avogadro 's number

Molar Volume

6.02E+23 per g-mole

22.4 L/g-mole

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## SUPPLEMENTS

		<u>Effective Date</u>
Supplement 1: Decay and In-growth Calculation .....	F.1-1	6/2012
Supplement 2: Approximating Resuspension and Weathering Parameters .....	F.2-1	6/2012

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## SUPPLEMENT 1 – DECAY AND IN-GROWTH CALCULATIONS

In order to model complex decay chains more completely, the Bateman equations (H. Bateman, “*Solution of a System of Differential Equations Occurring in the Theory of Radioactive Transformations*,” Proc. Cambridge Phil. Soc. IS, 423 (1910)) are used to determine the amount of a radionuclide present at the evaluation time ( $t_n$ ) based on the decay and in-growth of all radionuclides present in the mixture. A general overview of the calculations is presented below.

To perform this calculation, it is necessary to evaluate the production and decay of each radionuclide in the chain to determine the total amount of each radionuclide present at the evaluation time ( $t_n$ ). For example, in a 3-nuclide chain:

The activity of the parent radionuclide at  $t_n$  is:

$$A_{p,t_n} = A_{p,0} * e^{-\lambda_p t_n} \quad (\text{Eq. 1})$$

The activity of its first generation daughter, including Branching Ratio ( $BrR_{d1}$ ), at  $t_n$  is:

$$A_{d_1,t_n} = A_{p,0} * (\lambda_{d_1} * BrR_{d_1}) * \left( \frac{e^{-\lambda_p t_n} - e^{-\lambda_{d_1} t_n}}{\lambda_{d_1} - \lambda_p} \right) \quad (\text{Eq. 2})$$

The activity of its second generation daughter, including Branching Ratio ( $BrR_{d2}$ ), at  $t_n$  is:

$$A_{d_2,t_n} = A_{p,0} * (\lambda_{d_1} * BrR_{d_1} * \lambda_{d_2} * BrR_{d_2}) * \left[ \frac{e^{-\lambda_p t_n}}{(\lambda_{d_1} - \lambda_p)(\lambda_{d_2} - \lambda_p)} + \frac{e^{-\lambda_{d_1} t_n}}{(\lambda_p - \lambda_{d_1})(\lambda_{d_2} - \lambda_{d_1})} + \frac{e^{-\lambda_{d_2} t_n}}{(\lambda_p - \lambda_{d_2})(\lambda_{d_1} - \lambda_{d_2})} \right] \quad (\text{Eq. 3})$$

Because this second generation daughter ( $d_2$ ) is the first generation daughter of radionuclide  $d_1$ , the activity of  $d_2$  at  $t_n$  due to the initial amount of  $d_1$  can be determined from equation 3 as:

$$A_{d_2,t_n} = A_{d_1,0} * (\lambda_{d_2} * BrR_{d_2}) * \left( \frac{e^{-\lambda_{d_1} t_n} - e^{-\lambda_{d_2} t_n}}{\lambda_{d_2} - \lambda_{d_1}} \right) \quad (\text{Eq. 4})$$

The activity of  $d_2$  as a parent at  $t_n$  is:

$$A_{d_2,t_n} = A_{d_2,0} * e^{-\lambda_{d_2} t_n} \quad (\text{Eq. 5})$$

Therefore, the total amount of the second generation daughter ( $d_2$ ) present at time  $t_n$  can be calculated by adding these terms together to produce:

$$\begin{aligned}
A_{d_2, t_n} = & \left\{ A_{p,0} * (\lambda_{d_1} * BrR_{d_1} * \lambda_{d_2} * BrR_{d_2}) \right. \\
& * \left[ \frac{e^{-\lambda_p t_n}}{(\lambda_{d_1} - \lambda_p)(\lambda_{d_2} - \lambda_p)} + \frac{e^{-\lambda_{d_1} t_n}}{(\lambda_p - \lambda_{d_1})(\lambda_{d_2} - \lambda_{d_1})} + \frac{e^{-\lambda_{d_2} t_n}}{(\lambda_p - \lambda_{d_2})(\lambda_{d_1} - \lambda_{d_2})} \right] \\
& + \left[ A_{d_1,0} * (\lambda_{d_2} * BrR_{d_2}) * \left( \frac{e^{-\lambda_{d_1} t_n} - e^{-\lambda_{d_2} t_n}}{\lambda_{d_2} - \lambda_{d_1}} \right) \right] \\
& \left. + A_{d_2,0} * e^{-\lambda_{d_2} t_n} \right\} \quad (\text{Eq. 6})
\end{aligned}$$

In the general case, the activity of the “n<sup>th</sup>” daughter (assuming an initial mix of parent only) at time  $t_n$  would be:

$$A_{d_n, t_n} = A_{p,0} * (C_1 e^{-\lambda_p t_n} + C_2 e^{-\lambda_{d_1} t_n} + C_3 e^{-\lambda_{d_2} t_n} + \dots + C_n e^{-\lambda_{d_n} t_n})$$

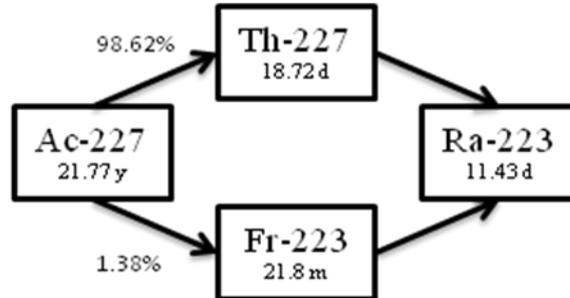
where:

$$\begin{aligned}
C_1 &= \frac{\lambda_{d_1} \lambda_{d_2} \dots \lambda_{d_n}}{(\lambda_{d_1} - \lambda_p)(\lambda_{d_2} - \lambda_p) \dots (\lambda_{d_n} - \lambda_p)} \\
C_2 &= \frac{\lambda_{d_1} \lambda_{d_2} \dots \lambda_{d_n}}{(\lambda_p - \lambda_{d_1})(\lambda_{d_2} - \lambda_{d_1}) \dots (\lambda_{d_n} - \lambda_{d_1})} \\
&\quad \vdots \\
C_n &= \frac{\lambda_{d_1} \lambda_{d_2} \dots \lambda_{d_n}}{(\lambda_p - \lambda_{d_n})(\lambda_{d_1} - \lambda_{d_n}) \dots (\lambda_{d_{n-1}} - \lambda_{d_n})} \quad (\text{Eq. 7})
\end{aligned}$$

**IMPORTANT:** Remember that when a radionuclide chain branches, each chain must be evaluated separately and then activities of radionuclides that are produced by more than one branch must be summed over all of the production methods to determine the total activity present at a given time.

**EXAMPLE 1**

Using the following decay chain in which Ra-223 is formed from two decay pathways:



What is the activity of Ra-223 100 days after a 1 Ci pure Ac-227 sample is created?

Given:

$$\lambda_{Ac} = 8.72E-05 \text{ d}^{-1}$$

$$\lambda_{Th} = 3.7E-02 \text{ d}^{-1} \quad BrR_{Ac,Th} = 0.9862$$

$$\lambda_{Fr} = 45.8 \text{ d}^{-1} \quad BrR_{Ac,Fr} = 0.0138$$

$$\lambda_{Ra} = 6.06E-02 \text{ d}^{-1} \quad BrR_{Th,Ra} = 1 \quad BrR_{Fr,Ra} = 1$$

Because this chain branches, it is necessary to calculate the amount of Ra-223 produced from each branch of the decay.

For the Th-227 branch, from equation 3 above:

$$A_{Ra, 100 \text{ days, Th}} = 1 \text{ Ci} * (3.7E-02 \text{ d}^{-1} * 0.9862 * 6.06E-02 \text{ d}^{-1} * 1) * \left[ \frac{e^{-8.72E-05 \text{ d}^{-1} * 100 \text{ d}}}{(3.7E-02 \text{ d}^{-1} - 8.72E-05 \text{ d}^{-1})(6.06E-02 \text{ d}^{-1} - 8.72E-05 \text{ d}^{-1})} + \frac{e^{-3.7E-02 \text{ d}^{-1} * 100 \text{ d}}}{(8.72E-05 \text{ d}^{-1} - 3.7E-02 \text{ d}^{-1})(6.06E-02 \text{ d}^{-1} - 3.7E-02 \text{ d}^{-1})} + \frac{e^{-6.06E-02 \text{ d}^{-1} * 100 \text{ d}}}{(8.72E-05 \text{ d}^{-1} - 6.06E-02 \text{ d}^{-1})(3.7E-02 \text{ d}^{-1} - 6.06E-02 \text{ d}^{-1})} \right]$$

$$= 0.922 \text{ Ci}$$

For the Fr-223 branch, from equation 4 above:

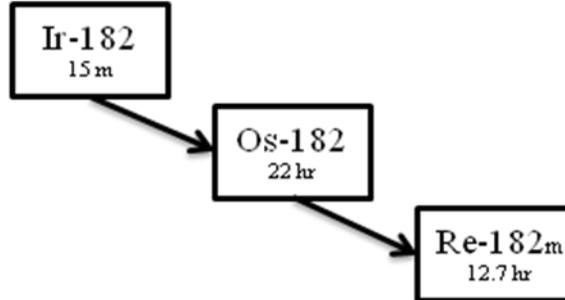
$$A_{\text{Ra, 100 days, Fr}} = 1 \text{ Ci} * (45.8 \text{ d}^{-1} * 0.0138 * 6.06\text{E-}02 \text{ d}^{-1} * 1) * \left[ \begin{array}{l} \frac{e^{-8.72\text{E-}05 \text{ d}^{-1} * 100 \text{ d}}}{(45.8 \text{ d}^{-1} - 8.72\text{E-}05 \text{ d}^{-1})(6.06\text{E-}02 \text{ d}^{-1} - 8.72\text{E-}05 \text{ d}^{-1})} \\ + \frac{e^{-3.7\text{E-}02 \text{ d}^{-1} * 100 \text{ d}}}{(8.72\text{E-}05 \text{ d}^{-1} - 45.8 \text{ d}^{-1})(6.06\text{E-}02 \text{ d}^{-1} - 45.8 \text{ d}^{-1})} \\ + \frac{e^{-6.06\text{E-}02 \text{ d}^{-1} * 100 \text{ d}}}{(8.72\text{E-}05 \text{ d}^{-1} - 6.06\text{E-}02 \text{ d}^{-1})(45.8 \text{ d}^{-1} - 6.06\text{E-}02 \text{ d}^{-1})} \end{array} \right]$$

$$= 0.0137 \text{ Ci}$$

The total Ra-223 activity after 100 days is then the sum of these two quantities, 0.936 Ci.

**EXAMPLE 2**

Using this decay chain:



What is the Re-182m activity 6 hours after the following sample activity is measured?

Ir-182	6.25E-02 Ci	$\lambda_{Ir} = 2.77 \text{ hr}^{-1}$
Os-182	1.04E-02 Ci	$\lambda_{Os} = 3.15\text{E-}02 \text{ hr}^{-1}$
Re-182m	3.97E-04 Ci	$\lambda_{Re} = 5.46\text{E-}02 \text{ hr}^{-1}$

From equation 6 above:

$$\begin{aligned}
 A_{Re, 6hr} = & \left[ 6.25\text{E-}02 \text{ Ci} * \left( 3.15\text{E-}02 \text{ hr}^{-1} * 1 * 5.46\text{E-}02\text{hr}^{-1} * 1 \right) * \left[ \frac{e^{-2.77 \text{ hr}^{-1} * 6 \text{ hr}}}{(3.15\text{E-}02 \text{ hr}^{-1} - 2.77 \text{ hr}^{-1})(5.46\text{E-}02\text{hr}^{-1} - 2.77 \text{ hr}^{-1})} + \frac{e^{-3.15\text{E-}02 \text{ hr}^{-1} * 6 \text{ hr}}}{(2.77 \text{ hr}^{-1} - 3.15\text{E-}02 \text{ hr}^{-1})(5.46\text{E-}02\text{hr}^{-1} - 3.15\text{E-}02 \text{ hr}^{-1})} + \frac{e^{-5.46\text{E-}02\text{hr}^{-1} * 6 \text{ hr}}}{(2.77 \text{ hr}^{-1} - 5.46\text{E-}02\text{hr}^{-1})(3.15\text{E-}02 \text{ hr}^{-1} - 5.46\text{E-}02\text{hr}^{-1})} \right] \right] \\
 & + \left[ 1.04\text{E-}02 \text{ Ci} * \left( 5.46\text{E-}02\text{hr}^{-1} * 1 \right) * \left( \frac{e^{-3.15\text{E-}02 \text{ hr}^{-1} * 6 \text{ hr}} - e^{-5.46\text{E-}02\text{hr}^{-1} * 6 \text{ hr}}}{5.46\text{E-}02\text{hr}^{-1} - 3.15\text{E-}02 \text{ hr}^{-1}} \right) \right] \\
 & + 3.97\text{E-}04 \text{ Ci} * e^{-5.46\text{E-}02\text{hr}^{-1} * 6 \text{ hr}} \\
 = & 3.10\text{E-}03 \text{ Ci}
 \end{aligned}$$

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## SUPPLEMENT 2 – CALCULATION OF RESUSPENSION AND WEATHERING PARAMETERS

The Resuspension and Weathering Parameters are similar in that they both involve radioactive decay and a physical removal process. These two effects would seem to be complementary, but in fact are competing and must be addressed separately over the integration period. Therefore, standard mathematical methods for combining equations are not appropriate and exact solutions are only achievable through numerical integration. This can be approximated by hand using a series technique, such as a Taylor expansion. Full treatment of this process is outside the scope of this Manual.

**The methods described below represent an approximate solution for parent radionuclides and should only be used if a computer code, such as Turbo FRMAC<sup>®</sup>, is not available to complete these calculations.**

This supplement addresses the calculation of the following quantities:

$KP_{i, TP}$  = Resuspension Parameter, value that adjusts the airborne radioactivity level of radionuclide  $i$  over the time phase under consideration ( $TP$ ) for radioactive decay and in-growth and the time-dependent resuspension factor ( $K_t$ ),  $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ ;

$K_t$  = Resuspension Factor, The fraction of radioactive material transferred from the surface to the atmosphere at a given time ( $t$ ) after initial deposition,  $\text{m}^{-1}$ .

$WP_{i, TP}$  = Weathering Parameter, the adjustment for radioactive decay and in-growth and the time-dependent weathering effects that change the amount of a radionuclide available to cause direct exposure or to be ingested over the time phase under consideration ( $TP$ ),  $\mu\text{Ci}\cdot\text{s}/\text{m}^2$ ;

$WF$  = Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind), unitless;

**NOTE:** Weathering is used in this manual both as a contributor to the Weathering Parameter and as an independent factor. This Supplement treats Weathering as a contributor to the WP. If a calculation involves weathering as an independent factor the section on Weathering may be performed as a stand-alone calculation.

### F2.1 Resuspension Parameter

The Resuspension Parameter (KP) adjusts the inhalation dose for radioactive decay ( $e^{-\lambda t}$ ) and the time-dependent Resuspension Factor (K) over the time phase under consideration.

**NOTE:** This KP model is the default approach, but may not be appropriate for the environmental conditions existing in the area under investigation. An alternate KP model may be substituted, with approval from local authorities, if the alternate model can be shown to more accurately model the resuspension in the area under investigation.

$$KP_{i,TP} = \int_{t_1}^{t_2} (K_t * Dp_{i,t}) dt \quad (\text{Eq. 1})$$

$$\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} = \int_s^s \left( \frac{1}{\text{m}} * \frac{\mu\text{Ci}}{\text{m}^2} \right)$$

where:

$KP_{i,TP}$  = Resuspension Parameter, value that adjusts the airborne radioactivity level of radionuclide  $i$  over the time phase under consideration ( $TP$ ) for radioactive decay and in-growth and the time-dependent resuspension factor ( $K_t$ ),  $\mu\text{Ci}\cdot\text{s}/\text{m}^3$ ;

$t_1$  = the start of the time phase (integration period) under consideration, s;

$t_2$  = the end of the time phase (integration period) under consideration, s;

$K_t$  = Resuspension Factor, the fraction of radioactive material transferred from the surface to the breathing zone at a given time ( $t$ ) after initial deposition,  $\text{m}^{-1}$ ;  
and

$Dp_{i,t}$  = Deposition, the areal activity of radionuclide  $i$  at time  $t$ ,  $\mu\text{Ci}/\text{m}^2$ .

**NOTE:** This value is calculated using the Bateman equations as demonstrated in Appendix F – Supplement 1.

### F2.1.1 Resuspension

Resuspension is the fraction of radioactive material transferred from the surface to the breathing zone at given time ( $t$  – in seconds) after initial deposition. The units of resuspension are  $\text{m}^{-1}$ , representing the air concentration ( $\mu\text{Ci}/\text{m}^3$ ) divided by the areal activity ( $\mu\text{Ci}/\text{m}^2$ ) in a given area.

Resuspension as a function of time is represented by Equation 2:

$$K_t = \left( 1.0\text{E-}05 * e^{-8.1\text{E-}07*t} \right) + \left( 7.0\text{E-}09 * e^{-2.31\text{E-}08*t} \right) + 1.0\text{E-}09 \quad (\text{Eq. 2})$$

where:

$K_t$  = Resuspension Factor, the fraction of radioactive material transferred from the surface to the breathing zone at a given time ( $t$ ) after initial deposition,  $\text{m}^{-1}$ ;  
and

$t$  = Time, the time elapsed from initial deposition, s.

The resuspension model used here is the standard FRMAC approach found in the Maxwell-Anspaugh paper “An improved model for prediction of resuspension” (Max11), but may not be appropriate for the environmental conditions existing in the area under investigation. An alternate resuspension model may be substituted, with approval from local decision makers, if the alternate model can be shown to more accurately model the resuspension in the area under investigation.

### F2.1.2 Combining Resuspension with Radioactive Decay and In-growth to produce the Resuspension Parameter

For a **parent radionuclide**, multiplying  $K_i$  by the radioactive decay yields:

$$KP_{i,TP} = \int_{t_1}^{t_2} \left[ \begin{array}{l} 1.0E-05 * e^{-8.1E-07*t} \\ + 7.0E-09 * e^{-2.31E-08*t} \\ + 1.0E-09 \end{array} \right] * \left( Dp_{i,t_0} * e^{-\lambda_i t} \right) dt \quad (\text{Eq. 3a})$$

where:

$Dp_{i,t_0}$  = Initial Deposition, the areal activity of radionuclide  $i$  at the time of deposition  $t_0$ ,  $\mu\text{Ci}/\text{m}^2$ ;

$\lambda_i$  = Decay constant for radionuclide  $i$ ,  $\text{s}^{-1}$ ;

This simplifies to:

$$KP_{i,TP} = Dp_{i,t_0} * \int_{t_1}^{t_2} \left[ \begin{array}{l} 1.0E-05 * e^{(-t*(\lambda_i + 8.1E-07))} \\ + 7.0E-09 * e^{(-t*(\lambda_i + 2.31E-08))} \\ + 1.0E-09 * e^{(-t*(\lambda_i))} \end{array} \right] dt \quad (\text{Eq. 3b})$$

Integrating over the time phase under consideration yields the following:

$$KP_{i,TP} = Dp_{i,t_0} * \left[ \begin{array}{l} \frac{1.0E-05 * \left( e^{(-t_2*(\lambda_i + 8.1E-07))} - e^{(-t_1*(\lambda_i + 8.1E-07))} \right)}{-\left( \lambda_i + 8.1E-07 \right)} \\ + \frac{7.0E-09 * \left( e^{(-t_2*(\lambda_i + 2.31E-08))} - e^{(-t_1*(\lambda_i + 2.31E-08))} \right)}{-\left( \lambda_i + 2.31E-08 \right)} \\ + \frac{1.0E-09 * \left( e^{(-t_2*(\lambda_i))} - e^{(-t_1*(\lambda_i))} \right)}{-\left( \lambda_i \right)} \end{array} \right] \quad (\text{Eq. 3c})$$

$$\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} = \frac{\mu\text{Ci}}{\text{m}^2} * \left[ \begin{array}{c} \frac{\text{m}^{-1} * \text{unitless}}{\text{s}^{-1}} \\ + \frac{\text{m}^{-1} * \text{unitless}}{\text{s}^{-1}} \\ + \frac{\text{m}^{-1} * \text{unitless}}{\text{s}^{-1}} \end{array} \right]$$

Calculations for daughters may be performed in the same manner by replacing ( $Dp_{i,t_0} * e^{-\lambda t}$ ) in Equation (3a) above with the Bateman equation that is appropriate for the “generation” of daughter under consideration (Found in Appendix F – Supplement 1).

## F2.2 Weathering Parameter

The Weathering Parameter (WP) adjusts for radioactive decay and in-growth and the time-dependent weathering factor (WF) over the time phase under consideration.

$$WP_{i,TP} = \int_{t_1}^{t_2} (WF_t * Dp_{i,t}) dt \quad (\text{Eq. 4})$$

$$\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^2} = \int_s^s \left( \text{unitless} * \frac{\mu\text{Ci}}{\text{m}^2} \right)$$

where:

$WP_{i,TP}$  = Weathering Parameter, the adjustment for radioactive decay and in-growth and the time-dependent weathering effects that change the amount of a radionuclide available to cause direct exposure or to be ingested over the time phase under consideration ( $TP$ ),  $\mu\text{Ci}\cdot\text{s}/\text{m}^2$ ;

$t_1$  = the start of the time phase (integration period) under consideration, s;

$t_2$  = the end of the time phase (integration period) under consideration, s;

$WF_t$  = Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind) from  $t_0$  (deposition) to  $t_n$  (evaluation time), unitless; (An02); and

$Dp_{i,t}$  = Deposition, the areal activity of radionuclide  $i$  at time  $t$ ,  $\mu\text{Ci}/\text{m}^2$ .

**NOTE:** This value is calculated using the Bateman equations as demonstrated in Appendix F – Supplement 1.

### F2.2.1 Weathering Factor

The Weathering Factor (WF) adjusts for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind). The FRMAC’s default WF model was developed using data from the Nevada Test Site and the Chernobyl nuclear power plant accident (An02).

**NOTE:** This WF model is the default approach, but may not be appropriate for the environmental conditions existing in the area under investigation. An alternate WF model may be substituted, with approval from local authorities, if the alternate model can be shown to more accurately model the weathering in the area under investigation.

$$WF_t = 0.4 * e^{-1.46E-08t} + 0.6 * e^{-4.44E-10t} \quad (\text{Eq. 5})$$

$$\text{unitless} = \text{unitless} * \left( e^{-(s^{-1} * s)} \right) + \text{unitless} * \left( e^{-(s^{-1} * s)} \right)$$

where:

$WF$  = Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind), unitless; and  
 $t$  = Time, the time elapsed from initial deposition, s.

**NOTE: Ignoring Weathering:** If desired, the WF can be ignored when calculating the external dose from groundshine. To ignore weathering, set the WF value to 1 (constant over time). This will cause the WP to be simply a radioactive decay and in-growth adjustment for each radionuclide over the time phase under consideration.

### F2.2.2 Combining the Weathering Factor and Radioactive Decay and In-growth to produce the Weathering Parameter

If weathering is addressed, the math in this part of the calculation is a little more complicated so the intermediate steps have been included.

For a **parent radionuclide**, multiplying the WF by the radioactive decay yields:

$$WP_{i,TP} = \int_{t_1}^{t_2} \left[ \left( 0.4 * e^{-1.46E-08t} + 0.6 * e^{-4.44E-10t} \right) * \left( Dp_{i,t_0} * e^{-\lambda_i t} \right) \right] dt \quad (\text{Eq. 6a})$$

where:

$Dp_{i,t_0}$  = Initial Deposition, the areal activity of radionuclide  $i$  at the time of deposition  
 $t_0$ ,  $\mu\text{Ci}/\text{m}^2$ ;  
 $\lambda_i$  = Decay constant for radionuclide  $i$ ,  $\text{s}^{-1}$ ;

This simplifies to:

$$WP_{i,TP} = Dp_{i,t_0} * \int_{t_1}^{t_2} \left[ 0.4 * e^{(-t * (\lambda_i + 1.46E-08))} + 0.6 * e^{(-t * (\lambda_i + 4.44E-10))} \right] dt \quad (\text{Eq. 6b})$$

Integrating over the time phase under consideration yields the following:

$$WP_{i,TP} = Dp_{i,t_0} * \left[ \begin{array}{l} \frac{0.4 * \left( e^{(-t_2 * (\lambda_i + 1.46E-08))} - e^{(-t_1 * (\lambda_i + 1.46E-08))} \right)}{-\left( \lambda_i + 1.46E-08 \right)} \\ + \frac{0.6 * \left( e^{(-t_2 * (\lambda_i + 4.44E-10))} - e^{(-t_1 * (\lambda_i + 4.44E-10))} \right)}{-\left( \lambda_i + 4.44E-10 \right)} \end{array} \right] \quad (\text{Eq. 6c})$$

$$\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^2} = \frac{\mu\text{Ci}}{\text{m}^2} * \left[ \begin{array}{l} \frac{\text{unitless} * \text{unitless}}{\text{s}^{-1}} \\ + \frac{\text{unitless} * \text{unitless}}{\text{s}^{-1}} \end{array} \right]$$

Calculations for daughters may be performed in the same manner by substituting the appropriate Bateman equation (Found in Appendix F – Supplement 1) for  $(Dp_{i,t_0} * e^{-\lambda t})$  in the equations above.

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