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**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

**September, 2010**

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico  87185 and Livermore, California  94550

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FRMAC Assessment Manual

# Overview and Methods

# Volume 1

Terrence D. Kraus
Assessment Work Group Co-Chair
Sandia National Laboratories

Arthur Shanks, Jr.
Derivative Classifier
Assessment Working Group Co-Chair
Sandia National Laboratories

Colleen T. O'Laughlin
Program Manager for CM/FRMAC Program
DOE/NNSA

Daniel J. Blumenthal
Consequence Management Program Manager
DOE/NNSA

Deborah A. Wilber
Director, Office of Emergency Response
DOE/NNSA

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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 agencies that can be expected to play the major roles during a radiological emergency, including: 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 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:

U.S. Department of Energy
National Nuclear Security Administration
Nevada Site Office
Attn: FRMAC Program Manager
P.O. Box 98518
Las Vegas, NV 89193-8518

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**FRMAC Assessment Working Group Members**

| | | | |
|---|---|---|---|
| Baskett, Ronald | LLNL | Laiche, Thomas | SNL |
| Blumenthal, Daniel | NNSA | McGuire, Stephen | NRC |
| Bowman, David | NNSA | McIntyre, Kathleen | BNL |
| Boyd, Wesley | EPA | Mena, RaJah | RSL |
| Brandon, Lou | NRC | Morgan, Ron | LANL |
| Clark Jr., Harvey | RSL | Murray, Michael | ORNL |
| Cleveland, Gordon | USDA | Nasstrom, John | LLNL |
| Costello, Cynthia | State of NY | Noska, Michael | FDA |
| Cunningham, William | FDA | O'Laughlin, Colleen | NNSA |
| Favret, Derek | USAF | Patterson, Jack | USDA |
| Foster, Kevin | LLNL | Petullo, Colleen | EPA |
| Fulton, John | SNL | Reed, Alexis | RSL |
| Hadley, Robb | LLNL | Shanks, Arthur | SNL |
| Homann, Steven | LLNL | Stanton, Colby | EPA |
| Hoover, Sarah | LANL | Telofski, Scott | EPA |
| Hunt, Brian | SNL | Tupin, Edward | EPA |
| Johnson, Norris | SRNS | Whitcomb, Robert | CDC |
| Kraus, Terry | SNL | Yu, Charley | ANL |

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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When sections are added or revised, their effective dates will be updated to indicate the date of revision. The most recent revisions will be indicated in RED text.

Please check this table periodically to ensure that your printed copy of Volume 1 is up to date by comparing the "Effective Date" in this table with the date in the header of each section. When a section is added or updated, only that section will need to be printed – the page numbers in the rest of the volume will be unaffected.

# Acronyms and Abbreviations

| | |
|---|---|
| **AGL** | Above ground level |
| **ALI** | Annual Limit of Intake |
| **AMAD** | Activity Median Aerodynamic Diameter |
| **AMS** | Aerial Measuring System |
| **ARAC** | Atmospheric Release Advisory Capability |
| **ARF** | Airborne release fraction |
| **ARG** | Accident Response Group |
| **ASHG** | Accident Site Health Group |
| **AWG** | Assessment Working Group |
| **BWR** | Boiling-Water Reactor |
| **CDC** | Centers for Disease Control and Prevention |
| **CMRT** | Consequence Management Response Team |
| **CPM** | Counts per Minute |
| **DAC** | Derived Air Concentration |
| **DCF** | Dose Conversion Factor |
| **DCFPAK** | Dose Conversion Factor Package |
| **DHS** | US Department of Homeland Security |
| **DIL** | Derived Intervention Level |
| **DOD** | US Department of Defense |
| **DOE** | US Department of Energy |
| **DOT** | US Department of Transportation |
| **DQO** | Data Quality Objective |
| **DRL** | Derived Response Level |
| **EPA** | US Environmental Protection Agency |
| **FDA** | US Food and Drug Administration |
| **FRMAC** | Federal Radiological Monitoring and Assessment Center |
| **GIS** | Geographic Information System |
| **GM** | Geiger-Mueller |
| **H&S** | Health and Safety |
| **HHS** | US Department of Health and Human Services |
| **ICRP** | International Commission on Radiological Protection |
| **KIPF** | Potassium Iodide Protection Factor |
| **LANL** | Los Alamos National Laboratory |
| **LET** | Linear Energy Transfer |
| **LLNL** | Lawrence Livermore National Laboratory |
| **LWR** | Light Water Reactor |
| **MDA** | Minimum Detectable Activity |

| | |
|---|---|
| **NARAC** | National Atmospheric Release Advisory Center |
| **NCRP** | National Council on Radiation Protection and Measurements |
| **NDA** | National Defense Area |
| **NNSA** | National Nuclear Security Administration |
| **NRC** | US Nuclear Regulatory Commission |
| **NSA** | National Security Area |
| **PAG** | Protective Action Guide |
| **PAR** | Protective Action Recommendations |
| **PNNL** | Pacific Northwest National Laboratory |
| **PPD** | Projected Public Dose |
| **PPE** | Personal Protective Equipment |
| **PWR** | Pressurized-Water Reactor |
| **QF** | Quality Factor |
| **RAP** | Radiological Assistance Program |
| **RBE** | Relative Biological Effectiveness |
| **RF** | Respirable fraction |
| **RHU** | Radioisotope Heater Unit |
| **RPF** | Respiratory Protection Factor |
| **RTG** | Radioisotope Thermoelectric Generator |
| **RTM** | Response Technical Manual |
| **SCA** | Single Channel Analyzer |
| **SCBA** | Self-Contained Breathing Apparatus |
| **SNL** | Sandia National Laboratories |
| **SNM** | Special Nuclear Material |
| **SRD** | Self Reading Dosimeter |
| **ST** | Stay Time |
| **TBL** | Turn Back Limit |
| **TED** | Total Effective Dose |
| **TF** | Transfer Factor |
| **TNT** | Trinitrotoluene |
| **USDA** | US Department of Agriculture |
| **WGPu** | Weapons-Grade Plutonium |

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# OVERVIEW

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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:

- Is intended for use by trained FRMAC Assessment Scientists. It is basis for training FRMAC Assessment Scientists, and defines the technical methods used when responding to radiological incidents.
- Represents the technical consensus of multiple federal agencies with expertise in and authority over aspects of radiological emergency response.
- Is only intended to address the early and intermediate phases of a radiological incident. It does not address recovery phase issues such as remediation.
- 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.
- 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 – Plume Phase Evaluations (RESERVED);
- Section 2 – Population Protection;
- Section 3 – Emergency Worker Protection;
- Section 4 – Ingestion Pathway Analysis; and
- Section 5 – Sample Management.

All variables use 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. 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 passes 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 Software Package

  The Turbo FRMAC 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 allows the assessment scientist to vary inputs and change default 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.

- 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.

- 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) 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 event 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. PLUME ASSESSMENT METHODS



THIS SECTION IS RESERVED FOR FUTURE DEVELOPMENT.

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# SECTION 2. DEPOSITION ASSESSMENT METHODS

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# Introduction to Deposition Assessment Methods

The methods in this section assist Assessment Scientists in evaluating potential hazards to members of the public from a radiological incident. Methods include developing DRLs and projecting doses by relating values from modeling projections or field monitoring results to established PAGs. (See Appendix C, Table 2-2 for PAG values.)

Methods in this section have been developed to address hazards from exposure to a ground deposition of radioactive material.

## 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 Ingestion Methods, Section 4.)
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. an Activity Averaged Breathing Rate of 0.92 $m^3$/hr; and
    f. inhalation of 1-micron Activity Median Aerodynamic Diameter (AMAD) particles in the Maximum lung clearance class.
6) Parent – Daughter inclusion rules:
    - Daughter radionuclides are included in calculations if:

   a. Daughter's half-life is less than the half-life of the ultimate parent (i.e., first parent in decay series), and
   b. Daughter's half-life is less than 1.5 yr.
- Daughter radionuclides that meet these rules are considered to be in equilibrium (secular, or transient when branching ratio ≠ 1) at deposition (t = 0, i.e., the daughter radionuclides are not grown in to equilibrium activities), and are assigned the parent's half life and decay constants for calculations.
- Daughter radionuclides that do not meet these rules are excluded from the calculations (as are all subsequent daughter radionuclides, regardless of half life).
- Optionally, an alternate calculation that models the decay and in-growth of the entire radionuclide decay chain may be used when the using the default Parent – Daughter inclusion rules stated above is not desired. See Appendix F, Supplement 1 for details on the calculation.

7) FRMAC's public 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 2.1 Example 1, Section E1.6.)

# Inputs

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

- 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.

- Other Factors:
    - Ground roughness;
    - Weathering;
    - Resuspension; and
    - Decay of radionuclides during the time period under consideration.

- Constants:
    - Breathing rate;
    - Inhalation dose coefficient;
    - External dose coefficient;
    - Dose limits (e.g., PAGs); and
    - Exposure to Dose conversion factor (default of 1.0 mrem/mR).

- Time Phase:
    - Evaluation Time ($t_n$) – The point in time, relative to the start of the event, for which the calculation is being performed; and
    - The start ($t_1$) and end ($t_2$) time of period under consideration. The EPA and DHS have established certain time phases (early, intermediate, etc.) with specified

durations, but the time phase may be set to any period chosen by local authorities for a specific event. The start of the time phase may be set to a time other than the time of the initial event to not include the unavoidable dose received before protective actions may be initiated.

The calculations presented in these methods are applicable to all EPA-defined as well as any user-defined time phases. To accommodate calculations for varying time phases, adjust the beginning ($t_1$) and ending ($t_2$) of the integration period to the desired values. For example, to calculate a value for the second year, set $t_1$ and $t_2$ to 366 and 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.)

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# METHOD 2.1 DEPOSITION DERIVED RESPONSE LEVEL

## Application

This method has been developed to calculate a Deposition Derived Response Level (Dp_DRL) for a deposition of radioactive material.

The Dp_DRL:

- Represents the ground concentration, or areal activity (µCi/m$^2$), at a given time ($t_n$) of a marker radionuclide in a mixture of radionuclides that will be expected to cause the entire mixture to produce a dose equal to the appropriate Protective Action Guide (PAG) over the time phase under consideration.

- 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 deposition value greater than the Dp_DRL indicates that the PAG has the potential to be exceeded.

- Is used to create data products and define contamination levels for a marker radionuclide to assist decision makers in determining where it may be advisable to implement protective actions (e.g., sheltering, evacuation, relocation).

## Discussion

The Dp_DRL combines a Total Dose Parameter for Deposition (TDP_Dp), made up of internal and external dose parameters, with the deposition (areal activity) values for each radionuclide present in a mixture and relates that product (MTDP_Dp) to the PAG for the time phase under consideration and the areal activity of the marker radionuclide.

The Dp_DRL is based on the ratio of activities of each radionuclide in a mixture, not the individual activity values of those radionuclides.

The marker radionuclide, chosen for ease of detection with available instrumentation, is used to eliminate the need to separately measure the concentration of every radionuclide in the environmental medium, once a relative ratio of the amount of each radionuclide present is known.

**NOTE:** The Dp_DRL may be calculated for Stochastic (Chronic) or Deterministic (Acute) doses. At this time, only Stochastic doses are calculated by this method; information for calculating Deterministic doses will be included at a future date.

## Assumptions

There are no additional assumptions beyond the default assumptions.

## Inputs

There are no additional inputs beyond the default inputs.

If incident-specific values have not been established, recommended default values for selected inputs are available in Appendix C.

## Outputs

The final output of this method is the Dp_DRL value for a marker radionuclide from a deposition of radioactive material.

### Final

Dp_DRL = Deposition Derived Response Level, the areal activity, at time $t_n$, of the marker radionuclide at which the dose from all radionuclides in a deposition mixture would result in a dose equal to the PAG for the time phase under consideration, µCi/m$^2$

### Intermediate

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

MTDP_Dp = Mixture Total Dose Parameter for Deposition for all radionuclides in the mixture of interest (mrem)

TDP_Dp = Total Dose Parameter for Deposition for each radionuclide (mrem•m$^2$/µCi)

InhDP_Dp = Inhalation Dose Parameter for Deposition (mrem•m$^2$/µCi)

ExDP_Dp = External Dose Parameter for Deposition (mrem•m$^2$/µCi)

## Calculation

Calculating the Dp_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, to complete these calculations.

Equation 2.1-1 represents the final form of the Dp_DRL calculation:

$$Dp\_DRL_{E,i(m),t_n} = \frac{PAG_{E,TP} * Dp_{i(m)} * e^{-\lambda_{i(m)} t_n} * WF_{t_n}}{MTDP\_Dp_{E,TP}} \quad \text{(Eq. 2.1-1)}$$

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

where:

$Dp\_DRL_{E,\,i\,(m),\,tn}$ = Deposition Derived Response Level, the areal activity at time $t_n$ of a marker radionuclide *i(m)* at which the dose to the whole body (*E*) from all radionuclides in a deposition mixture would result in a dose equal to the PAG for the time phase under consideration, μCi/m$^2$;
**NOTE:** The default value for $t_n$ is the start of the time phase under consideration ($t_1$), but it may be set to any time (before, during, or after the time phase). If this calculation is being performed for multiple time phases, $t_n$ is usually set to the start of the Early Phase for all calculations to allow for comparison of results.

$Dp_{i(m)}$ = Deposition, the areal activity of a marker radionuclide *i(m)* per unit area of ground at $t_0$ (deposition), μCi/m$^2$;

$PAG_{E,\,TP}$ = Protective Action Guide, as specified by the EPA or local authorities, for the whole body (*E*), for the time phase (*TP*) under consideration, mrem;

$\lambda_{i(m)}$ = Decay constant for the marker radionuclide *i(m)*, s$^{-1}$;

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

$e^{-\lambda tn}$ = Radioactive Decay adjustment for radionuclide *i* from $t_0$ (deposition) to $t_n$ (time of measurement, prediction, or evaluation), unitless;

$WF_{tn}$ = Weathering adjustment from $t_0$ (deposition) to $t_n$ (time of measurement, prediction, or evaluation), unitless; and
**NOTE:** See Appendix F, Supplement 2 for details on calculating WF.

$MTDP\_Dp_{E,\,TP}$ = Mixture Total Dose Parameter for Deposition, the sum of the external dose from groundshine and the internal dose from inhalation of resuspended material received by the whole body (*E*), over the time phase under consideration (*TP*), from the areal activity level of the mixture, mrem.

Equation 2.1-2 represents the full equation, showing all inputs used to calculate the MTDP_Dp from the base level without combining any terms:

$$Dp\_DRL = \frac{PAG * \left(Dp_{i(m)} * e^{-\lambda_{i(m)} t_n} * WF_{t_n}\right)}{\sum_i \left\{ \left( \left[BR * InhDC\right] * \left[\int_{t_1}^{t_2} \left(K * e^{-\lambda_i t}\right) dt\right] + \left[\int_{t_1}^{t_2} \left(WF * e^{-\lambda_i t}\right) dt\right] * \left[ExDC\_Dp * GRF\right] \right) * Dp_i \right\}}$$

(Eq. 2.1-2)

Figure 2.1-1 shows the full calculation tree used to develop the Dp_DRL and the intermediate outputs of Inhalation, External, and Total Dose Parameters for individual radionuclides and the Mixture Total Dose Parameter.

Following the figure are detailed instructions for working through all calculations required to determine the Dp_DRL.

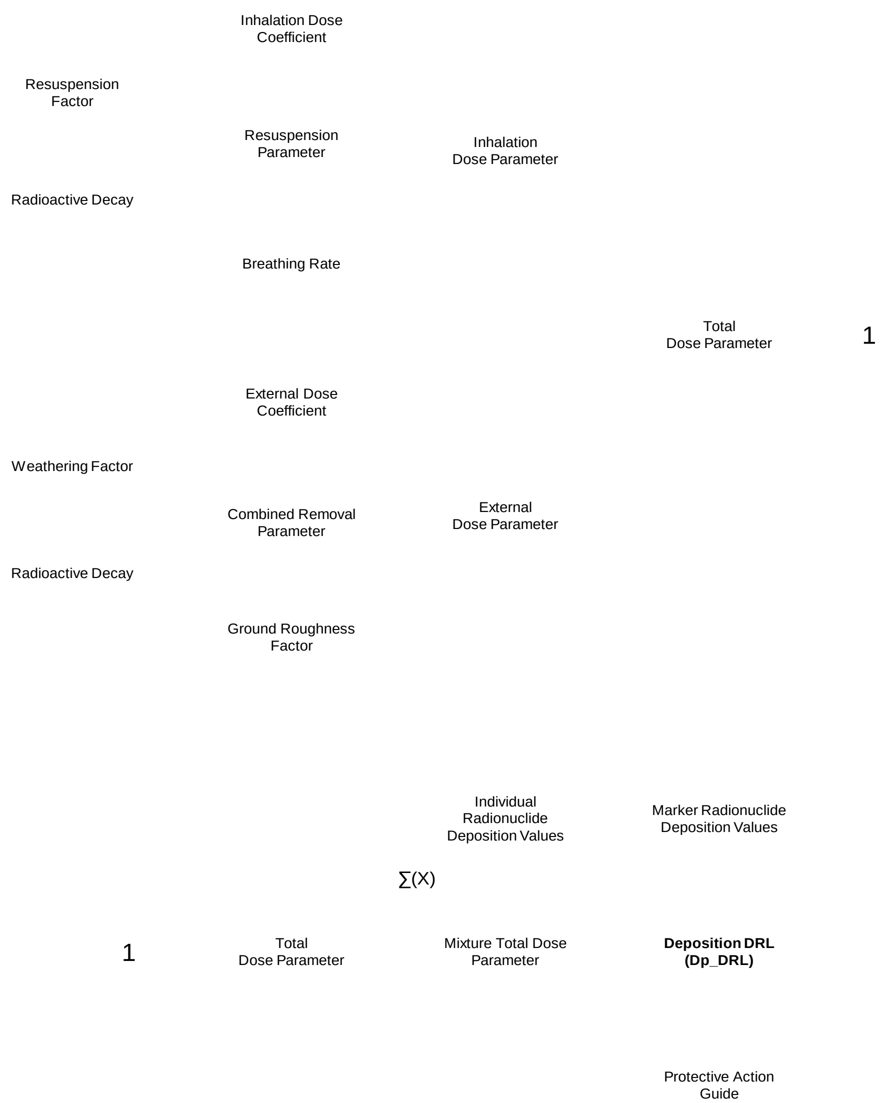


**Figure 2.1-1 Deposition Derived Response Level Calculation Tree**

# 1.0 Calculating the Deposition Derived Response Level

The Dp_DRL is a value that is used to relate an areal activity (e.g., $\mu Ci/m^2$) of a specific (marker) radionuclide ($Dp_{i(m)}$) present in a mixture to the hazard posed by the entire mixture over the time phase under consideration relative to the regulatory PAG.

A prime factor in determining the Dp_DRL is the Total Dose Parameter (TDP_Dp) for each radionuclide present in the mixture. The TDP_Dp is obtained by adding an Inhalation Dose Parameter (InhDP_Dp) and an External Dose Parameter (ExDP_Dp).

**NOTE:** If inhalation of resuspended radioactive material is not a concern, then the InhDP_Dp is essentially zero and the TDP_Dp is equal to the ExDP_Dp and Section 1.1 may be skipped.

The TDP_Dp for each radionuclide is then multiplied by the areal activity of that radionuclide present in the mixture ($Dp_i$) and those products are then summed over all of the radionuclides in the mixture. The resulting value, called the Mixture Total Dose Parameter for Deposition (MTDP_Dp), can then be related to the PAG and the areal activity of the chosen marker radionuclide, as shown in Equation 2.1-1, to determine the Dp_DRL.

The following sections provide step-by-step instructions for the manual calculation of a Dp_DRL, beginning with determining the TDP_Dp for each radionuclide, then finding a MTDP_Dp for the mixture, and finally calculating the Dp_DRL for the chosen marker radionuclide present in the mixture.

## 1.1 Calculation of the Internal Dose Component of the Total Dose Parameter

### Inhalation Dose Parameter

The Inhalation Dose Parameter (InhDP_Dp) calculation multiplies the dose coefficient for individual radionuclides per volume of air breathed (InhDC) by a daily-average value for volume of air breathed (BR) and a Resuspension Parameter (KP) to calculate the committed effective dose component from inhaling resuspended radioactivity over the time phase under consideration. The activity-weighted average volume of air breathed is based on the ICRP lung model and considers the breathing rate during different activities (e.g., sleep, heavy activity) and the fraction of time spent each day performing those activities.

$$InhDP\_Dp_{E,i,TP} = InhDC_{E,i} * KP_{i,TP} * BR \qquad \text{(Eq. 2.1-3)}$$

$$\frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}} = \frac{\text{mrem}}{\mu\text{Ci}} * \frac{\text{s}}{\text{m}} * \frac{\text{m}^3}{\text{s}}$$

where:

$InhDP\_Dp_{E,\,i,\,TP}$ = Inhalation Dose Parameter for Deposition, the committed effective dose received by the whole body (*E*), from the inhalation of resuspended radionuclide *i* over the time phase under consideration (*TP*), per unit of areal activity of the radionuclide deposited on the ground, mrem•m$^2$/µCi;

$InhDC_{E,i}$ = Inhalation Dose Coefficient, the committed effective dose coefficient for the whole body (*E*), for radionuclide *i* (values from ICRP 60+ dosimetry models, DCFPAK), mrem/ µCi;

$KP_{i,\,TP}$ = Resuspension Parameter, value that adjusts the airborne radioactivity level of radionuclide *i* over the time phase (*TP*) under consideration for radioactive decay and the time-dependent resuspension factor (*K*) (value obtained numerically from Turbo FRMAC), s/m; and

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

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

## 1.2 Calculation of the External Dose Component of the Total Dose Parameter

### External Dose Parameter

The External Dose Parameter (ExDP_Dp) multiplies the dose rate from groundshine per unit activity deposited on the ground (ExDC_Dp) by a ground roughness factor (GRF) and a Combined Removal Parameter (CRP) to calculate the effective dose from groundshine per unit activity deposited on the ground over the time period under consideration.

$$ExDP\_Dp_{E,i,TP} = ExDC\_Dp_{E,i} * CRP_{i,TP} * GRF \qquad \text{(Eq. 2.1-4)}$$

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

where:

$ExDP\_Dp_{E,\,i,\,TP}$ = External Dose Parameter for Deposition, the groundshine dose received by the whole body (*E*), over the time phase under consideration (*TP*), per unit of areal activity of radionuclide *i* deposited on the ground and adjusted for the ground roughness factor, mrem•m$^2$/µCi;

$ExDC\_Dp_{E,i}$ = External Dose Coefficient for deposition, the effective dose rate to the whole body (*E*) from the external exposure to radionuclide *i* per unit activity deposited on the ground(values from DCFPAK using ICRP 60+ dosimetry models), mrem•m$^2$/ µCi•s;

$CRP_{i,TP}$ = Combined Removal Parameter, value that adjusts for radioactive decay and weathering effects that decrease the amount of radionuclide i available to cause direct exposure or to be ingested over the time phase (*TP*) under consideration, s; and

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

*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.

## 1.3 Combining Internal and External Components of the Total Dose Parameter

### Total Dose Parameter

The Total Dose Parameter (TDP_Dp) is the sum of the external dose from groundshine (ExDP_Dp) and the internal (committed effective) dose from inhalation of resuspended material (InhDP_Dp) received per unit of radioactivity of radionuclide *i* deposited on the ground over the time phase under consideration.

$$TDP\_Dp_{E,i,TP} = InhDP\_Dp_{E,TP,i} + ExDP\_Dp_{E,i,TP} \qquad \text{(Eq. 2.1-5)}$$

$$\frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}} = \frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}} + \frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}}$$

where:

$TDP\_Dp_{E,i,TP}$ = Total Dose Parameter for Deposition, the sum of the external dose from groundshine and the internal (committed effective) dose from inhalation of resuspended material received, by the whole body (*E*), over the time phase under consideration (*TP*), per unit of areal activity of radionuclide *i* deposited on the ground, mrem•m$^2$/µCi;

$InhDP\_Dp_{E,i,TP}$ = Inhalation Dose Parameter for Deposition, the committed effective dose received by the whole body (*E*), from the inhalation of resuspended radionuclide *i* over the time phase under consideration (*TP*), per unit of areal activity of the radionuclide deposited on the ground, mrem•m$^2$/µCi; and

$ExDP\_Dp_{E,i,TP}$ = External Dose Parameter for Deposition, the groundshine dose received by the whole body (*E*), over the time phase under consideration (*TP*), per unit of areal activity of radionuclide *i* deposited on the ground and adjusted for the ground roughness factor, mrem•m$^2$/µCi.

## 1.4 Calculating the Total Dose Parameter for the Mixture

**NOTE:** See the default assumptions for daughter radionuclide inclusion rules.

**Mixture Total Dose Parameter for Deposition (MTDP_Dp)**

This quantity, based on all the radionuclides in the mixture, is obtained by multiplying the areal activity for each radionuclide by the associated TDPs and then summing those products for the entire mixture.

$$MTDP\_Dp_{E,TP} = \sum_i \left( Dp_i * TDP\_Dp_{E,\,i,TP} \right) \qquad \text{(Eq. 2.1-6)}$$

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

where:

$MTDP\_Dp_{E\ TP}$ = Mixture Total Dose Parameter for Deposition, the sum of the external dose from groundshine and the internal dose from inhalation of resuspended material received by the whole body (*E*), over the time phase under consideration (*TP*), from the areal activity level of the mixture, mrem;

$Dp_i$ = Deposition, the areal activity of radionuclide *i*, μCi/m$^2$; and

$TDP\_Dp_{E,\,i,\,TP}$ = Total Dose Parameter for Deposition, the sum of the external dose from groundshine and the internal (committed effective) dose from inhalation of resuspended material received, by the whole body (*E*), over the time phase under consideration (*TP*), per unit of areal activity of radionuclide *i* deposited on the ground, mrem•m$^2$/μCi.

## 1.5 Comparing the MTDP_Dp to the PAG

Once the MTDP_Dp has been calculated, it can be used to determine the Dp_DRL by comparing it to the product of the PAG and the areal activity for the chosen marker radionuclide using the following equation.

$$Dp\_DRL_{E,i(m),t_n} = \frac{PAG_{E,TP} * Dp_{i(m)} * e^{-\lambda_{i(m)} t_n} * WF_{t_n}}{MTDP\_Dp_{E,TP}} \qquad \text{(Eq. 2.1-7)}$$

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

where:

$Dp\_DRL_{E,\,i(m),\,tn}$ = Deposition Derived Response Level, the areal activity at time $t_n$ of a marker radionuclide *i(m)*, at which the dose to the whole body (*E*) from all radionuclides in a deposition mixture would result in a dose equal to the PAG for the time phase under consideration, µCi/m$^2$;
**NOTE:** The default value for $t_n$ is the start of the time phase under consideration ($t_1$), but it may be set to any time (before, during, or after the time phase). If this calculation is being performed for multiple time phases, $t_n$ is usually set to the start of the Early Phase for all calculations to allow for comparison of results.

$Dp_{i(m)}$ = Deposition, the areal activity of a marker radionuclide *i(m)* per unit area of ground at $t_0$ (deposition), µCi/m$^2$;

$PAG_{E,\,TP}$ = Protective Action Guide, as specified by the EPA or local authorities, for the whole body (*E*), for the time phase (*TP*) under consideration, mrem;

$\lambda_{i(m)}$ = Decay constant for the marker radionuclide, s$^{-1}$;

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

$e^{-\lambda tn}$ = Radioactive Decay adjustment for radionuclide *i* from $t_0$ (deposition) to $t_n$ (time of measurement, prediction, or evaluation), unitless;

$WF_{tn}$ = Weathering adjustment from $t_0$ (deposition) to $t_n$ (time of measurement, prediction or evaluation), unitless; and
**NOTE:** See Appendix F, Supplement 2 for details on calculating WF.

$MTDP\_Dp_{E\ TP}$ = Mixture Total Dose Parameter for Deposition, the sum of the external dose from groundshine and the internal dose from inhalation of resuspended material received by the whole body (E), over the time phase under consideration (TP), from the areal activity level of the mixture, mrem.

**NOTE:** This equation is identical to Eq. 2.1-1.

# EXAMPLE 1

**Problem: Calculate Deposition DRL for First-Year Time Phase for the Following Mixture (deposited at t=0).**

**Table 2.1-E1**

| Radionuclide | Deposition (µCi/m$^2$) | $t_{1/2}$ |
|---|---|---|
| $^{241}$Am | 4.15E-02 | 432 yr |
| $^{60}$Co | 2.74E+04 | 5.27 yr |
| $^{90}$Sr | 9.25E+04 | 29.1 yr |

To determine the Dp_DRL, the intermediate terms for the Inhalation (InhDP_Dp), External (ExDP_Dp), and Total (TDP_Dp) Dose Parameters must first be calculated for each radionuclide and then combined with the areal activity (Deposition or $Dp_i$, for each radionuclide) into the Mixture Total Dose Parameter (MTDP_Dp).

Using the daughter inclusion rules from the Assumptions section above yields the following adjusted radionuclide mixture:

**Table 2.1-E2**

| Radionuclide | Deposition (µCi/m$^2$) | $t_{1/2}$ |
|---|---|---|
| $^{241}$Am | 4.15E-02 | 432 yr |
| $^{60}$Co | 2.74E+04 | 5.27 yr |
| $^{90}$Sr | 9.25E+04 | 29.1 yr |
| $^{90}$Y | 9.25E+04 | 7.3E-03 yr |

**NOTE:** Because the $t_{1/2}$ of the first $^{241}$Am daughter ($^{237}$Np) is both longer than the $t_{1/2}$ of the parent and longer than 1.5 years, $^{237}$Np and all subsequent daughters are not in equilibrium and thus are not included in the Dp_DRL calculation.

## E1.1 Calculating InhDP_Dp (Equation 2.1-3)

This calculation requires the Inhalation Dose Coefficient (InhDC), the Breathing Rate (BR) and the Resuspension Parameter (KP).

### E1.1.1 Calculating the Resuspension Parameter (See Appendix F, Supplement 2)

**NOTE:** The integral does not have an exact solution if K (the Resuspension Factor) is in the time-varying form presented above and thus cannot be solved analytically. A program capable of numerical integration, such as Turbo FRMAC, must be used to solve the integral.

**Table 2.1-E3**

| Radionuclide | $\lambda_i$ ($s^{-1}$) | $t_1$ (s) | $t_2$ (s) | $KP_i$ – First Year [a] (s/m) |
|---|---|---|---|---|
| $^{241}Am$ | 5.08E-11 | 0 | 3.16E+07 | 0.596 |
| $^{60}Co$ | 4.17E-09 | 0 | 3.16E+07 | 0.585 |
| $^{90}Sr$ | 7.54E-10 | 0 | 3.16E+07 | 0.594 |
| $^{90}Y$ | 7.54E-10 [b] | 0 | 3.16E+07 | 0.594 |

[a] Value from Turbo FRMAC 2.1.
[b] Because the daughter is in equilibrium with the parent, the λ for the parent is used.

### E1.1.2 Calculating the InhDP_Dp Using Equation 2.1-3

Example InhDP_Dp calculation for $^{241}$Am and InhDP_Dp values for the radionuclide mixture for the first-year time phase.

$$InhDP\_Dp_{^{241}Am} = 3.57\text{E+}05\,\frac{\text{mrem}}{\mu\text{Ci}} * 0.596\,\frac{\text{s}}{\text{m}} * 2.56\text{E-}04\,\frac{\text{m}^3}{\text{s}} = 54.6\,\frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}}$$

**Table 2.1.E4**

| Radionuclide | InhDC[a] (mrem/ μCi) | $KP_i$ for First Year[b] (s/m) | Breathing Rate ($m^3$/s) | InhDP_Dp First Year (mrem • $m^2$/μCi) |
|---|---|---|---|---|
| $^{241}Am$ | 3.57E+05 | 0.596 | 2.56E-04 | 54.6 |
| $^{60}Co$ | 1.14E+02 | 0.585 | 2.56E-04 | 1.74E-02 |
| $^{90}Sr$ | 5.81E+02 | 0.594 | 2.56E-04 | 8.88E-02 |
| $^{90}Y$ | 5.55E+00 | 0.594 | 2.56E-04 | 8.52E-04 |

[a] Value from DCFPAK 1.6 Update 1 (ICRP 60+) for 1 micron particles. If particle size is known to be other than 1 micron, choose appropriate value.
[b] Value from Turbo FRMAC 2.1.

## E1.2 Calculating ExDP_Dp (Equation 2.1-4)

This calculation requires the External Dose Coefficient (ExDC), the Combined Removal Parameter (CRP) and the Ground Roughness Factor (GRF).

### E1.2.1 Calculating the Combined Removal Parameter (See Appendix F, Supplement 2)

**Table 2.1-E5**

| Radionuclide | $\lambda_i$ ($s^{-1}$) | $t_1$ (s) | $t_2$ (s) | CRP – First Year (s) |
|---|---|---|---|---|
| $^{241}$Am | 5.08E-11 | 0 | 3.16E+07 | 2.89E+07 |
| $^{60}$Co | 4.17E-09 | 0 | 3.16E+07 | 2.71E+07 |
| $^{90}$Sr | 7.54E-10 | 0 | 3.16E+07 | 2.86E+07 |
| $^{90}$Y | 7.54E-10 [a] | 0 | 3.16E+07 | 2.86E+07 |

[a] Because the daughter is in equilibrium with the parent, the λ for the parent is used.

### E1.2.2 Calculating the ExDP_Dp Using Equation 2.1-4

Example ExDP_Dp calculation for $^{241}$Am and ExDP_Dp values for the radionuclide mixture for the first-year time phase.

$$ExDP\_Dp_{^{241}Am} = 8.62\text{E-}08 \frac{\text{mrem} \cdot \text{m}^2}{\text{s} \cdot \mu\text{Ci}} * 2.89\text{E+}07\text{s} * 0.82 = 2.04 \frac{\text{mrem} \cdot \text{m}^2}{\mu\text{Ci}}$$

**Table 2.1-E6**

| Radionuclide | ExDC_Dp [a] (mrem • m$^2$/s • µCi) | CRP for First Year (s) | GRF (unitless) | ExDP_Dp First Year (mrem • m$^2$/µCi) |
|---|---|---|---|---|
| $^{241}$Am | 8.62E-08 | 2.89E+07 | 0.82 | 2.04 |
| $^{60}$Co | 8.51E-06 | 2.71E+07 | 0.82 | 1.89E+02 |
| $^{90}$Sr | 6.07E-09 | 2.86E+07 | 0.82 | 1.42E-01 |
| $^{90}$Y | 4.07E-07 | 2.86E+07 | 0.82 | 9.55 |

[a] Values from DCFPAK 1.6 Update 1 (ICRP 60+).

## E1.3 Calculating TDP_Dp (Equation 2.1-5)

Example TDP_Dp calculation for $^{241}$Am and TDP_Dp values for the radionuclide mixture for the first-year time phase.

$$TDP\_Dp_{^{241}Am} = 54.6 \frac{\text{mrem} \cdot \text{m}^2}{\mu\text{Ci}} + 2.04 \frac{\text{mrem} \cdot \text{m}^2}{\mu\text{Ci}} = 56.64 \frac{\text{mrem} \cdot \text{m}^2}{\mu\text{Ci}}$$

**Table 2.1-E7**

| Radionuclide | InhDP_Dp First Year (mrem • m²/μCi) | ExDP_Dp First Year (mrem • m²/μCi) | TDP_Dp First Year (mrem • m²/μCi) |
|---|---|---|---|
| $^{241}$Am | 54.6 | 2.04 | 56.64 |
| $^{60}$Co | 1.74E-02 | 1.89E+02 | 1.89E+02 |
| $^{90}$Sr | 8.88E-02 | 1.42E-01 | 2.31E-01 |
| $^{90}$Y | 8.52E-04 | 9.55 | 9.55 |

# E1.4 Calculating MTDP_Dp (Equation 2.1-6)

This calculation multiplies the TDP_Dp by the areal activity ($Dp_i$) for each radionuclide in the mixture and sums these products.

**Table 2.1-E8**

| Radionuclide | $Dp_i$ (μCi/m²) | TDP_Dp – First Year (mrem • m²/μCi) | $Dp_i$ • TDP_Dp – First Year (mrem) |
|---|---|---|---|
| $^{241}$Am | 4.15E-02 | 56.64 | 2.35 |
| $^{60}$Co | 2.74E+04 | 1.89E+02 | 5.18E+06 |
| $^{90}$Sr | 9.25E+04 | 2.31E-01 | 2.14E+04 |
| $^{90}$Y | 9.25E+04 | 9.55 | 8.83E+05 |
| | | MTDP_Dp (∑) | 6.08E+06 |

# E1.5 Calculating Dp_DRL (Equation 2.1-1 or 2.1-7)

Example Dp_DRL calculation for $^{60}$Co (marker) and Dp_DRL values for the radionuclide mixture for the first-year time phase.

PAG = 2000 mrem
MTDP_Dp = 6.08E+06 mrem

$$Dp\_DRL_{^{60}Co} = \frac{2000\,\text{mrem} * 2.74\text{E+04}\,\frac{\mu\text{Ci}}{\text{m}^2} * 1 * 1}{6.08\text{E+06 mrem}} = 9.01\,\frac{\mu\text{Ci}}{\text{m}^2}$$

**Table 2.1-E9**

| Radionuclide | $Dp_i$ ($\mu Ci/m^2$) | $e^{-\lambda tn}$ | $WF_{tn}$ | 1st Year Dp_DRL [a] ($\mu Ci/m^2$) |
|---|---|---|---|---|
| $^{241}Am$ | 4.15E-02 | 1 | 1 | 1.36E-05 |
| $^{60}Co$ | 2.74E+04 | 1 | 1 | 9.01 |
| $^{90}Sr$ | 9.25E+04 | 1 | 1 | 30.4 |
| $^{90}Y$ | 9.25E+04 | 1 | 1 | 30.4 |

[a] Because the first year time phase starts at $t_0$ (deposition), there is no adjustment for radioactive decay or weathering.

# E1.6 Calculating a Dp_DRL 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 a Dp_DRL for a specific organ, three changes from the default method must be made. The Inhalation Dose Coefficient (InhDC) and External Dose Coefficient (ExDC) must be changed to that of the organ in question and then used to calculate an MTDP_Dp for that organ to be compared to an organ-specific PAG. To demonstrate this calculation the same radionuclide mixture used in the whole-body calculations will be used with the skin chosen as the organ of interest.

**NOTE:** Shaded areas in the tables below indicate the values that differ from the whole-body example demonstrated previously.

Organ of Interest: Skin
PAG: 50 rem

**Table 2.1-E4** would become **Table 2.1-E4a**

| Radionuclide | InhDC[a] (mrem/μCi) | $KP_i$ for First Year[b] (s/m) | Breathing Rate ($m^3/s$) | InhDP_Dp – First Year (mrem • $m^2$/μCi) |
|---|---|---|---|---|
| $^{241}Am$ | 2.74E+04 | 0.596 | 2.56E-04 | 4.20 |
| $^{60}Co$ | 2.05E+01 | 0.585 | 2.56E-04 | 3.08E-03 |
| $^{90}Sr$ | 2.20E+00 | 0.594 | 2.56E-04 | 3.36E-04 |
| $^{90}Y$ | 1.21E-01 | 0.594 | 2.56E-04 | 1.85E-05 |

[a] Organ of interest is skin, values from DCFPAK 1.6 Update 1 (ICRP 60+).
[b] Value from Turbo FRMAC 2.1.

**Table 2.1-E6** would become **Table 2.1-E6a**:

| Radionuclide | ExDC_Dp [a] (mrem • $m^2$/s • µCi) | CRP for First Year (s) | GRF (unitless) | ExDP_Dp First Year (mrem • $m^2$/µCi) |
|---|---|---|---|---|
| $^{241}$Am | 3.08E-07 | 2.89E+07 | 0.82 | 7.30 |
| $^{60}$Co | 1.02E-05 | 2.71E+07 | 0.82 | 227 |
| $^{90}$Sr | 5.18E-07 | 2.86E+07 | 0.82 | 12.1 |
| $^{90}$Y | 3.89E-05 | 2.86E+07 | 0.82 | 911 |

[a] Organ of interest is skin, values from DCFPAK 1.6 Update 1 (ICRP 60+).

Adding the InhDP_Dp and ExDP_Dp yields the TDP_Dp, thus

**Table 2.1-E7** would become **Table 2.1-E7a:**

| Radionuclide | InhDP_Dp – First Year (mrem • $m^2$/µCi) | ExDP_Dp – First Year (mrem • $m^2$/µCi) | TDP_Dp – First Year (mrem • $m^2$/µCi) |
|---|---|---|---|
| $^{241}$Am | 4.20 | 7.30 | 11.5 |
| $^{60}$Co | 3.08E-03 | 227 | 227 |
| $^{90}$Sr | 3.36E-04 | 12.1 | 12.1 |
| $^{90}$Y | 1.85E-05 | 911 | 911 |

Multiplying by the areal activity ($Dp_i$) and summing yields the MTDP_Dp.

**Table 2.1-E8** would become **Table 2.1-E8a:**

| Radionuclide | $Dp_i$ (µCi/$m^2$) | TDP_Dp – First Year (mrem • $m^2$/µCi) | $Dp_i$ • TDP_Dp – First Year (mrem) |
|---|---|---|---|
| $^{241}$Am | 4.15E-02 | 11.5 | 4.77E-01 |
| $^{60}$Co | 2.74E+04 | 227 | 6.22E+06 |
| $^{90}$Sr | 9.25E+04 | 12.1 | 1.12E+06 |
| $^{90}$Y | 9.25E+04 | 911 | 8.43E+07 |
| | | MTDP_Dp (∑) | 9.16E+07 |

Finally, to calculate the Dp_DRL for $^{60}$Co (marker) for the first-year time phase:

$PAG_{(skin)}$ = 50,000 mrem
$MTDP\_Dp_{(skin)}$ = 9.16E+07 mrem

$$Dp\_DRL_{Skin,60_{Co}} = \frac{50{,}000\,\text{mrem} * 2.74\text{E+04}\,\frac{\mu\text{Ci}}{\text{m}^2} * 1 * 1}{9.16\text{E+07 mrem}} = 15.0\ \frac{\mu\text{Ci}}{\text{m}^2}$$

**Table 2.1-E9** would become **Table 2.1-E9a**:

| Radionuclide | $Dp_i$ ($\mu$Ci/m$^2$) | $e^{-\lambda tn}$ | $WF_{tn}$ | Dp_DRL – First Year [a] ($\mu$Ci/m$^2$) |
|---|---|---|---|---|
| $^{241}$Am | 4.15E-02 | 1 | 1 | 2.27E-05 |
| $^{60}$Co | 2.74E+04 | 1 | 1 | 15.0 |
| $^{90}$Sr | 9.25E+04 | 1 | 1 | 50.5 |
| $^{90}$Y | 9.25E+04 | 1 | 1 | 50.5 |

[a] Because the first year time phase starts at $t_0$ (deposition) there is no adjustment for radioactive decay or weathering.

# E1.7 Comparison of Deposition Derived Response Levels (Effective [2 rem] vs. Skin [50 rem])

The following table identifies and compares the intermediate values for the whole body and organ-based Dp_DRL calculations (based on a first-year time phase).

**Table 2.1-E10**

| Radionuclide | | $^{241}$Am | $^{60}$Co | $^{90}$Sr | $^{90}$Y |
|---|---|---|---|---|---|
| $Dp_i$ ($\mu$Ci/m$^2$) | | **4.15E-02** | **2.74E+04** | **9.25E+04** | **9.25E+04** |
| InhDP_Dp (mrem•m$^2$/µCi) | Effective | 54.6 | 1.74E-02 | 8.88E-02 | 8.52E-04 |
| | Skin | 4.20 | 3.08E-03 | 3.36E-04 | 1.85E-05 |
| ExDP_Dp (mrem•m$^2$/µCi) | Effective | 2.04 | 1.89E+02 | 1.42E-01 | 9.55 |
| | Skin | 7.30 | 2.27E+02 | 12.1 | 9.11E+02 |
| TDP_Dp (mrem•m$^2$/µCi) | Effective | 56.64 | 1.89E+02 | 2.31E-01 | 9.55 |
| | Skin | 11.5 | 2.27E+02 | 12.1 | 9.11E+02 |
| MTDP_Dp (mrem) | Effective | 6.08E+06 | | | |
| | Skin | 9.16E+07 | | | |
| Dp_DRL (µCi/m$^2$) | Effective | 1.36E-05 | 9.01 | 30.4 | 30.4 |
| | Skin | 2.27E-05 | 15.0 | 50.5 | 50.5 |

# METHOD 2.2 DEPOSITION DOSE AND EXPOSURE RATE DERIVED RESPONSE LEVELS

## Application

This method has been developed to calculate a Deposition Dose Rate Derived Response Level ($Dp\_DRL_{DR}$) and Deposition Exposure Rate Derived Response Level ($Dp\_DRL_{XR}$) for a deposition of radioactive material.

The $Dp\_DRL_{DR}$:

- Represents the dose rate (mrem/hr, measured at 1 m above the ground) at a given time ($t_n$), from all radionuclides in a deposition mixture that will be expected to produce a dose equal to the appropriate Protective Action Guide (PAG) over the time phase under consideration.

The $Dp\_DRL_{XR}$:

- Represents the exposure rate (mR/hr, measured at 1 m above the ground) at a given time ($t_n$), from all radionuclides in a deposition mixture that will be expected to produce a dose equal to the appropriate Protective Action Guide (PAG) over the time phase under consideration.

Both the $Dp\_DRL_{DR}$ and the $Dp\_DRL_{XR}$ are:

- 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 rate value greater than the DRL indicates that the PAG has the potential to be exceeded.
- Used to create data products and define dose and/or exposure rates to assist decision makers in determining where implementing protective actions (e.g., sheltering, evacuation, relocation) may be advisable.
- Calculated using the Mixture Total Dose Parameter for Deposition (MTDP_Dp) value calculated in Method 2.1.

## Discussion

These DRLs relate a measured dose (or exposure) rate to the total of the external dose from material deposited on the ground (i.e., groundshine) and the dose from the inhalation of resuspended material.

These DRLs combine an External Dose Factor (ExDF) with the deposition (areal activity) values for each radionuclide present in a mixture and relates that product (MExDF_Dp) to the PAG for the time phase under consideration and the Mixture Total Dose Parameter for Deposition (MTDP_Dp – calculated in Method 2.1) to calculate the $Dp\_DRL_{DR}$. The $Dp\_DRL_{XR}$ is then obtained by dividing the $Dp\_DRL_{DR}$ by an Exposure to Dose Conversion Factor (XDCF).

These DRLs are based on the ratio of activities of each radionuclide in a mixture, not the individual activity values of those radionuclides.

## 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:

> Mixture Total Dose Parameter for Deposition (MTDP_Dp) – Calculated using Method 2.1.

If incident-specific values have not been established, recommended default values for selected inputs are available in Appendix C.

## Outputs

The final output of this method is the $Dp\_DRL_{DR}$ or $Dp\_DRL_{XR}$ for a deposition of radioactive material.

### Final

$Dp\_DRL_{DR}$ = Deposition Dose Rate Derived Response Level, the external dose rate, at time $t_n$, at which the dose from all radionuclides in a deposition mixture would result in a dose equal to the PAG for the time phase under consideration, mrem/hr

$Dp\_DRL_{XR}$ = Deposition Exposure Rate Derived Response Level, the external exposure rate, at time $t_n$, at which the dose from all radionuclides in a deposition mixture would result in a dose equal to the PAG for the time phase under consideration, mR/hr

**Intermediate**

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

ExDF_Dp = External Dose Factor for deposition for each radionuclide in the mixture of interest (mrem/hr per µCi/$m^2$)
MExDF_Dp = Mixture External Dose Factor for all radionuclides in the mixture of interest (mR/hr)

# Method 2.2.1 Deposition Dose Rate Derived Response Level ($Dp\_DRL_{DR}$)

# Calculation

The $Dp\_DRL_{DR}$ is a value that is used to relate a dose rate measurement from a survey instrument to the hazard posed by the deposition of a mixture of radioactive materials over the time phase under consideration relative to the regulatory PAG.

Calculating the $Dp\_DRL_{DR}$ 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, to complete these calculations.

Equation 2.2-1 represents the final form of the $Dp\_DRL_{DR}$ calculation.

$$Dp\_DRL_{DR,E,t_n} = PAG_{E,TP} * \frac{MExDF\_Dp_{E,t_n}}{MTDP\_Dp_{E,TP}} \quad \text{(Eq. 2.2-1)}$$

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

where:

$Dp\_DRL_{DR,\,E,\,tn}$ = Deposition Dose Rate Derived Response Level, the external dose rate at time $t_n$ at which the dose from all radionuclides in a deposition mixture would result in a dose to the whole body ($E$) equal to the PAG for the time phase under consideration, mrem/hr; **NOTE:** The default value for $t_n$ is the start of the time phase under consideration ($t_1$), but it may be set to any time (before, during, or after the time phase). If this calculation is being performed for multiple time phases, $t_n$ is usually set to the start of the Early Phase for all calculations to allow for comparison of results.

$PAG_{E,TP}$ = Protective Action Guide, as specified by the EPA or local authorities, for the whole body (*E*), for the time phase (*TP*) under consideration, mrem;

$MExDF\_Dp_{E,tn}$ = Mixture External Dose Factor for Deposition, the external dose rate received by the whole body (*E*) at time $t_n$, from a radionuclide mixture deposited on the ground, mrem/hr; and

$MTDP\_Dp_{E,TP}$ = Mixture Total Dose Parameter for Deposition (See Method 2.1), mrem.

Equation 2.2-2 represents the full equation, showing all inputs used to calculate the MExDF_Dp from the base level without combining any terms:

$$Dp\_DRL_{DR,t_n} = PAG * WF_{t_n} * \frac{\sum_i \left\{ \left( Dp_i * e^{-\lambda_i t_n} \right) * \left( ExDC\_Dp_i * GRF \right) \right\}}{MTDP\_Dp} \quad \text{(Eq. 2.2-2)}$$

**NOTE:** Because the dose from inhalation of resuspended material is included in the MTDP_Dp term calculated in Method 2.1, there is no need to consider inhalation as a separate part of this method.

The following sections provide step-by-step instructions for the manual calculation of an $Dp\_DRL_{DR}$, beginning with determining the ExDF for each radionuclide, then finding a MExDF_Dp for the mixture, and finally calculating the $Dp\_DRL_{DR}$ for the mixture.

## Calculating the External Dose Factor

The External Dose Factor (ExDF) calculation multiplies a radionuclide-specific External Dose Coefficient (ExDC) by a Ground Roughness Factor (*GRF*) to calculate the effective dose from groundshine per unit of activity of that radionuclide deposited on the ground.

$$ExDF\_DP_{E,i} = ExDC\_Dp_{E,i} * GRF \quad \text{(Eq. 2.2-3)}$$

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

where:

$ExDF\_Dp_{E,i}$ = External Dose Factor for deposition, the external dose rate to the whole body (*E*) per unit activity deposited on the ground from radionuclide *i* and adjusted for the ground roughness factor, mrem•m$^2$/ hr•µCi;

$ExDC\_Dp_{E,i}$ = External Dose Coefficient for deposition, the effective dose rate to the whole body (*E*) from the external exposure to radionuclide *i* per unit activity deposited on the ground (values from DCFPAK using ICRP 60+ dosimetry models), mrem•m$^2$/hr•µCi;

*GRF* = Ground Roughness Factor, a unitless constant (0.82) that compensates for the fact that the external exposure is not coming from an infinite flat plane (AN02);

## Calculating the Mixture External Dose Factor

The Mixture External Dose Factor (MExDF_Dp) for a given time ($t_n$) based on all the radionuclides in the mixture, is obtained by multiplying the time-adjusted areal activity for each radionuclide by the associated External Dose Factor (ExDF) and then summing those products for the entire mixture.

$$MExDF\_Dp_{E,t_n} = WF_{t_n} * \sum_i \left( Dp_i * e^{-\lambda_i t_n} * ExDF\_Dp_{E,i} \right) \quad \text{(Eq. 2.2-4)}$$

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

where:

$MExDF\_Dp_{E,tn}$ = Mixture External Dose Factor for Deposition, the external dose rate received by the whole body ($E$) at time $t_n$, from a radionuclide mixture deposited on the ground, mR/hr;
**NOTE:** The default value for $t_n$ is the start of the time phase under consideration ($t_1$), but it may be set to any time (before, during, or after the time phase). If this calculation is being performed for multiple time phases, $t_n$ is usually set to the start of the Early Phase for all calculations to allow for comparison of results.

$Dp_i$ = Deposition, the areal activity of radionuclide $i$, µCi/m$^2$;

$\lambda_i$ = Decay constant for radionuclide $i$, s$^{-1}$;

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

$e^{-\lambda tn}$ = Radioactive Decay adjustment for radionuclide $i$ from $t_0$ (deposition) to $t_n$ (time of measurement, prediction, or evaluation), unitless;

$WF_{tn}$ = Weathering adjustment from $t_0$ (deposition) to $t_n$ (time of measurement, prediction, or evaluation), unitless; and
**NOTE:** See Appendix F, Supplement 2 for details on calculating WF.

$ExDF\_Dp_{E,i}$ = External Dose Factor for deposition, the external dose rate to the whole body ($E$) per unit activity deposited on the ground from radionuclide $i$ and adjusted for the ground roughness factor, mrem•m$^2$/ hr•µCi.

## Comparing the MExDF_Dp to the PAG

Once the MExDF_Dp for the mixture has been calculated for a specific time, it can be used to determine the $Dp\_DRL_{DR}$ by comparing it to the PAG and the Mixture Total Dose Parameter (MTDP_Dp from Method 2.1) value using the following equation.

$$Dp\_DRL_{DR,E,t_n} = PAG_{E,TP} * \frac{MExDF\_Dp_{E,t_n}}{MTDP\_Dp_{E,TP}} \quad \text{(Eq. 2.2-5)}$$

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

where:

$Dp\_DRL_{DR,E,t_n}$ = Deposition Dose Rate Derived Response Level, the external dose rate, at time $t_n$, at which the dose from all radionuclides in a deposition mixture would result in a dose to the whole body ($E$) equal to the PAG for the time phase under consideration, mrem/hr; **NOTE:** The default value for $t_n$ is the start of the time phase under consideration ($t_1$), but it may be set to any time (before, during, or after the time phase). If this calculation is being performed for multiple time phases, $t_n$ is usually set to the start of the Early Phase for all calculations to allow for comparison of results.

$PAG_{E,TP}$ = Protective Action Guide, as specified by the EPA or local authorities, for the whole body ($E$), for the time phase ($TP$) under consideration, mrem;

$MExDF\_Dp_{E,tn}$ = Mixture External Dose Factor for Deposition, the external dose rate received by the whole body ($E$) at time $t_n$ from a radionuclide mixture deposited on the ground, mrem/hr; and

$MTDP\_Dp_{E,TP}$ = Mixture Total Dose Parameter for Deposition (See Method 2.1), mrem.

**NOTE:** This equation is identical to Eq. 2.2-1.

## Method 2.2.2 Deposition Exposure Rate Derived Response Level ($Dp\_DRL_{XR}$)

To calculate the Exposure Rate Derived Response Level ($Dp\_DRL_{XR}$), simply divide the $Dp\_DRL_{DR}$ by the Exposure to Dose Conversion Factor (XDCF).

$$Dp\_DRL_{XR,E,t_n} = \frac{Dp\_DRL_{DR,E,t_n}}{XDCF} \qquad \text{(Eq. 2.2-6)}$$

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

# EXAMPLE 1

**Problem: Calculate the Deposition Dose Rate DRL for 1st-Year Time Phase for the Following Mixture (deposited at t=0).**

**Table 2.2-E1**

| Radionuclide | Deposition (µCi/m$^2$) | $t_{1/2}$ |
|---|---|---|
| $^{241}$Am | 4.15E-02 | 432 yr |
| $^{60}$Co | 2.74E+04 | 5.27 yr |
| $^{90}$Sr | 9.25E+04 | 29.1 yr |

To determine the $Dp\_DRL_{DR}$, the intermediate term for the External Dose Factor (ExDF) must first be calculated for each radionuclide and then combined with the areal activity ($Dp_i$) for each radionuclide and the Mixture External Dose Factor (MExDF_Dp).

Using the daughter inclusion rules from the Assumptions section above yields the following adjusted radionuclide mixture:

**Table 2.2-E2**

| Radionuclide | Deposition (µCi/m$^2$) | $t_{1/2}$ |
|---|---|---|
| $^{241}$Am | 4.15E-02 | 432 yr |
| $^{60}$Co | 2.74E+04 | 5.27 yr |
| $^{90}$Sr | 9.25E+04 | 29.1 yr |
| $^{90}$Y | 9.25E+04 | 7.3E-03 yr |

**NOTE:** Because the $t_{1/2}$ of the first $^{241}$Am daughter ($^{237}$Np) is both longer than the $t_{1/2}$ of the parent and longer than 1.5 years, $^{237}$Np and all subsequent daughters are not in equilibrium and thus are not included in the $Dp\_DRL_{DR}$ calculation.

## E1.1 Calculating ExDF_Dp (Equation 2.2-3)

This calculation requires the External Dose Coefficient (ExDC_Dp) and the Ground Roughness Factor (GRF).

Example ExDF_Dp calculation for $^{241}$Am and ExDF_Dp values for the radionuclide mixture for the first-year time phase.

$$ExDF_{^{241}Am} = 3.10\text{E-}04 \frac{\text{mrem}\cdot\text{m}^2}{\text{hr}\cdot\mu\text{Ci}} * 0.82 = 2.54\text{E-}04 \frac{\text{mrem}\cdot\text{m}^2}{\text{hr}\cdot\mu\text{Ci}}$$

**Table 2.2-E3**

| Radionuclide | ExDC_Dp [a] (mrem•m$^2$) per (hr•µCi) | GRF (unitless) | ExDF_Dp (mrem•m$^2$) per (hr•µCi) |
|---|---|---|---|
| $^{241}$Am | 3.10E-04 | 0.82 | 2.54E-04 |
| $^{60}$Co | 3.06E-02 | 0.82 | 2.51E-02 |
| $^{90}$Sr | 2.18E-05 | 0.82 | 1.79E-05 |
| $^{90}$Y | 1.46E-03 | 0.82 | 1.20E-03 |
| [a] Values from DCFPAK 1.6 Update 1 (ICRP 60+). | | | |

## E1.2 Calculating MExDF_Dp (Equation 2.2-4)

This calculation multiplies the ExDF by the time-adjusted areal activity ($Dp_i$) for each radionuclide in the mixture and sums these products.

**Table 2.2-E4**

| Radionuclide | $Dp_i$ (µCi/m$^2$) | $e^{-\lambda tn}$ | $WF_{tn}$ | ExDF_Dp (mrem•m$^2$) per (hr•µCi) | $Dp_i$ • ExDF_Dp (mrem/hr) |
|---|---|---|---|---|---|
| $^{241}$Am | 4.15E-02 | 1 | 1 | 2.54E-04 | 1.05E-05 |
| $^{60}$Co | 2.74E+04 | 1 | 1 | 2.51E-02 | 688 |
| $^{90}$Sr | 9.25E+04 | 1 | 1 | 1.79E-05 | 1.66 |
| $^{90}$Y | 9.25E+04 | 1 | 1 | 1.20E-03 | 111 |
| | | | | MExDF_Dp | 801 |
| Because the first-year time phase starts at $t_0$ (deposition), there is no adjustment for radioactive decay or weathering. | | | | | |

## E1.3 Calculating $Dp\_DRL_{DR}$ (Equation 2.2-1 or 2.2-5)

$Dp\_DRL_{DR}$ calculation for the radionuclide mixture for the first-year time phase.

Organ of Interest: Whole Body
PAG: 2 rem
MTDP_Dp: 6.08E+06 mrem (from Method 2.1)

$$Dp\_DRL_{DR,E} = \frac{2000\,\text{mrem} * 801\,\frac{\text{mrem}}{\text{hr}}}{6.08\text{E}{+}06\ \text{mrem}} = 0.263\ \frac{\text{mrem}}{\text{hr}}$$

## E1.4 Calculating the $Dp\_DRL_{DR}$ 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 $Dp\_DRL_{DR}$ for a specific organ, two changes from the default method must be made. The External Dose Coefficient (ExDC) must be changed to that of the organ in question and then used to calculate a MExDF_Dp for that organ to be compared to an organ-specific PAG. To demonstrate this calculation the same radionuclide mixture used in the whole-body calculations will be used with the skin chosen as the organ of interest. The calculation assumes a first-year time phase.

**NOTE:** Shaded areas indicate the values that differ from the whole-body example demonstrated previously.

Organ of Interest: Skin
PAG: 50 rem
MTDP_Dp: 9.16E+07 mrem (from Method 2.1)

**Table 2.2-E3** would become **Table 2.2-E3a**:

| Radionuclide | ExDC_Dp [a] (mrem•m$^2$) per (hr•µCi) | GRF (unitless) | ExDF_Dp (mrem•m$^2$) per (hr•µCi) |
|---|---|---|---|
| $^{241}$Am | 1.11E-03 | 0.82 | 9.07E-04 |
| $^{60}$Co | 3.67E-02 | 0.82 | 3.01E-02 |
| $^{90}$Sr | 1.86E-03 | 0.82 | 1.53E-03 |
| $^{90}$Y | 1.40E-01 | 0.82 | 1.15E-01 |
| [a] Organ of interest is skin. Values from DCFPAK 1.6 Update 1 (ICRP 60+). | | | |

Multiplying by the areal activity ($Dp_i$) and summing yields the MExDF_Dp; thus:

**Table 2.2-E4** would become **Table 2.2-E4a:**

| Radionuclide | $Dp_i$ (µCi/m$^2$) | ExDF_Dp (mrem•m$^2$) per (hr•µCi) | $Dp_i$ • ExDF_Dp (mrem/hr) |
|---|---|---|---|
| $^{241}$Am | 4.15E-02 | 9.07E-04 | 3.76E-05 |
| $^{60}$Co | 2.74E+04 | 3.01E-02 | 825 |
| $^{90}$Sr | 9.25E+04 | 1.53E-03 | 141 |
| $^{90}$Y | 9.25E+04 | 1.15E-01 | 1.06E+04 |
| | | MExDF_Dp | 1.16E+04 |

Finally, to calculate the $Dp\_DRL_{DR}$ for the mixture for the first-year time phase:

$$Dp\_DRL_{DR,Skin} = \frac{50,000\,\text{mrem} * 1.16\text{E}+04\,\frac{\text{mrem}}{\text{hr}}}{9.16\text{E+07 mrem}} = 6.31\,\frac{\text{mrem}}{\text{hr}}$$

# E1.5 Comparison of Dose Rate Derived Response Levels (Effective [2 rem] vs. Skin [50 rem])

The following table identifies and compares the intermediate values for the whole body and organ-based $Dp\_DRL_{DR}$ calculations, based on a first-year time phase.

**Table 2.2-5**

| **Radionuclide** | | **$^{241}$Am** | **$^{60}$Co** | **$^{90}$Sr** | **$^{90}$Y** |
|---|---|---|---|---|---|
| **$Dp_i$ (µCi / m$^2$)** | | **4.15E-02** | **2.74E+04** | **9.25E+04** | **9.25E+04** |
| *ExDF_Dp* (mrem•m$^2$) per (hr•µCi) | Effective | 2.54E-04 | 2.51E-02 | 1.79E-05 | 1.20E-03 |
| | Skin | 9.07E-04 | 3.01E-02 | 1.53E-03 | 1.15E-01 |
| *MExDF_Dp* (mR/hr) | Effective | 801 | | | |
| | Skin | 1.16E+04 | | | |
| *MTDP_Dp* [a] (mrem) | Effective | 6.08E+06 | | | |
| | Skin | 9.16E+07 | | | |
| *$Dp\_DRL_{DR}$* (mrem/hr) | Effective | 0.263 | | | |
| | Skin | 6.31 | | | |

[a] From Method 2.1.

# METHOD 2.3 DEPOSITION ALPHA DERIVED RESPONSE LEVEL

## Application

This method has been developed to calculate a Deposition Alpha Derived Response Level ($Dp\_DRL_\alpha$) for a deposition of radioactive material.

The $Dp\_DRL_\alpha$:

- Represents the ground concentration, or areal alpha activity (µCi/m$^2$), at a given time ($t_n$) of a mixture of radionuclides that will be expected to cause the mixture to produce a dose equal to the appropriate Protective Action Guide (PAG) over the time phase under consideration.
- 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 deposition value greater than the $Dp\_DRL_\alpha$ indicates that the PAG has the potential to be exceeded.
- Is used to create data products and define areal alpha activity to assist decision makers in determining where it may be advisable to implement protective actions (e.g., sheltering, evacuation, relocation).
- Is calculated using the Deposition Derived Response Level (Dp_DRL) value calculated in Method 2.1.

Because it is difficult to foresee what instruments will be used by monitoring personnel, it 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 α cpm/100 cm$^2$) for a given radionuclide mixture. Rather, the value calculated by this method is an intermediate value and must be adjusted for conditions in the field (e.g., instrument efficiency, surface conditions, and environmental conditions).

The FRMAC Monitoring and Sampling Division is responsible for converting their monitoring and sampling data from cpm/probe area into assessment units (µCi/m$^2$) that can be compared with the values calculated by this method.

## Discussion

The $Dp\_DRL_\alpha$ is a value obtained by multiplying the calculated Dp_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 Dp_DRL for each radionuclide is determined using a regulatory PAG, this summation represents the number of “alpha events” that would indicate the presence of a mixture of radionuclides that would cause an individual to receive a dose equal to the PAG.

Calculating a $Dp\_DRL_{\alpha}$ 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.

Field monitoring instruments can often distinguish between alpha radiation and other forms of radiations (e.g., $\beta^-$) due to the detector's signal-discriminating capabilities. However it can still be difficult to determine the magnitude of the detector's response that is due solely to alpha radiation because of confounding factors, including:

- Crosstalk: Many field monitoring instruments that detect alpha radiation also detect beta radiation and there is some crosstalk between the scalars for the different radiation types. Therefore, in an alpha and beta radiation field, a fraction of the alpha signal will actually be due to beta radiation.
- Gamma Interference: Some types (e.g., scintillation, Geiger-Mueller) of field monitoring instruments that detect alpha radiation also detect gamma radiation and some of these instruments (e.g., Geiger-Mueller) are not able to distinguish between these radiation types. Although the gamma detection efficiency is typically much lower than the alpha detection efficiency, the ability of an alpha detector to reliably quantify only the alpha radiation signal may be significantly compromised in areas with a high gamma radiation component.
- Neutron Interference: Some types (e.g., scintillation) of field monitoring instruments that detect alpha radiation also detect neutron radiation and some of these instruments are not able to distinguish between these radiation types. Therefore the ability of an alpha detector to reliably quantify only the alpha radiation signal may be significantly compromised in areas with a high neutron radiation component.

## 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:

- Deposition Derived Response Level (Dp_DRL) for each radionuclide in the mixture – Calculated using Method 2.1.
- Alpha Yield, the alpha activity per total (nuclear transformation) activity of radionuclide *i*, $\mu Ci_{\alpha}/\mu Ci_{nt}$.

If incident-specific values have not been established, recommended default values for selected inputs are available in Appendix C.

# Outputs

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

### Final

$Dp\_DRL_{\alpha}$ = Deposition Alpha Derived Response Level, the areal alpha activity at time $t_n$ of the mixture at which the dose from all radionuclides in a deposition mixture would result in a dose equal to the PAG for the time phase under consideration, $\mu Ci_{\alpha}/m^2$.

### Intermediate

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

None

# Calculation

The calculation of the $Dp\_DRL_{\alpha}$ determines the areal alpha activity of the mixture at which the dose from all radionuclides in the mixture would result in a dose equal to the PAG for the time phase under consideration.

The FRMAC Assessment Division uses the following method to calculate the $Dp\_DRL_{\alpha}$ values. The FRMAC Monitoring & Sampling Division will compare the sampling and monitoring data to the respective DRL to determine if the PAG for the time phase under consideration has been exceeded.

$$Dp\_DRL_{\alpha,t_n} = \sum_i \left( Dp\_DRL_{i,t_n} * Y_{\alpha,i} \right) \qquad \text{(Eq. 2.3-1)}$$

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

where:

$Dp\_DRL_{\alpha,tn}$ = Deposition Alpha Derived Response Level, the areal alpha activity of the mixture at time $t_n$ (time of measurement, prediction, or evaluation) at which the dose from all radionuclides in a deposition mixture would result in a dose equal to the PAG for the time phase under consideration, $\mu Ci_\alpha/m^2$;

$Dp\_DRL_{i,tn}$ = Deposition Derived Response Level, the areal activity at time $t_n$ of radionuclide *i* at which the dose from all radionuclides in a deposition mixture would equal the PAG for the time phase under consideration, $\mu Ci_{nt}/m^2$; and

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

**NOTE:** The value calculated from this method is in "assessment units" ($\mu Ci/m^2$). This is the value that will be reported to the FRMAC Monitoring and Sampling Division. Monitoring and Sampling personnel are responsible for converting "field units" (e.g., cpm/100 $cm^2$) into $\mu Ci/m^2$ to enable comparison with the calculated DRL to determine whether protective actions may be advisable.

# EXAMPLE 1

**Problem: Calculate Deposition Alpha DRL for the Start of the Early Time Phase for the following mixture (deposited at t=0):**

**Table 2.3-E1**

| Radionuclide | Deposition ($\mu Ci/m^2$) | $t_{1/2}$ (s) |
|---|---|---|
| $^{212}Bi$ | 1.00 | 3.63E+03 |
| $^{137}Cs$ | 1.00 | 9.47E+08 |

Using the daughter inclusion rules from the Assumptions Section above yields the following adjusted radionuclide mixture:

**Table 2.3-E2**

| Radionuclide | Deposition ($\mu Ci/m^2$) Based on Branching Ratio | $t_{1/2}$ (s) |
|---|---|---|
| $^{212}Bi$ | 1.00 | 3.63E+03 |
| $^{212}Po$ | 0.641 | 3.05E-07 [a] |
| $^{208}Tl$ | 0.359 | 1.84E+02 [a] |
| $^{137}Cs$ | 1.00 | 9.47E+08 |
| $^{137m}Ba$ | 0.946 | 1.53E+02 [a] |

[a] Because these daughters are assumed to be in equilibrium, the half life of the parent will be used for the calculations.

## E1.1 Calculating $Dp\_DRL_\alpha$ (Equation 2.3-1):

This calculation requires the Deposition Derived Response Level (Dp_DRL) for each radionuclide from the mixture for the early phase. Table 2.3-E3 shows the values calculated using Method 2.1.

**Table 2.3-E3**

| Radionuclide | $Dp_i$ ($\mu Ci/m^2$) | $e^{-\lambda tn}$ | $WF_{tn}$ | Alpha Yield | Early Phase DRL ($\mu Ci/m^2$) |
|---|---|---|---|---|---|
| $^{212}Bi$ | 1.00 | 1 | 1 | 0.3594 | 1.65E+03 |
| $^{212}Po$ | 0.641 | 1 | 1 | 1 | 1.06E+03 |
| $^{208}Tl$ | 0.359 | 1 | 1 | 0 | 5.94E+02 |
| $^{137}Cs$ | 1.00 | 1 | 1 | 0 | 1.65E+03 |
| $^{137m}Ba$ | 0.946 | 1 | 1 | 0 | 1.56E+03 |

Because the early time phase starts at $t_0$ (deposition) there is no need to adjust for radioactive decay or weathering to determine the Dp_DRL at the start of the time phase.

Applying these values in equation 2.3-1 yields:

$$Dp\_DRL_{\alpha,t_0} = \left(1.65\mathrm{E}+03\frac{\mu\mathrm{Ci}}{\mathrm{m}^2}*0.3594\frac{\mu\mathrm{Ci}_\alpha}{\mu\mathrm{Ci}}\right)+\left(1.06\mathrm{E}+03\frac{\mu\mathrm{Ci}}{\mathrm{m}^2}*1\frac{\mu\mathrm{Ci}_\alpha}{\mu\mathrm{Ci}}\right)$$

$$= 1.65\mathrm{E}{+}03\frac{\mu\mathrm{Ci}_\alpha}{\mathrm{m}^2}$$

**NOTE:** $^{208}$Tl, $^{137}$Cs, and $^{137m}$Ba do not have an alpha decay component and are therefore not included in this calculation.

# METHOD 2.4 DEPOSITION BETA DERIVED RESPONSE LEVEL

## Application

This method has been developed to calculate a Deposition Beta Derived Response Level ($Dp\_DRL_{\beta-}$) for a deposition of radioactive material.

The $Dp\_DRL_{\beta-}$:

- Represents the ground concentration, or areal beta activity (µCi/m$^2$), at a given time ($t_n$) of a mixture of radionuclides that will be expected to cause the mixture to produce a dose equal to the appropriate Protective Action Guide (PAG) over the time phase under consideration.
- 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 deposition value greater than the $Dp\_DRL_{\beta-}$ indicates that the PAG has the potential to be exceeded.
- Is used to create data products and define areal beta activity to assist decision makers in determining where it may be advisable to implement protective actions (e.g., sheltering, evacuation, relocation).
- Is calculated using the Deposition Derived Response Level (Dp_DRL) value calculated in Method 2.1.

Because it is difficult to foresee what instruments will be used by monitoring personnel, it 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 cm$^2$) for a given radionuclide mixture. Rather, the value calculated by this method is an intermediate value and must be adjusted for conditions in the field (e.g., instrument efficiency, surface conditions, and environmental conditions).

The FRMAC Monitoring and Sampling Division is responsible for converting their monitoring and sampling data from cpm/probe area into assessment units (µCi/m$^2$) that can be compared with the values calculated by this method.

## Discussion

The $Dp\_DRL_{\beta-}$ is a value obtained by multiplying the calculated Dp_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 Dp_DRL for each radionuclide is determined using a regulatory PAG, this summation represents the number of “beta events” that would indicate the presence of a mixture of radionuclides that would cause an individual to receive a dose equal to the PAG.

Calculating a $Dp\_DRL_{\beta-}$ 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;

  NOTE: FRMAC Assessment uses a default energy threshold of 70 kev (roughly the stopping power of one layer of Mylar® film) to determine which decays to include. This threshold can be modified in the Turbo FRMAC software package to address different instrument detection capabilities.

- Energy variance: varying maximum energies (and corresponding efficiencies) of beta emissions from different radionuclides;
- Detector characteristics: The mass thickness ($mg/cm^2$) 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.

NOTE: The Turbo FRMAC software package and the associated DCFPAK database include contributions from standard beta decay as well as other modes of decay (e.g., internal conversion electrons) that produce particles that would be interpreted by detectors as "beta decay." Each of these decay modes is included in the $Dp\_DRL_{\beta-}$ calculation for all decays that could be detected by an instrument.

Field monitoring instruments that detect beta radiation are often capable of detecting other forms of ionizing radiation (e.g., gamma radiation), but are unable to distinguish between these different radiation types. Therefore it can be difficult to determine the magnitude of the detector's response that is due solely to beta radiation. Some of the confounding factors include:

- Crosstalk: Many field monitoring instruments that detect beta radiation also detect alpha radiation and there is some crosstalk between the scalars for the different radiation types. Therefore, in an alpha and beta radiation field, a fraction of the beta signal will actually be due to alpha radiation.
- Gamma Interference: Conventional field instruments typically cannot distinguish between beta particles and gamma radiation. Some types (e.g., scintillation) of beta-radiation detectors have higher gamma detection efficiencies than other types (e.g., thin-walled gas-filled). Although the gamma detection efficiency is typically much lower than the beta detection efficiency, the ability of a beta detector to reliably

quantify only the beta radiation signal may be significantly compromised in areas with a high gamma radiation component.

- Neutron Interference: Some types (e.g., scintillation) of field monitoring instruments that detect beta radiation also detect neutron radiation and some of these instruments are not able to distinguish between these radiation types. Therefore, the ability of a beta detector to reliably quantify only the beta radiation signal may be significantly compromised in areas with a high neutron radiation component.
- Many radionuclides that undergo beta decay also emit Auger electrons and fluorescence photons at various energies. These emissions may produce spurious pulses in a typical beta radiation field monitoring instruments.

# 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:

- Deposition Derived Response Level (Dp_DRL) for each radionuclide in the mixture – Calculated using Method 2.1.
- Beta Yield, the beta activity per total (nuclear transformation) activity of radionuclide *i*, $\mu Ci_{\beta}/\mu Ci_{nt}$.

If incident-specific values have not been established, recommended default values for selected inputs are available in Appendix C.

# Outputs

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

### Final

$Dp\_DRL_{\beta-}$ = Deposition Beta Derived Response Level, the areal beta activity at time $t_n$ of the mixture at which the dose from all radionuclides in a deposition mixture would result in a dose equal to the PAG for 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

# Calculation

The calculation of the $Dp\_DRL_{\beta-}$ determines the areal beta activity of the mixture at which the dose from all radionuclides in the mixture would result in a dose equal to the PAG for the time phase under consideration.

The FRMAC Assessment Division uses the following method to calculate the $Dp\_DRL_{\beta-}$ values. The FRMAC Monitoring & Sampling Division will compare the sampling and monitoring data to the respective DRL to determine if the PAG for the time phase under consideration has been exceeded.

$$Dp\_DRL_{\beta-,t_n} = \sum_i \left( Dp\_DRL_{i,t_n} * Y_{\beta^-,i} \right) \qquad \text{(Eq. 2.4-1)}$$

$$\frac{\mu Ci_{\beta^-}}{m^2} = \frac{\mu Ci_{nt}}{m^2} * \frac{\mu Ci_{\beta^-}}{\mu Ci_{nt}}$$

where:

$Dp\_DRL_{\beta-,tn}$ = Deposition Beta Derived Response Level, the areal beta activity of the mixture, at time $t_n$ at which the dose from all radionuclides in a deposition mixture would result in a dose equal to the PAG for the time phase under consideration, $\mu Ci_\beta/m^2$;

$Dp\_DRL_{i,tn}$ = Deposition Derived Response Level, the areal activity, at time $t_n$ of radionuclide *i* at which the dose from all radionuclides in a deposition mixture would equal the PAG for the time phase under consideration, $\mu Ci_{nt}/m^2$; and

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

**NOTE:** The value calculated from this method is in "assessment units" ($\mu Ci/m^2$). This is the value that will be reported to the FRMAC Monitoring and Sampling Division. Monitoring and Sampling personnel are responsible for converting "field units" (e.g., $cpm/100\ cm^2$) into $\mu Ci/m^2$ to enable comparison with the calculated DRL to determine whether protective actions may be advisable.

# EXAMPLE 1

**Problem: Calculate Beta DRL for the Early Time Phase for the following mixture (deposited at t=0).**

**Table 2.4-E1**

| Radionuclide | Deposition ($\mu Ci/m^2$) | $t_{1/2}$ (s) |
|---|---|---|
| $^{212}Bi$ | 1.00 | 3.63E+03 |
| $^{137}Cs$ | 1.00 | 9.47E+08 |

Using the daughter inclusion rules from the Assumptions Section above yields the following adjusted radionuclide mixture:

**Table 2.4-E2**

| Radionuclide | Deposition ($\mu Ci/m^2$) Based on Branching Ratio | $t_{1/2}$ (s) |
|---|---|---|
| $^{212}Bi$ | 1.00 | 3.63E+03 |
| $^{212}Po$ | 0.641 | 3.05E-07 [a] |
| $^{208}Tl$ | 0.359 | 1.84E+02 [a] |
| $^{137}Cs$ | 1.00 | 9.47E+08 |
| $^{137m}Ba$ | 0.946 | 1.53E+02 [a] |

[a] Because these daughters are assumed to be in equilibrium, the half life of the parent will be used for the calculations.

## E1.1 Calculating $\beta^-$_DRL (Equation 2.4-1):

This calculation requires the Deposition Derived Response Level (Dp_DRL) for each radionuclide from the mixture for the Early Phase. Table 2.4-E3 shows the values calculated using Method 2.1.

**Table 2.4-E3**

| Radionuclide | $Dp_i$ ($\mu Ci/m^2$) | $e^{-\lambda tn}$ | $WF_{tn}$ | Beta Yield | Early Phase DRL ($\mu Ci/m^2$) |
|---|---|---|---|---|---|
| $^{212}Bi$ | 1.00 | 1 | 1 | 0.6406 | 1.65E+03 |
| $^{212}Po$ | 0.641 | 1 | 1 | 0 | 1.06E+03 |
| $^{208}Tl$ | 0.359 | 1 | 1 | 1 | 5.94E+02 |
| $^{137}Cs$ | 1.00 | 1 | 1 | 1 | 1.65E+03 |
| $^{137m}Ba$ | 0.946 | 1 | 1 | 0 | 1.56E+03 |

Because the early time phase starts at $t_0$ (deposition) days, there is no need to adjust for radioactive decay or weathering to determine the Dp_DRL at the start of the time phase.

Applying these values in equation 2.4-1 yields:

$$Dp\_DRL_{\beta-,t_0} = \left(1.65\text{E}+03\frac{\mu\text{Ci}}{\text{m}^2}*0.6406\frac{\mu\text{Ci}_{\beta^-}}{\mu\text{Ci}}\right)+\left(5.94\text{E}+02\frac{\mu\text{Ci}}{\text{m}^2}*1\frac{\mu\text{Ci}_{\beta^-}}{\mu\text{Ci}}\right)+\left(1.65\text{E}+03\frac{\mu\text{Ci}}{\text{m}^2}*1\frac{\mu\text{Ci}_{\beta^-}}{\mu\text{Ci}}\right)$$

$$= 3.30\text{E}+03\frac{\mu\text{Ci}_{\beta^-}}{\text{m}^2}$$

**NOTE:** $^{212}$Po and $^{137m}$Ba do not have a beta decay component and are therefore not included in this calculation.

# METHOD 2.5 DEPOSITION PROJECTED PUBLIC DOSE

## Application

This method has been developed to calculate the Deposition Projected Public Dose (Dp_PPD), the dose received by members of the public, from a deposition of radioactive material. The Dp_PPD may be calculated from a measured areal activity, Deposition PPD ($Dp\_PPD_{Dp}$) or external dose rate, Deposition Dose Rate PPD ($Dp\_PPD_{DR}$).

The Dp_PPD:

- Uses a measured areal activity of a marker 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 external dose from material deposited on the ground (i.e., groundshine) and the dose from the inhalation of resuspended material.

- Is compared to Protective Action Guides (PAGs) for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA92) or the Department of Homeland Security (DHS) (DHS08).

- Is used to create data products and define dose levels to assist decision makers in determining where it may be advisable to implement protective actions (e.g., sheltering, evacuation, relocation).

- Is calculated from the Deposition Derived Response Level ($Dp\_DRL_{Dp}$) value calculated in Method 2.1 or the Deposition Dose Rate Derived Response Level ($Dp\_DRL_{DR}$) value calculated in Method 2.2.

## Discussion

The Dp_PPD is a value obtained by:

- Multiplying the local deposition (areal activity) of a radionuclide at the start of the time phase by the Total Dose Parameter for Deposition for that radionuclide and time phase and summing that product over all the radionuclides in the mixture, or

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

## 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:

- Total Dose Parameter for Deposition (TDP_Dp) for each radionuclide and Mixture Total Dose Parameter for Deposition (MTDP_Dp) for the mixture – Calculated using Method 2.1.

- Deposition Dose Rate Derived Response Level ($Dp\_DRL_{DR}$) for the mixture – Calculated using Method 2.2.

- Mixture External Dose Factor for Deposition (MExDF_Dp) for the mixture – Calculated using Method 2.2.

If incident-specific values have not been established, recommended default values for selected inputs are available in Appendix C.

## Outputs

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

### Final

$Dp\_PPD_{Dp}$ = Deposition Projected Public Dose over the time phase under consideration, mrem

$Dp\_PPD_{DR}$ = Deposition Dose Rate Projected Public Dose over the time phase under consideration, mrem

### Intermediate

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

None

# Method 2.5.1 Deposition Projected Public Dose ($Dp\_PPD_{Dp}$)

## Calculation

This method can be used to calculate both Stochastic (Chronic) and Deterministic (Acute) Public Doses. Use the Stochastic or Deterministic Dp_DRL as appropriate.

**NOTE:** Deterministic DRLs will be included in a future revision.

**NOTE:** Weathering Factor is not included in this calculation because the activities are based on sample results that inherently account for weathering effects.

Calculate the Dp_PPD by multiplying the local deposition (areal activity) at the start of the time phase of a radionuclide by the Total Dose Parameter for Deposition for that radionuclide and time phase and summing that product over all radionuclides in the mixture.

$$Dp\_PPD_{Dp_{E,TP}} = \sum_i Dp_{i,t_1} * TDP\_Dp_{E,i,TP} \qquad \text{(Eq. 2.5-1)}$$

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

$Dp\_PPD_{Dp,E,TP}$ = Deposition Projected Public Dose, to the whole body (*E*), over the time phase (*TP*) under consideration, mrem;

$Dp_{i,t1}$ = Deposition, the measured or predicted areal activity of radionuclide *i* per unit area of ground at the start of the time phase under consideration ($t_1$), μCi/$m^2$; and

$TDP\_Dp_{E,i\ TP}$ = Total Dose Parameter for Deposition, the sum of the external dose from groundshine and the internal (committed effective) dose from inhalation of resuspended material received by the whole body (*E*), over the time phase under consideration (*TP*) per unit of areal activity of radionuclide *i* deposited on the ground, mrem•$m^2$/μCi.

**NOTE:** This calculation is identical to that for the Mixture Total Dose Parameter for Deposition (MTDP_Dp) calculated in Method 2.1.

# Method 2.5.2 Deposition Dose Rate Projected Public Dose ($Dp\_PPD_{DR}$)

## Calculation

Calculate the $Dp\_PPD_{DR}$ by comparing a measured dose rate with the time-adjusted $Dp\_DRL_{DR}$ for the mixture to establish a ratio of the projected dose to the PAG and estimate the projected dose over a specified time phase.

$$\frac{ExDR_{t_n}}{Dp\_DRL_{DR_{E,t_n}}} = \frac{Dp\_PPD_{DR_{E,TP}}}{PAG_{E,TP}} \quad \text{(Eq. 2.5-2a)}$$

Solving for DR_PPD, (Eq. 2.5-2a) can be rewritten as:

$$Dp\_PPD_{DR_{E,TP}} = \frac{ExDR_{t_n} * PAG_{E,TP}}{Dp\_DRL_{DR_{E,t_n}}} \quad \text{(Eq. 2.5-2b)}$$

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

where:

$Dp\_PPD_{DR,E,TP}$ = Deposition Dose Rate Projected Public Dose, the projected dose to the whole body (*E*) over the time phase (*TP*) under consideration from a measured external dose rate, mrem;

$ExDR_{tn}$ = Measured External Dose Rate at time $t_n$, mrem/hr;

$t_n$ = Evaluation Time, the point in time, relative to the start of the event, at which the measurement, prediction or evaluation is performed, s;
**NOTE:** The default value for $t_n$ is the start of the time phase under consideration ($t_1$), but it may be set to any time (before, during, or after the time phase).

$PAG_{E,TP}$ = Protective Action Guide, as specified by the EPA or local authorities, for the whole body (*E*) for the time phase (*TP*) under consideration, mrem; and

$Dp\_DRL_{DR,E,tn}$ = Deposition Dose Rate Derived Response Level to the whole body (*E*) at time $t_n$, mrem/hr (see Equation 2.2-5 from Method 2.2).

Equation 2.2-5 from Method 2.2 shows that:

$$Dp\_DRL_{DR_{E,t_n}} = PAG_{E,TP} * \frac{MExDF\_Dp_{E,t_n}}{MTDP\_Dp_{E,TP}} \quad \text{(Eq. 2.2-5)}$$

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

Substituting for $Dp\_DRL_{DR}$ in Eq. 2.5-2b yields:

$$Dp\_PPD_{DR_{E,TP}} = ExDR_{t_n} * \frac{MTDP\_Dp_{E,TP}}{MExDF\_Dp_{E,t_n}} \quad \text{(Eq. 2.5-3)}$$

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

## EXAMPLE 1

**Problem: Calculate the Deposition Projected Public Dose for the First-year Time Phase for the following mixture (deposited at t=0).**

**Table 2.5-E1**

| Radionuclide | Deposition ($\mu Ci/m^2$) | $\lambda_i$ ($s^{-1}$) |
|---|---|---|
| $^{241}Am$ | 4.15E-02 | 5.08E-11 |
| $^{60}Co$ | 2.74E+04 | 4.17E-09 |
| $^{90}Sr$ | 9.25E+04 | 7.54E-10 |

Using the daughter inclusion rules yields the following adjusted radionuclide mixture:

**Table 2.5-E2**

| Radionuclide | Deposition ($\mu Ci/m^2$) | $\lambda_i$ ($s^{-1}$) |
|---|---|---|
| $^{241}Am$ | 4.15E-02 | 5.08E-11 |
| $^{60}Co$ | 2.74E+04 | 4.17E-09 |
| $^{90}Sr$ | 9.25E+04 | 7.54E-10 |
| $^{90}Y$ | 9.25E+04 | 7.54E-10 [a] |
| [a] Because the daughter is in equilibrium with the parent, the λ for the parent is used. | | |

**NOTE:** Because the $t_{1/2}$ of the first $^{241}Am$ daughter ($^{237}Np$) is both longer than the $t_{1/2}$ of the parent and longer than 1.5 years, $^{237}Np$ and all subsequent daughters are not considered to be in equilibrium and are not included in the PPD calculation.

## E1.1 Calculating $Dp\_PPD_{Dp}$

This calculation requires the Total Dose Parameter for Deposition (TDP_Dp) for each radionuclide in the mixture. Table 2.5-E3 shows the values calculated in Method 2.1 (Table 2.1-E8) for the first-year time phase evaluated at deposition ($t_1$=0).

**Table 2.5-E3**

| Radionuclide | $Dp_i$ ($\mu Ci/m^2$) | TDP_Dp – First Year (mrem • $m^2/\mu Ci$) | $Dp_i$ • TDP_Dp – First Year (mrem) |
|---|---|---|---|
| $^{241}Am$ | 4.15E-02 | 56.64 | 2.35 |
| $^{60}Co$ | 2.74E+04 | 1.89E+02 | 5.18E+06 |
| $^{90}Sr$ | 9.25E+04 | 2.31E-01 | 2.14E+04 |
| $^{90}Y$ | 9.25E+04 | 9.55 | 8.83E+05 |
| | | MTDP_Dp (∑) | 6.08E+06 |

Applying the values for $Dp_i$ and TDP_Dp, Equation 2.5-1 becomes:

$$Dp\_PPD_{Dp,E,TP} = \left[ \begin{array}{l} \left( 4.15\text{E-02} \dfrac{\mu\text{Ci}}{\text{m}^2} * 56.64 \dfrac{\text{mrem} \cdot \text{m}^2}{\mu\text{Ci}} \right) \\ + \left( 2.74\text{E+04} \dfrac{\mu\text{Ci}}{\text{m}^2} * 1.89\text{E+02} \dfrac{\text{mrem} \cdot \text{m}^2}{\mu\text{Ci}} \right) \\ + \left( 9.25\text{E+04} \dfrac{\mu\text{Ci}}{\text{m}^2} * 2.31\text{E-01} \dfrac{\text{mrem} \cdot \text{m}^2}{\mu\text{Ci}} \right) \\ + \left( 9.25\text{E+04} \dfrac{\mu\text{Ci}}{\text{m}^2} * 9.55 \dfrac{\text{mrem} \cdot \text{m}^2}{\mu\text{Ci}} \right) \end{array} \right] = 6.08\text{E+06 mrem}$$

**NOTE:** This value is also the MTDP_Dp for the mixture for the first year time phase.

## E1.2 Calculating a Dp_PPD$_{Dp}$ 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 Dp_PPD$_{Dp}$ for a specific organ:

Determine the MTDP_Dp (which is equal to the Dp_PPD$_{Dp}$) for the sampling location for the organ of interest (see Method 2.1, Example 1, Section E1.6 – Table 2.1-E8a).

# EXAMPLE 2

**Problem: Calculate the Deposition 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 performed on Day 100 ($t_n$=100 days).

**Table 2.5-E1** (repeated)

| Radionuclide | Deposition ($\mu Ci/m^2$) | $\lambda_i$ ($s^{-1}$) |
|---|---|---|
| $^{241}Am$ | 4.15E-02 | 5.08E-11 |
| $^{60}Co$ | 2.74E+04 | 4.17E-09 |
| $^{90}Sr$ | 9.25E+04 | 7.54E-10 |

Using the daughter inclusion rules yields the following adjusted radionuclide mixture:

**Table 2.5-E2** (repeated)

| Radionuclide | Deposition ($\mu Ci/m^2$) | $\lambda_i$ ($s^{-1}$) |
|---|---|---|
| $^{241}Am$ | 4.15E-02 | 5.08E-11 |
| $^{60}Co$ | 2.74E+04 | 4.17E-09 |
| $^{90}Sr$ | 9.25E+04 | 7.54E-10 |
| $^{90}Y$ | 9.25E+04 | 7.54E-10 [a] |
| [a] Because the daughter is in equilibrium with the parent, the λ for the parent is used. | | |

**NOTE:** Because the $t_{1/2}$ of the first $^{241}Am$ daughter ($^{237}Np$) is both longer than the $t_{1/2}$ of the parent and longer than 1.5 years, $^{237}Np$ and all subsequent daughters are not considered to be in equilibrium and are not included in the $PPD_S$ calculation.

## E2.1 Calculating $MExDF\_Dp_{tn}$

This calculation requires the External Dose Factors (*ExDF*) for each radionuclide in the mixture and a time within the time phase at which the measurement ($ExDR_{tn}$) was taken.

**Table 2.5-E4**

| Radionuclide | $Dp_i$ (µCi/m$^2$) | $e^{-\lambda tn}$ | $WF_{tn}$ | ExDF (mrem•m$^2$) per (hr•µCi) | $Dp_{i,tn}$ • ExDF (mR/hr) |
|---|---|---|---|---|---|
| $^{241}Am$ | 4.15E-02 | 1 | 0.950 | 2.54E-04 | 1.00E-05 |
| $^{60}Co$ | 2.74E+04 | 0.965 | 0.950 | 2.51E-02 | 630 |
| $^{90}Sr$ | 9.25E+04 | 0.994 | 0.950 | 1.79E-05 | 1.56 |
| $^{90}Y$ | 9.25E+04 | 0.994 | 0.950 | 1.20E-03 | 105 |
| | | | | $MExDF\_Dp_{tn}$ | 737 |

Because the measurement was made at $t_n$ =100 days, adjust for radioactive decay and weathering to determine the MExDF_Dp at the measurement time.
[a] See Method 2.2, Example 1, Section E1.1 for calculation of ExDF values.

## E2.2 Calculating the $Dp\_PPD_{DR}$

Measurement ($ExDR_{tn}$) = 0.05 mrem/hr at $t_n$
$t_n$ = 100 days after deposition
*MTDP_Dp* = 6.08E+06 mrem (value from Turbo FRMAC)
$MExDF\_Dp_{tn}$ = 737 mrem/hr

Equation 2.5-4 yields:

$$Dp\_PPD_{DR,E,TP} = 0.05 \frac{\text{mrem}}{\text{hr}} * \frac{6.08\text{E+06 mrem}}{737 \frac{\text{mrem}}{\text{hr}}}$$

$Dp\_PPD_{DR}$ = 412 mrem for the first year.

## E2.3 Calculating an $Dp\_PPD_{DR}$ for an Individual Organ

To calculate a $Dp\_PPD_{DR}$ for a specific organ, determine the $Dp\_DRL_{DR}$ for the organ and compare to the organ-specific PAG as demonstrated above (see Method 2.2, Example 1, Section E1.4).

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# METHOD 2.6 SKIN DOSE

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

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# METHOD 2.7 DETERMINING RETURN TIMES

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

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# METHOD 2.8 ASSESSING NUCLEAR DETONATIONS

## Application

This method has been developed to calculate Doses, Stay Times, and Improvised Nuclear Device Derived Response Levels for a deposition of radioactive fallout after a nuclear detonation.

The $IND\_DRL_{DR}$

- Represents the dose rate (mrem/hr, measured at 1 m above the ground) at a given time ($t_n$), from all radionuclides in the fallout mixture that will be expected to produce a dose equal to the appropriate Protective Action Guide (PAG) over the time phase under consideration.

- 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 dose rate value greater than the $IND\_DRL_{DR}$ indicates that the PAG has the potential to be exceeded.

- 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.

## Discussion

The $IND\_DRL_{DR}$ 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 $IND\_DRL_{DR}$ 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) Doses and $IND\_DRL_{DR}$ are based on external gamma exposure only. Assume one rad external dose is equivalent to one rem.

2) During the time from 0.5 to 5,000 hours, the decay of fallout activity at a given location may be approximated by Equation 2.8-1 (Gl77):

$$ExDR_t = ExDR_r * t^{-x} \quad \text{(Eq. 2.8-1)}$$

where:

$ExDR_t$ = Dose rate at time t (hours after detonation), mrem/hr;
$ExDR_r$ = Reference 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 2.8.3 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**.

3) 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.

If incident-specific values have not been established, recommended default values for selected inputs are available in Appendix C.

# Outputs

### Final

$IND\_DRL_{DR}$ = Improvised Nuclear Device Derived Response Level, the external dose rate, at time $t_n$, at which the dose from all radionuclides in a fallout deposition mixture would result in a dose equal to 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 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 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 2.8.4 for instructions on calculating this value if requested.

# Method 2.8.1 Nuclear Fallout Dose

# Calculation

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

The dose received from radioactive fallout over a given time phase can be expressed by Equation 2.8-2:

$$\text{Dose} = ExDR_r * \int_{t_1}^{t_2} t^{-x} dt \quad \text{(Eq. 2.8-2)}$$

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

where:

$ExDR_r$ = Reference 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 2.8.4 for instructions on calculating this value if requested.

Integrating this equation produces:

$$\text{Dose} = ExDR_r * \left( \frac{t_2^{-x+1} - t_1^{-x+1}}{-x+1} \right) \quad \text{(Eq. 2.8-3)}$$

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

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 2.8-1:

$$ExDR_r = \frac{ExDR_t}{t^{-x}} \qquad \text{(Eq. 2.8-1, Modified)}$$

## Method 2.8.2 IND_DRL$_{DR}$ for nuclear fallout

## Calculation

Determining the IND_DRL$_{DR}$ requires knowledge of when the detonation occurred, what time the evaluation of IND_DRL$_{DR}$ will be made relative to that time, and the PAG to be applied.

When we limit the dose received over the time phase to the PAG, the equation becomes:

$$\text{PAG} = ExDR_{r,PAG} * \int_{t_1}^{t_2} t^{-x} dt \qquad \text{(Eq. 2.8-4)}$$

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

where:

$PAG_{E,\ TP}$ = Protective Action Guide, as specified by the EPA or local authorities, for the whole body (*E*), for the time phase (*TP*) under consideration, mrem;

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

Integrating this equation produces:

$$PAG = ExDR_{r,PAG} * \left( \frac{t_2^{-x+1} - t_1^{-x+1}}{-x+1} \right) \qquad \text{(Eq. 2.8-5a)}$$

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

Solving this equation for $ExDR_r$ yields:

$$ExDR_{r,PAG} = PAG * \left( \frac{-x+1}{t_2^{-x+1} - t_1^{-x+1}} \right) \quad \text{(Eq. 2.8-5b)}$$

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

This represents the 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 $IND\_DRL_{DR}$ for a measurement time $t_n$, apply the power function to the $ExDR_r$ calculated above.

$$IND\_DRL_{DR_{t_n}} = ExDR_{t_n} = ExDR_{r,PAG} * t_n^{-x} \quad \text{(Eq. 2.8-6)}$$

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

where:

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

Therefore the $IND\_DRL_{DR}$ for time $t_n$ in terms of the PAG is:

$$IND\_DRL_{DR_{t_n}} = PAG * \left( \frac{-x+1}{t_2^{-x+1} - t_1^{-x+1}} \right) * t_n^{-x} \quad \text{(Eq. 2.8-7a)}$$

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

Or, for the default value of x = 1.2:

$$IND\_DRL_{DR_{t_n}} = PAG * \left( \frac{-0.2}{t_2^{-0.2} - t_1^{-0.2}} \right) * t_n^{-1.2} \quad \text{(Eq. 2.8-7b)}$$

## Method 2.8.3 Nuclear Fallout Stay Time:

## Calculation

This calculation uses the reference 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 2.8-3) 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.

$$\text{Dose} = ExDR_r * \left( \frac{t_2^{-x+1} - t_1^{-x+1}}{-x+1} \right) \quad \text{(Eq. 2.8-3)}$$

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

Solving for $t_2$:

$$t_2^{-x+1} = \frac{\text{Dose} * (-x+1)}{ExDR_r} + t_1^{-x+1} \quad \text{(Eq. 2.8-8a)}$$

Taking the natural log of both sides:

$$(-x+1)\ln t_2 = \ln\left[ \frac{\text{Dose} * (-x+1)}{ExDR_r} + t_1^{-x+1} \right] \quad \text{(Eq. 2.8-8b)}$$

Solving for $t_2$:

$$\ln t_2 = \frac{\ln\left[ \frac{\text{Dose} * (-x+1)}{ExDR_r} + t_1^{-x+1} \right]}{-x+1} \quad \text{(Eq. 2.8-8c)}$$

Therefore:

$$t_2 = e^{\left\{ \frac{\ln\left[ \frac{\text{Dose} * (-x+1)}{ExDR_r} + t_1^{-x+1} \right]}{-x+1} \right\}} \quad \text{(Eq. 2.8-8d)}$$

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

# Method 2.8.4 Calculating the "power function" ($t^{-x}$):

## 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) (GL77). 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:

$ExDR_a$ = dose rate measured at time $t_a$, mrem/hr;
$ExDR_b$ = dose rate measured at time $t_b$, mrem/hr;
$ExDR_r$ = reference dose rate at 1 hour after detonation, mR/hr;

By the rule of the power function:

$$ExDR_a = ExDR_r * t_a^{-x} \quad \text{and} \quad ExDR_b = ExDR_r * t_b^{-x} \qquad \text{(Eq. 2.8-9a)}$$

Therefore:

$$ExDR_r = \frac{ExDR_a}{t_a^{-x}} = \frac{ExDR_b}{t_b^{-x}} \qquad \text{(Eq. 2.8-9b)}$$

and,

$$\frac{ExDR_b}{ExDR_a} = \frac{t_b^{-x}}{t_a^{-x}} \Rightarrow \left(\frac{t_b}{t_a}\right)^{-x} \qquad \text{(Eq. 2.8-9c)}$$

Taking the natural log of both sides:

$$\ln\left(\frac{ExDR_b}{ExDR_a}\right) = -x \ln\left(\frac{t_b}{t_a}\right) \qquad \text{(Eq. 2.8-9d)}$$

Solving for -x:

$$-x = \frac{\ln\left(\frac{ExDR_b}{ExDR_a}\right)}{\ln\left(\frac{t_b}{t_a}\right)} \qquad \text{(Eq. 2.8-9e)}$$

# Method 2.8.5 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 2.8-3,

$$\text{Dose} = ExDR_r * \left( \frac{t_2^{-x+1} - t_1^{-x+1}}{-x+1} \right) \quad \text{(Eq. 2.8-3)}$$

when x=1, this is changed to:

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

Calculating $IND\_DRL_{DR}$ using Equation 2.8-7a,

$$IND\_DRL_{DR_{t_n}} = PAG * \left( \frac{-x+1}{t_2^{-x+1} - t_1^{-x+1}} \right) * t_n^{-x} \quad \text{(Eq. 2.8-7a)}$$

when x=1, this is changed to:

$$IND\_DRL_{DR_{t_n}} = \frac{PAG}{\left( \ln t_2 - \ln t_1 \right)} * t_n^{-x}$$

And, calculating Stay Time using Equation 2.8-9d:

$$t_2 = e^{\left\{ \frac{\ln\left[ \frac{\text{Dose}*(-x+1)}{ExDR_r} + t_1^{-x+1} \right]}{-x+1} \right\}} \quad \text{(Eq. 2.8-8d)}$$

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 $IND\_DRL_{DR}$ 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 ($t_1$) 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 $t^{-x}$ using Equation 2.8-8e

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

## E1.2 Calculating $IND\_DRL_{DR}$ at $t_n$ = 48 hours using Equation 2.8-7a

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

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

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

## EXAMPLE 2

**Problem: Calculate the 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 dose is calculated using equation 2.8-3:

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

x = 1.21 from Example 1,

$ExDR_r$ is calculated using the modified form of Equation 2.8-1:

$$ExDR_r = \frac{ExDR_t}{t^{-x}} = \frac{5.1 \frac{\text{rem}}{\text{hr}}}{12^{-1.21}} = 103 \frac{\text{rem}}{\text{hr}}$$

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 <u>12 hours</u> after detonation, the dose would be:

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

# 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 2.8-9d:

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

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

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# SECTION 3. WORKER PROTECTION METHODS

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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.

### 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 Ingestion Methods, Section 4.)
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. an Breathing Rate for Light Activity (Adult Male) of 1.5 $m^3$/hr; and
    f. inhalation of 1-micron Activity Median Aerodynamic Diameter (AMAD) particles in the Maximum lung clearance class.
6) Parent – Daughter inclusion rules:

- Daughter radionuclides are included in calculations if:
    a. Daughter's half-life is less than the half-life of the ultimate parent (i.e., first parent in decay series), and
    b. Daughter's half-life is less than 1.5 yr.
- Daughter radionuclides that meet these rules are considered to be in equilibrium (secular, or transient when branching ratio ≠ 1) at deposition (t = 0, i.e., the daughter radionuclides are not grown in to equilibrium activities), and are assigned the parent's half life and decay constants for calculations.
- Daughter radionuclides that do not meet these rules are excluded from the calculations (as are all subsequent daughter radionuclides, regardless of half life).
- Optionally, an alternate calculation that models the decay and in-growth of the entire radionuclide decay chain may be used when the using the default Parent – Daughter inclusion rules stated above is not desired. See Appendix F, Supplement 1 for details on the calculation.

7) FRMAC's public 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 2.1 Example 1, Section E1.6.)

## Inputs

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

- 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.

- Other Factors:
    - Ground roughness;
    - Weathering;
    - Resuspension; and
    - Decay of radionuclides during the time period under consideration.

- Constants:
    - Breathing rate;
    - Inhalation dose coefficient;
    - External dose coefficient;
    - Dose limits (e.g., PAGs); and
    - Exposure to Dose conversion factor (1.0 mrem/mR).

- Time Phase:
    - Evaluation Time ($t_n$) – The point in time, relative to the start of the event, for which the calculation is being performed; and
    - 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.)

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# METHOD 3.1 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 Protective Action Guides (PAGs) for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA92) or the Department of Homeland Security (DHS) (DHS08).

## Discussion

This method is primarily used to calculate the Turn-Back Limit (TBL) (e.g., mR/hr or mrem/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 3.2.

# 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.

If incident-specific values have not been established, recommended default values for selected inputs are available in Appendix C.

# Outputs

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

### Final

TBL = Worker Turn-Back Limit (mrem/hr)
ST = Stay Time (hr)

### 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 event and the shift length for the worker(s) being evaluated.

$$TBL = \frac{Dose\ Limit}{ST} \qquad \text{(Eq. 3.1-1)}$$

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

where:

*TBL* = Worker 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.

$$ST = \frac{Dose\ Limit}{ExDR} \tag{Eq. 3.1-2}$$

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

where:

*ST* = Stay Time, how long the worker will be allowed to work in the contaminated area, hr;
*ExDR* = External dose rate in the work area, 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 ≥ 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 3.2 ADVANCED WORKER PROTECTION

## 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 will be expected to 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 dose (or exposure) value greater than the TBL indicates that the PAG has the potential to be exceeded.
- Is calculated from the Inhalation Dose Parameter for Deposition (InhDP_Dp) and the External Dose Parameter for Deposition (ExDP_Dp) values calculated in Method 2.1.

## 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:

Other Factors – Respiratory protection factor (RPF), Potassium Iodide protection factor (KIPF).

Inhalation and External Dose Parameters for Deposition (InhDP_Dp and ExDP_Dp) for each radionuclide in the mixture, based on the start and end times and dose limit for the worker's shift (calculated using Method 2.1).

**NOTE:** Consult with Health and Safety personnel to determine appropriate input values for the planned worker shift.

If incident-specific values have not been established, recommended default values for selected inputs are available in Appendix C.

# Outputs

The final output of this method is the turn-back limit (mrem or mR) for a given work shift.

### Final

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 (*TP*) of interest, $mrem_{inh+external}/mrem_{external}$.
**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

# 1.0 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 event 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.

$$TBL\_D_{TP} = \frac{Dose\ Limit}{ExTDCF_{TP}} \qquad \text{(Eq. 3.2-1)}$$

$$\text{mrem}_{external} = \frac{\text{mrem}_{inh+external}}{\text{mrem}_{inh+external} / \text{mrem}_{external}}$$

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 (*TP*) under consideration that would result in the worker receiving the dose limit, $\text{mrem}_{\text{external}}$;

*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 (*TP*) of interest, $\text{mrem}_{\text{inh+external}}/\text{mrem}_{\text{external}}$.

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 ($XDCF_{A\ or\ C}$) (0.7 mrem/mR for acute dose or 1.0 mrem/mR for chronic dose) to determine the Turn-Back Limit for Integrated External Exposure (TBL_X) in $\text{mR}_{\text{external}}$.

$$TBL\_X_{TP} = \frac{TBL\_D_{TP}}{XDCF_{A\ \text{or}\ C}} \qquad \text{(Eq. 3.2-2)}$$

$$\text{mR}_{external} = \frac{\text{mrem}_{external}}{\text{mrem} / \text{mR}}$$

## 1.1 Calculation of the External to Total Dose Conversion Factor

The External to Total Dose Conversion Factor ($\text{ExTDCF}_{\text{TP}}$) 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 3.2-3(a-c).

$ExTDCF_{TP}$ =

$$\frac{\sum_i \left( \frac{InhDP\_Dp_{i,TP} * Dp_i * e^{-\lambda_i t_1} * WF_{t_1}}{KIPF * RPF} \right) + \sum_i \left( ExDP\_Dp_{i,TP} * Dp_i * e^{-\lambda_i t_1} * WF_{t_1} \right)}{\sum_i \left( ExDP\_Dp_{i,TP} * Dp_i * e^{-\lambda_i t_1} * WF_{t_1} \right)} \quad \text{(Eq. 3.2-3a)}$$

which can be expanded to:

$$= \frac{\sum_i \left( \frac{InhDP\_Dp_{i,TP} * Dp_i * e^{-\lambda_i t_1} * WF_{t_1}}{KIPF * RPF} \right)}{\sum_i \left( ExDP\_Dp_{i,TP} * Dp_i * e^{-\lambda_i t_1} * WF_{t_1} \right)} + \frac{\sum_i \left( ExDP\_Dp_{i,TP} * Dp_i * e^{-\lambda_i t_1} * WF_{t_1} \right)}{\sum_i \left( ExDP\_Dp_{i,TP} * Dp_i * e^{-\lambda_i t_1} * WF_{t_1} \right)}$$

(Eq.3.2-3b)

which simplifies to:

$$ExTDCF_{TP} = \frac{WF_{t_1} * \sum_i \left( \frac{InhDP\_DP_{i,TP} * Dp_i * e^{-\lambda_i t_1}}{KIPF * RPF} \right)}{WF_{t_1} * \sum_i \left( ExDP\_Dp_{i,TP} * Dp_i * e^{-\lambda_i t_1} \right)} + 1 \quad \text{(Eq. 3.2-3c)}$$

**NOTE:** Because $WF_{t1}$ is independent of radionuclide, it may be removed from the summation terms and then cancelled out of the numerator and denominator for the final equation.

$$ExTDCF_{TP} = \frac{\sum_i \left( \frac{InhDP\_DP_{i,TP} * Dp_i * e^{-\lambda_i t_1}}{KIPF * RPF} \right)}{\sum_i \left( ExDP\_Dp_{i,TP} * Dp_i * e^{-\lambda_i t_1} \right)} + 1 \quad \text{(Eq. 3.2-3d)}$$

$$\frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}} = \frac{\left( \frac{\frac{\mu\text{Ci}}{\text{m}^2} * \frac{\text{mrem}_{\text{inh}}}{\mu\text{Ci}/\text{m}^2} * \text{unitless}}{\text{unitless} * \text{unitless}} \right)}{\left( \frac{\mu\text{Ci}}{\text{m}^2} * \frac{\text{mrem}_{\text{external}}}{\mu\text{Ci}/\text{m}^2} * \text{unitless} \right)} + \frac{\text{mrem}_{\text{external}}}{\text{mrem}_{\text{external}}}$$

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 (*TP*) of interest, $mrem_{inh+external}/mrem_{external}$;

$Dp_i$ = Deposition, the areal activity of radionuclide *i*, µCi/m$^2$;

$InhDP\_Dp_{E,i,TP}$ = Inhalation Dose Parameter for Deposition, the committed effective dose received by the whole body (*E*), from the inhalation of resuspended radionuclide *i* over the time phase under consideration (*TP*), per unit of areal activity of the radionuclide deposited on the ground, mrem•m$^2$/µCi;

$\lambda_i$ = Decay constant for radionuclide *i*, s$^{-1}$;

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

$e^{-\lambda t1}$ = Radioactive Decay correction for radionuclide *i* from $t_0$ (deposition) to $t_1$ (start of the time phase), unitless;

$WF_{t1}$ = Weathering correction from $t_0$ (deposition) to $t_1$ (start of the time phase), unitless; and
**NOTE:** See Appendix F, Supplement 2 for details on calculating WF.

$ExDP\_Dp_{E,i,TP}$ = External Dose Parameter for Deposition, the groundshine dose received by the whole body (*E*) over the time phase under consideration (*TP*), per unit of areal activity of radionuclide *i* deposited on the ground and adjusted for the ground roughness factor, mrem•m$^2$/µCi;

*RPF* = Respiratory Protection Factor, which defaults to 1 when no respirators are used, unitless; and

*KIPF* = Potassium Iodide Protection Factor, which defaults to 1 for all non-iodine isotopes or when no KI is administered, unitless.

**NOTE:** Consult Health and Safety personnel for appropriate values for *RPF* and/or *KIPF*.

Typical RPF values are:

Half-face Air-purifying Respirator: 10
Full-face Air-purifying Respirator: 50
Pressure-Demand SCBA: 10,000

## 1.2 Comparison of the ExTDCF to the workers' Dose Limit.

When the ExTCDF has been calculated, the following equation may be used to calculate the turn-back limit for the workers.

$$TBL\_D_{TP} = \frac{Dose\ Limit}{ExTDCF_{TP}} \qquad \text{(Eq. 3.2-4)}$$

$$\text{mrem}_{external} = \frac{\text{mrem}_{inh+external}}{\text{mrem}_{inh+external} / \text{mrem}_{external}}$$

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 (*TP*) under consideration that would result in the worker receiving the dose limit, $\text{mrem}_{\text{external}}$;

*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 (*TP*) of interest, $\text{mrem}_{\text{inh+external}}/\text{mrem}_{\text{external}}$.

**NOTE:** This equation is identical to Eq. 3.2-1.

## 1.3 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.

$$Dose = \text{SRD Readout} * ExTDCF_{TP} \qquad \text{(Eq. 3.2-5)}$$

$$\text{mrem}_{inh+external} = \text{mrem}_{external} * \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}$$

where:

*Dose* = Worker (or receptor) dose, mrem;

SRD Readout = Current reading on Self-Reading Dosimeter, 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 (*TP*) of interest, $\text{mrem}_{\text{inh+external}}/\text{mrem}_{\text{external}}$.

If the dosimeter reads out in units of exposure (mR), the $\text{XDCF}_{\text{A or C}}$ must be included.

$$Dose = \text{SRD Readout} * XDCF_{A \text{ or } C} * ExTDCF_{TP} \qquad \text{(Eq. 3.2-6)}$$

$$\text{mrem}_{inh+external} = \text{mrem}_{external} * \frac{\text{mrem}_{external}}{\text{mR}_{external}} * \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}$$

where:

$XDCF_A$ = Exposure to Dose Conversion Factor (acute), the constant used to convert external exposure (mR) to midline (bone marrow) dose (mrem), 0.7 mrem/mR.

$XDCF_C$ = 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 without a respirator starting shortly after Deposition with a worker Dose Limit of 5000 mrem for the following mixture (deposited at t=0).**

**Table 3.2-E1**

| Radionuclide | Deposition ($\mu Ci/m^2$) | $t_{1/2}$ (yr) |
|---|---|---|
| $^{241}Am$ | 4.15E-02 | 432 |
| $^{60}Co$ | 2.74E+04 | 5.27 |
| $^{90}Sr$ | 9.25E+04 | 29.1 |

Using the daughter inclusion rules from the Assumptions section above yields the following adjusted radionuclide mixture:

**Table 3.2-E2**

| Radionuclide | Deposition ($\mu Ci/m^2$) | $t_{1/2}$ (yr) |
|---|---|---|
| $^{241}Am$ | 4.15E-02 | 432 yr |
| $^{60}Co$ | 2.74E+04 | 5.27 yr |
| $^{90}Sr$ | 9.25E+04 | 29.1 yr |
| $^{90}Y$ | 9.25E+04 | 7.3E-03 yr |

**NOTE:** Because the $t_{1/2}$ of the first $^{241}Am$ daughter ($^{237}Np$) is both longer than the $t_{1/2}$ of the parent and longer than 1.5 years, $^{237}Np$ and all subsequent daughters are not in equilibrium and thus are not included in the Dp_DRL calculation.

## E1.1 Calculating the ExTDCF (Equation 3.2-3)

This calculation requires the values for InhDP_Dp and ExDP_Dp from Method 2.1.

**Table 3.2-E3**

| Radionuclide | $Dp_i$ (µCi/m²) | ExDP_Dp [a] (mrem per µCi/m²) | InhDP_Dp [a] (mrem per µCi/m²) | $Dp_i$ • ExDP_Dp (mrem)[b] | $Dp_i$ • InhDP_Dp (mrem)[b] |
|---|---|---|---|---|---|
| $^{241}$Am | 4.15E-02 | 2.04E-03 | 4.30 | 8.47E-05 | 1.79E-01 |
| $^{60}$Co | 2.74E+04 | 0.201 | 1.37E-03 | 5.51E+03 | 3.75E+01 |
| $^{90}$Sr | 9.25E+04 | 1.43E-04 | 7.01E-03 | 1.32E+01 | 6.49E+02 |
| $^{90}$Y | 9.25E+04 | 9.61E-03 | 6.68E-05 | 8.89E+02 | 6.18 |
| | | | ∑ | **6.41E+03** | **6.92E+02** |

[a] Values from TurboFRMAC 2.1 – Breathing rate for “Light Activity”.
[b] Because the work shift begins shortly after deposition, there is no need to account for decay or weathering in these calculations.

$$ExTDCF_{TP} = \frac{\dfrac{6.92\text{E}+02}{1*1}}{6.41\text{E}+03} + 1 = 1.11\,\frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}$$

## E1.2 Calculating the TBL_D (Equation 3.2-1)

The Turn-Back Limit for Integrated External Dose for this radionuclide mixture with a Dose Limit of 5000 mrem would be:

$$TBL\_D_{TP} = \frac{5000\ \text{mrem}_{inh+external}}{1.11\,\dfrac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}} \approx 4500\ \text{mrem}_{external}$$

The Turn-Back Limit for Integrated External Exposure would be:

$XDCF_C$ = 1.0 mrem/mR

$$TBL\_X_{TP} = \frac{4500\ \text{mrem}_{external}}{1.0\ \text{mrem}/\text{mR}} = 4500\ \text{mR}_{external}$$

This means that when a worker’s dosimeter indicates an external dose of 4500 mrem (exposure of 4500 mR), the worker has potentially received 5000 mrem of total (external + inhalation) dose and should exit the work area.

## EXAMPLE 2

**Problem: Calculate the worker Turn-Back Limit for an 8-hour shift with and without a full-face air-purifying respirator starting 4 days after Deposition with a Dose Limit of 5000 mrem for the following mixture (deposited at t=0). Potassium Iodide has been administered.**

**Table 3.2-E4**

| Radionuclide | Deposition ($\mu Ci/m^2$) | $t_{1/2}$ (days) |
|---|---|---|
| $^{131}I$ | 712 | 8.04 |
| $^{238}Pu$ | 50 | 3.20E+04 |

The daughter inclusion rules from the Assumptions section above yield no additions to the radionuclide mixture.

## E2.1 Calculating the ExTDCF (Equation 3.2-3)

This calculation requires the values for InhDP_Dp and ExDP_Dp from Method 2.1.

**Table 3.2-E5**

| Radionuclide | $Dp_i$ ($\mu Ci/m^2$) | ExDP_Dp [a] (mrem per $\mu Ci/m^2$) | InhDP_Dp [a] (mrem per $\mu Ci/m^2$) | $e^{-\lambda t1}$ [b] | $Dp_i \bullet e^{-\lambda t1}$ • ExDP_Dp (mrem) | $Dp_i \bullet e^{-\lambda t1}$ • InhDP_Dp (mrem) |
|---|---|---|---|---|---|---|
| $^{131}I$ | 712 | 2.22E-02 | 5.53E-05 | 0.708 | 11.2 | 2.79E-03 [c] |
| $^{238}Pu$ | 50 | 5.46E-05 | 1.16 | 1 | 2.73E-03 | 57.9 |
| | | | | ∑ | **11.2** | **57.9** |

[a] Values from TurboFRMAC 2.1 – Breathing Rate for "Light Activity".
[b] Because the time phase starts at $t_1$ =4 days there is a need to adjust for radioactive decay. (Weathering is also considered, but is not included in the hand calculation because it cancels out of the equation – See Section 1.1.)
[c] This value includes a KIPF of 10.

With a respirator:

$$ExTDCF_{TP} = \frac{\left(\frac{5.53\text{E-}05 * 712 * 0.708}{10 * 50}\right) + \left(\frac{1.16 * 50 * 1}{1 * 50}\right)}{(2.22\text{E-}02 * 712 * 0.708) + (5.46\text{E-}05 * 50 * 1)} + 1$$

$$ExTDCF_{TP} = \frac{5.60\text{E-}05 + 1.16}{11.2} + 1 = 1.10 \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}$$

Without a respirator:

$$ExTDCF_{TP} = \frac{\left(\frac{5.53\text{E-}05 * 712 * 0.708}{10 * 1}\right) + \left(\frac{1.16 * 50 * 1}{1 * 1}\right)}{\left(2.22\text{E-}02 * 712 * 0.708\right) + \left(5.46\text{E-}05 * 50 * 1\right)} + 1$$

$$ExTDCF_{TP} = \frac{2.79\text{E-}03 + 58.0}{11.2} + 1 = 6.18\ \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}$$

## E2.2 Calculating the TBL_D and TBL_X (Equation 3.2-1, 3.2-2)

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:

$$TBL\_D_{TP} = \frac{5000\ \text{mrem}_{inh+external}}{1.10\ \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}} \approx 4550\ \text{mrem}_{external}$$

$$TBL\_X_{TP} = \frac{4550\ \text{mrem}_{external}}{1.0\ \text{mrem}/\text{mR}} \approx 4550\ \text{mR}_{external}$$

Without a respirator:

$$TBL\_D_{TP} = \frac{5000\ \text{mrem}_{inh+external}}{6.18\ \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}} \approx 809\ \text{mrem}_{external}$$

$$TBL\_X_{TP} = \frac{809\ \text{mrem}_{external}}{1.0\ \text{mrem}/\text{mR}} = 809\ \text{mR}_{external}$$

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# METHOD 3.3 ADVANCED WORKER PROTECTION STAY TIME CALCULATION

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

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# METHOD 3.4 WORKER SKIN DOSE

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

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# SECTION 4. 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 ($E_{50}$) and 5 rem to any specific organ ($H_{T,50}$), 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:

- Transfer Factors assume a long-term exposure during which equilibrium is reached.
- Transfer Factors used in these methods for terrestrial plants are based on dry weight.
- 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 4.1 DERIVED INTERVENTION LEVELS

## Application

This method has been developed to calculate Derived Intervention Levels (DILs) for radioactive material deposited on consumables.

The DIL:

- Represents the activity concentration (μCi/$kg_{wet}$) of radioactive material found 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.
- Is derived from the PAG for radiological emergency planning established by the Food and Drug Agency (FDA) (FDA98). A projected or measured value of radioactivity greater than the DIL indicates that the PAG has the potential to be exceeded.
- Applies to the activity concentration in the food "as prepared for consumption" or "wet."
- 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.
- 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 4.1-1 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 $^{103}$Ru and $^{106}$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 ($kg_{wet}$/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 5.2.
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 4.7).
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:

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).

Other Factors – Decay of radionuclides during the time period under consideration.

Constants – Fraction of diet contaminated, daily food intake rate, ingestion dose coefficient, dose limits (e.g., FDA PAGs).

If incident-specific values have not been established, recommended default values for selected inputs are available in Appendix C.

**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

The final output of this method is the DIL for a radionuclide contaminant.

### Final

$DIL_i$ = Derived Intervention Level, the activity concentration level of radionuclide *i* at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to exceed the applicable ingestion PAG, $\mu Ci/kg_{wet}$.

### Intermediate

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

None

## Method 4.1.1 DILs for FDA-Listed Radionuclides

Table 4.1-1 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 4.1.2 for all other radionuclides.

**Table 4.1-1 FDA-Listed Ingestion DILs (FDA 1998)**

| Radionuclide Group | FDA DIL[a] ($Bq/kg_{wet}$) | FDA DIL[a] ($\mu Ci/kg_{wet}$) |
|---|---|---|
| **Principal Nuclides** | | |
| $^{90}Sr$ | 160 | 4.3E-03 |
| $^{131}I$ | 170 | 4.6E-03 |
| $^{134}Cs + ^{137}Cs$ | 1200 | 3.2E-02 |
| $^{134}Cs$ | 930 | 2.5E-02 |
| $^{137}Cs$ | 1360 | 3.7E-02 |
| $^{238}Pu + ^{239}Pu + ^{241}Am$ | 2 | 5.4E-05 |
| $^{238}Pu$ | 2.5 | 6.8E-05 |
| $^{239}Pu$ | 2.2 | 6.0E-05 |
| $^{241}Am$ | 2 | 5.4E-05 |
| $^{103}Ru + ^{106}Ru$ | $(^{103}Ru/6800) + (^{106}Ru/450) < 1$ | $(^{103}Ru/0.18) + (^{106}Ru/1.2E\text{-}02) < 1$ |
| $^{103}Ru$ | 6800 | 0.18 |
| $^{106}Ru$ | 450 | 1.2E-02 |
| **Other Nuclides** | | |
| $^{89}Sr$ | 1400 | 3.8E-02 |
| $^{91}Y$ | 1200 | 3.2E-02 |
| $^{95}Zr$ | 4000 | 0.11 |
| $^{95}Nb$ | 12000 | 0.32 |
| $^{132}Te$ | 4400 | 0.12 |
| $^{129}I$ | 56 | 1.5E-03 |
| $^{133}I$ | 7000 | 0.19 |
| $^{140}Ba$ | 6900 | 0.19 |
| $^{141}Ce$ | 7200 | 0.19 |
| $^{144}Ce$ | 500 | 1.4E-02 |
| $^{237}Np$ | 4 | 1.1E-04 |
| $^{239}Np$ | 28000 | 0.76 |
| $^{241}Pu$ | 120 | 3.2E-03 |
| $^{242}Cm$ | 19 | 5.1E-04 |
| $^{244}Cm$ | 2 | 5.4E-05 |

[a] 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., $^{134}Cs + ^{137}Cs$, $^{238}Pu + ^{239}Pu + ^{241}Am$, and $^{103}Ru + ^{106}Ru$).

# Method 4.1.2 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, to complete these calculations. All calculated values must be approved by an FDA representative on the Advisory Team prior to publication.

Equation 4.1-1 shows the DIL calculation.

$$DIL_{organ,age,i} = \frac{PAG_{organ}}{FDC_{age,i} * DFIR_{age} * EDI_i * IngDC_{organ,age,i}} \quad \text{(Eq. 4.1-1)}$$

$$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} = \frac{\text{mrem}}{\text{unitless} * \frac{\text{kg}_{\text{wet}}}{\text{d}} * \text{d} * \frac{\text{mrem}}{\mu\text{Ci}}}$$

where:

$DIL_{organ,age,i}$ = Derived Intervention Level, the activity concentration level of radionuclide *i* at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to exceed the applicable ingestion PAG, $\mu$Ci/$kg_{wet}$;

$PAG_{organ}$ = Protective Action Guide, as specified by the FDA or local authorities, for the target organ, mrem;

$FDC_{age,i}$ = Fraction of Diet Contaminated, default value of 0.3, (except $^{132}$Te, $^{131}$I, $^{133}$I and $^{239}$Np in the diet of an infant (3 months and 1 yr) for which it is 1.0), unitless;
**NOTE:** 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 for the age group under consideration (see Appendix C, Table 10), $kg_{wet}$/d;

$EDI_i$ = Effective Days of Intake, the number of days required for the radionuclide to decay to <1% of its initial activity (set to 365 if value is greater), d; and

$$EDI_i = \frac{-\ln(0.01)}{\lambda_i} \quad \text{where } \lambda_i = \frac{\ln 2}{t_{1/2_i}} \quad \text{(Eq. 4.1-2)}$$

**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/µCi.

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 (µCi/$kg_{wet}$).

# EXAMPLE 1

**Problem: Calculate the Derived Intervention Level for $^{136}$Cs.**

$^{136}$Cs is not an FDA-listed radionuclide; therefore the DIL must be calculated according to Method 4.1.2. Determining a final DIL requires calculating the DIL for each age group for each organ and choosing the most conservative value.

$$DIL_{organ,age,i} = \frac{PAG_{organ}}{FDC_{age,i} * DFIR_{age} * EDI_i * IngDC_{organ,age,i}} \qquad \text{(Eq. 4.1-1)}$$

$$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} = \frac{\text{mrem}}{\text{unitless} * \frac{\text{kg}_{\text{wet}}}{\text{d}} * \text{d} * \frac{\text{mrem}}{\mu\text{Ci}}}$$

The $EDI_i$ for $^{136}$Cs ($t_{1/2}$ = 13.1 d):

$$EDI_i = \frac{4.6}{5.29\text{E-}02} = 87 \text{ d} \quad \text{where } \lambda_i = \frac{0.693}{13.1} = 5.29\text{E-}02 \qquad \text{(Eq. 4.1-2)}$$

Table 4.1-E1 shows the values, calculated using Equation 4.1-1, for each age group for the Whole Body and for the organ with the highest IngDC.

**Table 4.1-E1**

| Age Group | Organ | IngDC (mrem/µCi) | FDC | DFIR ($kg_{wet}$/d) | EDI (d) | PAG (mrem) | DIL (µCi/$kg_{wet}$) |
|---|---|---|---|---|---|---|---|
| **Infant (3 month)** | **Whole Body** | **53.7** | **0.3** | **1.14** | **87** | **500** | **0.31** |
| | LLI [a] | 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 | **0.31** |

[a] Lower Large Intestine

The reported DIL should be 0.31 µCi/$kg_{wet}$ for $^{136}$Cs based on the (most restrictive) Infant/Whole Body value.

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# METHOD 4.2 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):

- Represents the ground concentration, or areal activity (μCi/m$^2$), of radionuclide *i* that will be expected to cause the crop/produce growing in that area to exceed the Derived Intervention Level (DIL) for that radionuclide.

- 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 deposition value greater than the Crop_DRL indicates that the PAG has the potential to be exceeded.

- 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.

- 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).

- Is calculated using the DIL calculated in Method 4.1

## Discussion

The Crop_DRL predicts the amount of radioactivity deposited on a crop (μCi/m$^2$) that would cause the crop to exceed the DIL. Sampling efforts should concentrate on the area where the contamination is equal to 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 $^{103}Ru$ and $^{106}Ru$).
2) Are based on the most restrictive DIL for each radionuclide based on age group and target organ. See Method 4.1 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 $kg_{wet}/m^2$ for fresh produce.
5) Assume a soil density of 1600 $kg_{soil}/m^3$.
6) Assume a mixing depth of 1.0E-03 m for the first growing season and 0.15 after plowing (EPA89).
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 5.2.
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., $^{134}Cs$ + $^{137}Cs$) 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:

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).

Constants – Crop Retention Factor, Crop Yield, Transfer Factors for different food types and for each radionuclide.

Other Factors – Decay and weathering of radionuclides during the time period under consideration, soil mixing depth.

Appropriate DIL for each radionuclide – Calculated using Method 4.1.

If incident-specific values have not been established, recommended default values for selected inputs are available in Appendix C.

**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

The final output of this method is the Crop_DRL value for a radionuclide contaminant on the growing area.

### Final

$Crop\_DRL_{mat,i}$ = Ingestion Derived Response Level for mature Crop/Produce, the ground concentration, or areal activity (µCi/m$^2$), of radionuclide *i* that will be expected to cause the crop/produce growing in that area to exceed the applicable Derived Intervention Level (DIL), µCi/kg$_{wet}$.

$Crop\_DRL_{imm,i}$ = Ingestion Derived Response Level for immature Crop/Produce, the ground concentration, or areal activity (µCi/m$^2$), of radionuclide *i* that will be expected to cause the crop/produce growing in that area to exceed the applicable Derived Intervention Level (DIL), µCi/kg$_{wet}$.

### Intermediate

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

None

# Method 4.2.1 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 4.2-1 shows the $Crop\_DRL_{mat,i}$ calculation.

$$Crop\_DRL_{mat,i} = \frac{DIL_{organ,age,i} * Y}{CRF_i * e^{-\lambda_i t_m}} \qquad \text{(Eq. 4.2-1)}$$

$$\frac{\mu\text{Ci}}{\text{m}^2} = \frac{\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \frac{\text{kg}_{\text{wet}}}{\text{m}^2}}{\text{unitless} * \text{unitless}}$$

where:

$Crop\_DRL_{mat,i}$ = Ingestion Derived Response Level for mature Crop/Produce, the ground concentration, or areal activity (µCi/m$^2$), of radionuclide *i* that will be expected to cause the crop/produce growing in that area to exceed the applicable Derived Intervention Level (DIL), µCi/kg;

$DIL_{organ,age,i}$ = Derived Intervention Level, the activity concentration level of radionuclide *i* for which the ingestion dose to the most sensitive population (age group) and target organ has the potential to exceed the applicable ingestion PAG, µCi/$kg_{wet}$;

$Y$ = Crop Yield, the mass of crop grown per area of land, $kg_{wet}/m^2$;

$CRF$ = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop, unitless;

$\lambda_i$ = Decay constant for the radionuclide *i*, $d^{-1}$; and

$t_m$ = Time to Market, the number of days from harvest to consumption (default 1), d.

## Method 4.2.2 Crop_DRL for Immature Crop/Produce

This method is used to predict the level of radioactive material (e.g., µCi/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 4.2-2 shows the $Crop\_DRL_{imm,i}$ calculation.

$$Crop\_DRL_{imm,i} = \frac{DIL_{organ,age,i}}{\left( \frac{CRF * \left( \frac{1\text{-}e^{-\lambda_w t_f}}{\lambda_w * t_f} \right)}{Y} + \frac{TF_{crop,i} * MCF_{D-W,f}}{d_m * \rho_{soil}} \right) * \left( \frac{1\text{-}e^{-\lambda_i t_f}}{\lambda_i * t_f} \right) * e^{-\lambda_i t_m}} \quad \text{(Eq. 4.2-2)}$$

$$\frac{\mu\text{Ci}}{\text{m}^2} = \frac{\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}}{\left( \frac{\text{unitless} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}}}{\frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \frac{\left( \frac{\mu\text{Ci}}{\text{kg}_{\text{dry}}} \Big/ \frac{\mu\text{Ci}}{\text{kg}_{\text{soil}}} \right) * \frac{\text{kg}_{\text{dry}}}{\text{kg}_{\text{wet}}}}{\text{m} * \frac{\text{kg}_{\text{soil}}}{\text{m}^3}} \right) * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \text{unitless}}$$

where:

*Crop_DRL*$_{imm,i}$ = Ingestion Derived Response Level for immature Crop/Produce, the ground concentration, or areal activity ($\mu$Ci/m$^2$), of radionuclide *i* that will be expected to cause the crop/produce growing in that area to exceed the applicable Derived Intervention Level (DIL), $\mu$Ci/kg$_{wet}$.

*DIL*$_{organ,age,i}$ = Derived Intervention Level, the activity concentration level of radionuclide *i* for which the ingestion dose to the most sensitive population (age group) and target organ has the potential to exceed the applicable ingestion PAG, $\mu$Ci/kg$_{wet}$;

*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 (default 4.62E-02, corresponds to a 15 day half life) d$^{-1}$;

$t_f$ = Field Time, the time the crop spends growing in the field from deposition or sampling to harvest, d;

$\left(\frac{1\text{-}e^{-\lambda_w t_f}}{\lambda_w * t_f}\right)$ = 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 (default 2.0 for produce), $kg_{wet}/m^2$;

$TF_{crop,i}$ = Transfer Factor for a food crop, the fraction of radionuclide *i* deposited on the ground that is transferred to the plant during the growing season, $\mu Ci/kg_{dry}$ per $\mu Ci/kg_{soil}$;

$MCF_{D\text{-}W,f}$ = Mass Conversion Factor (dry to wet), the ratio of dry mass to wet mass for a food type (f), $kg_{dry}/kg_{wet}$;

$d_m$ = Mixing Depth (default 1.0E-03 for the first growing season and 0.15 after plowing) (EPA89), m;

$\rho_{soil}$ = Soil density (default 1600), $kg_{soil}/m^3$;

$\lambda_i$ = Decay constant for radionuclide *i*, $d^{-1}$;

$\left(\frac{1\text{-}e^{-\lambda_i t_f}}{\lambda_i * t_f}\right)$ = 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 (default 1), d.

# EXAMPLE 1

**Problem: Calculate the Mature Crop/Produce Ingestion DRL for $^{60}$Co.**

The most conservative DIL for $^{60}$Co is 0.02 µCi/$kg_{wet}$ (3 month old, whole body).

Assuming that the crop is ready for immediate harvest, Equation 4.2-1 can be used to calculate the DRL.

$$Crop\_DRL_{mat,i} = \frac{DIL_{organ,age,i} * Y}{CRF_i * e^{-\lambda_i t_m}} \qquad \text{(Eq. 4.2-1)}$$

$$\frac{\mu\text{Ci}}{\text{m}^2} = \frac{\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \frac{\text{kg}_{\text{wet}}}{\text{m}^2}}{\text{unitless} * \text{unitless}}$$

Assuming:

$CRF$ = 0.2
$Y$ = 2.0 $kg_{wet}/m^2$;
$\lambda_{Co}$ = 3.6E-04 $d^{-1}$; and
$t_m$ = 1 d.

$$Crop\_DRL_{^{60}Co} = \frac{0.02\frac{\mu\text{Ci}}{\text{kg}} * 2\frac{\text{kg}}{\text{m}^2}}{0.2 * \text{e}^{-3.6\text{E-04d}^{-1} * 1\text{d}}} = 0.2\frac{\mu\text{Ci}}{\text{m}^2}$$

# EXAMPLE 2

**Problem: Calculate the Immature Crop/Produce Ingestion DRL for $^{60}$Co on Lettuce.**

The most conservative DIL for $^{60}$Co is 0.02 µCi/$kg_{wet}$ (3 month old, whole body).

Assuming that the lettuce has already been planted and will be harvested in 90 days, Equation 4.2-2 can be used to calculate the DRL.

$$Crop\_DRL_{imm,i} = \frac{DIL_{organ,age,i}}{\left( \frac{CRF * \left( \frac{1\text{-}e^{-\lambda_w t_f}}{\lambda_w * t_f} \right)}{Y} + \frac{TF_{crop,i} * MCF_{D-W,f}}{d_m * \rho_{soil}} \right) * \left( \frac{1\text{-}e^{-\lambda_i t_f}}{\lambda_i * t_f} \right) * e^{-\lambda_i t_m}} \quad \text{(Eq. 4.2-2)}$$

Assuming:

$CRF$ = 0.2
$\lambda_w$ = 4.62E-02 $d^{-1}$;
$t_f$ = 90 d;
$Y$ = 2.0 $kg_{wet}/m^2$;
$TF_{lettuce,i}$ = 0.23 µCi/$kg_{dry}$ per µCi/$kg_{soil}$;
$MCF_{D\text{-}W,f}$ = 0.2 $kg_{dry}/kg_{wet}$ for leafy vegetables;
$d_m$ = 1.0E-03 m;
$\rho_{soil}$ = 1600 $kg_{soil}/m^3$;
$\lambda_{Co}$ = 3.6E-04 $d^{-1}$; and
$t_m$ = 1 d.

$$Crop\_DRL_{imm,^{60}Co} = \frac{0.02 \frac{\mu Ci}{kg_{wet}}}{\left( \frac{0.2 * \frac{1\text{-}e^{-4.62E\text{-}02d^{-1} * 90d}}{4.62E\text{-}02d^{-1} * 90d}}{2.0 \frac{kg_{wet}}{m^2}} + \frac{0.23 \left( \frac{\mu Ci}{kg_{dry}} \Big/ \frac{\mu Ci}{kg_{soil}} \right) * 0.2 \frac{kg_{dry}}{kg_{wet}}}{1.0E\text{-}03\ m * 1600 \frac{kg_{soil}}{m^3}} \right) * \frac{1\text{-}e^{-3.6E\text{-}04d^{-1} * 90d}}{3.6E\text{-}04d^{-1} * 90d} * e^{-3.6E\text{-}04d^{-1} * 1d}}$$

$$= 0.39 \frac{\mu Ci}{m^2}$$

# METHOD 4.3 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:

- Represents:
    1. $Milk\_DRL_{area,A,i}$: The ground concentration, or areal activity (µCi/m$^2$), of radionuclide *i* deposited over a grazing area that would result in a grazing animal's milk exceeding the Derived Intervention Level (DIL) for that radionuclide;
    2. $Milk\_DRL_{mass,A,i}$: The mass concentration (µCi/kg$_{wet}$), of radionuclide *i* in animal feed that would result in the animal's milk exceeding the Derived Intervention Level (DIL) for that radionuclide; or
    3. $Milk\_DRL_{water,A,i}$: The water concentration (µCi/l), of radionuclide *i* in an animal's drinking water that would result in the animal's milk exceeding the Derived Intervention Level (DIL) for that radionuclide.

- 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 that the PAG has the potential to be exceeded.

- 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.

- 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).

- Is calculated using the DIL calculated in Method 4.1.

## Discussion

The Milk_DRL predicts the amount of radioactivity deposited either on an animal's grazing area (µCi/m$^2$) or in an animal's feed or water (µCi/kg$_{wet}$ or µCi/l) that would cause the animal's milk to exceed 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 $^{103}$Ru and $^{106}$Ru).
2) Are based on the most restrictive DIL for each radionuclide based on age group and target organ. See Method 4.1 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 $kg_{wet}$/d for feed, 60 l/d for water, and 0.5 $kg_{soil}$/d for soil.
   - Goat – 6 $kg_{wet}$/d for feed, 8 l/d for water, and 0.06 $kg_{soil}$/d for soil.
5) Assume a forage yield of 0.7 $kg_{wet}/m^2$ for pastureland.
6) Assume a milk density of 1.04 $kg_{wet}$/l.
7) Assume a soil density of 1600 $kg_{soil}/m^3$.
8) Assume a mixing depth of 1.0E-03 m for the first growing season and 0.15 after plowing (EPA89).
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 5.2.

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., $^{134}Cs+^{137}Cs$) 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:

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).

Constants – Crop Retention Factor, Crop Yield, Animal Daily Intake Rates (Feed, Water, Soil), Transfer Factor for Milk for each radionuclide, density of milk.

Other Factors – Decay of radionuclides during the time period under consideration, fraction of animals’ diet contaminated, soil mixing depth.

Appropriate DIL for each radionuclide – Calculated using Method 4.1.

If incident-specific values have not been established, recommended default values for selected inputs are available in Appendix C.

**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

The final output of this method is the Milk_DRL value for a radionuclide contaminant for the growing area.

### Final

$Milk\_DRL_i$ = Ingestion Derived Response Level for Milk, expressed as one of the following:

1. $Milk\_DRL_{area}$: The ground concentration, or areal activity (µCi/m$^2$), of radionuclide *i* deposited over a grazing area that would result in a grazing

animal's milk exceeding the Derived Intervention Level (DIL) for that radionuclide;

2. $Milk\_DRL_{mass}$: The mass concentration ($\mu Ci/kg_{wet}$) of radionuclide *i* in animal feed that would result in the animal's milk exceeding the Derived Intervention Level (DIL) for that radionuclide; or
3. $Milk\_DRL_{water}$: The water concentration (µCi/l) of radionuclide *i* in an animal's drinking water that would result in the animal's milk exceeding 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 4.3.1 Ingestion DRL for Milk based on areal activity (µCi/m²) on forage

This method calculates the areal activity level ($\mu Ci/m^2$) of a radionuclide deposited over a grazing area that would result in a grazing animal's milk exceeding the DIL for the radionuclide.

## Calculation

Equation 4.3-1 shows this $Milk\_DRL_{area}$ calculation.

$$Milk\_DRL_{area,A,i} = \frac{DIL_{organ,age,i} * \rho_{milk}}{\left[\frac{(CRF * AFDIR)}{Y} + \frac{ASDIR}{\rho_{soil} * d_m}\right] * FDC_F * TF_{Milk,A,i} * e^{-\lambda_i t_m}} \quad \text{(Eq. 4.3-1)}$$

$$\frac{\mu Ci}{m^2} = \frac{\frac{\mu Ci}{kg_{wet}} * \frac{kg_{wet}}{l}}{\left[\frac{\left(\text{unitless} * \frac{kg_{wet}}{d}\right)}{\frac{kg_{wet}}{m^2}} + \frac{\frac{kg_{soil}}{d}}{\frac{kg_{soil}}{m^3} * m}\right] * \text{unitless} * \frac{\mu Ci/l}{\mu Ci/d} * \text{unitless}}$$

where:

$Milk\_DRL_{area,A,i}$ = Ingestion Derived Response Level for Milk, the ground concentration, or areal activity, of radionuclide *i* that will be expected to cause the milk produced by grazing animals (*A*) to exceed the Derived Intervention Level (DIL) for that radionuclide, $\mu Ci/m^2$;

$DIL_{organ, age, i}$ = Derived Intervention Level, the activity concentration level of radionuclide *i* at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to exceed the applicable ingestion PAG, $\mu Ci/kg_{wet}$;
$\rho_{milk}$ = Milk density, $kg_{wet}/l$;
*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, $kg_{wet}/d$;
*Y* = Crop Yield, the mass of crop grown per area of land, $kg_{wet}/m^2$;
*ASDIR* = Animal Soil Daily Ingestion Rate, the daily rate at which an animal consumes soil, $kg_{soil}/d$;
$\rho_{soil}$ = Soil density, $kg_{soil}/m^3$;
$d_m$ = Mixing Depth, m;
$FDC_F$ = Fraction of Diet Contaminated (feed), the fraction of the animal's diet that is from contaminated feed (default 1.0), unitless;
**NOTE:** 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, µCi/l per µCi/d;
$\lambda_i$ = Decay constant for the radionuclide *i*, $d^{-1}$;
$t_m$ = Time to Market, the number of days from harvest to consumption (default 2), d; and
$e^{-\lambda_i t_m}$ = Radioactive Decay adjustment for radionuclide *i* over time $t_m$, unitless.

## Method 4.3.2 Ingestion DRL for Milk based on radionuclide concentration ($\mu Ci/kg_{wet}$) in forage mass

This method calculates the mass concentration level ($\mu Ci/kg_{wet}$) of a radionuclide in animal feed that would result in the animal's milk exceeding the DIL for the radionuclide.

## Calculation

Equation 4.3-2 shows this $Milk\_DRL_{mass}$ calculation.

$$Milk\_DRL_{mass,A,i} = \frac{DIL_{organ,age,i} * \rho_{milk}}{AFDIR * FDC_F * TF_{Milk,A,i} * e^{-\lambda_i t_m}} \qquad \text{(Eq. 4.3-2)}$$

$$\frac{\mu Ci}{kg_{wet}} = \frac{\frac{\mu Ci}{kg_{wet}} * \frac{kg_{wet}}{l}}{\frac{kg_{wet}}{d} * unitless * \frac{\mu Ci/l}{\mu Ci/d} * unitless}$$

where:

| | | |
|---|---|---|
| $Milk\_DRL_{mass,A,i}$ | = | Ingestion Derived Response Level for Milk, the mass concentration of radionuclide *i* that will be expected to cause the milk produced by grazing animals (*A*) to exceed the Derived Intervention Level (DIL) for that radionuclide, $\mu Ci/kg_{wet}$; |
| $DIL_{organ,\ age,\ i}$ | = | Derived Intervention Level, the activity concentration level of radionuclide *i* at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to exceed the applicable ingestion PAG, $\mu Ci/kg_{wet}$; |
| $\rho_{milk}$ | = | Milk density, $kg_{wet}/l$; |
| *AFDIR* | = | Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed, $kg_{wet}/d$; |
| $FDC_F$ | = | Fraction of Diet Contaminated (feed), the fraction of the animal's diet that is from contaminated feed (default 1.0), unitless; **NOTE:** 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, μCi/l per μCi/d; |
| $\lambda_i$ | = | Decay constant for the radionuclide *i*, $d^{-1}$; |
| $t_m$ | = | Time to Market, the number of days from harvest to consumption (default 2), 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 4.3.3 Ingestion DRL for Milk based on radionuclide concentration (μCi/l) in water

This method calculates the concentration level (μCi/l) of a radionuclide in an animal's drinking water that would result in the animal's milk exceeding the DIL for the radionuclide.

## Calculation

Equation 4.3-3 shows this $Milk\_DRL_{water}$ calculation.

$$Milk\_DRL_{water,A,i} = \frac{DIL_{organ,age,i} * \rho_{milk}}{AWDIR * FDC_W * TF_{Milk,A,i} * e^{-\lambda_i t_m}} \qquad \text{(Eq. 4.3-3)}$$

$$\frac{\mu Ci}{l} = \frac{\frac{\mu Ci}{kg_{wet}} * \frac{kg_{wet}}{l}}{\frac{l}{d} * unitless * \frac{\mu Ci/l}{\mu Ci/d} * unitless}$$

where:

$Milk\_DRL_{water,A,i}$ = Ingestion Derived Response Level for Milk, the water concentration of radionuclide *i* that will be expected to cause the milk produced by animals drinking contaminated water (*A*) to exceed the Derived Intervention Level (DIL) for that radionuclide, µCi/l;

$DIL_{organ,\ age,\ i}$ = Derived Intervention Level, the activity concentration level of radionuclide *i* at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to exceed the applicable ingestion PAG, µCi/$kg_{wet}$;

$\rho_{milk}$ = Milk density, $kg_{wet}$/l;

*AWDIR* = Animal Water Daily Ingestion Rate, the daily rate at which an animal consumes water, l/d;

$FDC_W$ = Fraction of Diet Contaminated (water), the fraction of an animal's diet that is from contaminated water (default 1.0), unitless;
**NOTE:** 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, µCi/l per µCi/d;

$\lambda_i$ = Decay constant for the radionuclide *i*, $d^{-1}$;

$t_m$ = Time to Market, the number of days from harvest to consumption (default 2), d; and

$e^{-\lambda itm}$ = 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 Cow Milk Ingestion DRL for $^{60}$Co in units of areal activity (µCi/m$^2$)**

The most conservative DIL for $^{60}$Co is 0.02 µCi/kg$_{wet}$ (3 month old, whole body).

Equation 4.3-1 can be used to calculate the DRL.

$$Milk\_DRL_{area,A,i} = \frac{DIL_{organ,age,i} * \rho_{milk}}{\left[\frac{(CRF * AFDIR)}{Y} + \frac{ASDIR}{\rho_{soil} * d_m}\right] * FDC_F * TF_{Milk,A,i} * e^{-\lambda_i t_m}}$$

Assuming:

$\rho_{milk}$ = 1.04 kg$_{wet}$/l,
$CRF$ = 0.5,
$AFDIR_{cow}$ = 50 kg$_{wet}$/d,
$Y$ = 0.7 kg$_{wet}$/m$^2$,
$ASDIR_{cow}$ = 0.5 kg$_{soil}$/d,
$\rho_{soil}$ = 1600 kg$_{soil}$/m$^3$,
$d_m$ = 1.0E-03 m,
$FDC_F$ = 1.0,
$TF_{Milk,cow,60Co}$ = 3.0E-04 µCi/l per µCi/d,
$\lambda_{Co}$ = 3.60E-04 d$^{-1}$, and
$t_m$ = 2 days.

The $Milk\_DRL_{area}$ for $^{60}$Co for cow milk equals:

$$Milk\_DRL_{area,cow,^{60}Co} = \frac{0.02\frac{\mu Ci}{kg_{wet}} * 1.04\frac{kg_{wet}}{l}}{\left[\left(\frac{0.5 * 50\frac{kg_{wet}}{d}}{0.7\frac{kg_{wet}}{m^2}}\right) + \frac{0.5\frac{kg_{soil}}{d}}{1600\frac{kg_{soil}}{m^3} * 1.0E\text{-}03\ m}\right] * 1 * 3.0E\text{-}04\frac{\mu Ci/l}{\mu Ci/d} * e^{-3.6E\text{-}04 d^{-1} * 2d}} = 1.92\frac{\mu Ci}{m^2}$$

Therefore cows grazing in areas with $^{60}$Co contamination on the ground greater than 1.92 µCi/m$^2$ have the potential to produce milk that would exceed the DIL. Milk that exceeds the DIL could produce a dose that exceeds the PAG when consumed by a 3 month old.

## EXAMPLE 2

**Problem: Calculate the Cow Milk Ingestion DRL for $^{60}Co$ in units of mass concentration (µCi/$kg_{wet}$)**

The most conservative DIL for $^{60}Co$ is 0.02 µCi/$kg_{wet}$ (3 month old, whole body).

Equation 4.3-2 can be used to calculate the DRL.

$$Milk\_DRL_{mass,A,i} = \frac{DIL_{organ,age,i} * \rho_{milk}}{AFDIR * FDC_F * TF_{Milk,A,i} * e^{-\lambda_i t_m}}$$

Assuming:

$\rho_{milk}$ = 1.04 $kg_{wet}$/l,
$AFDIR_{cow}$ = 50 $kg_{wet}$/d,
$FDC_F$ = 1.0,
$TF_{Milk,cow,60Co}$ = 3.0E-04 µCi/l per µCi/d,
$\lambda_{Co}$ = 3.60E-04 $d^{-1}$, and
$t_m$ = 2 days.

The $Milk\_DRL_{mass}$ for $^{60}Co$ for cow milk equals:

$$Milk\_DRL_{mass,cow,^{60}Co} = \frac{0.02\frac{\mu Ci}{kg_{wet}} * 1.04\frac{kg_{wet}}{l}}{50\frac{kg_{wet}}{d} * 1 * 3.0E\text{-}04\frac{\mu Ci/l}{\mu Ci/d} * e^{-3.6E-04*2}} = 1.38\frac{\mu Ci}{kg_{wet}}$$

Therefore cows that eat forage with $^{60}Co$ contamination greater than 1.38 µCi/$kg_{wet}$ have the potential to produce milk that would exceed the DIL. Milk that exceeds the DIL could produce a dose that exceeds the PAG when consumed by a 3 month old.

## EXAMPLE 3

**Problem: Calculate the Cow Milk Ingestion DRL for $^{60}$Co in units of water concentration (µCi/l)**

The most conservative DIL for $^{60}$Co is 0.02 µCi/$kg_{wet}$ (3 month old, whole body).

Equation 4.3-3 can be used to calculate the DRL.

$$Milk\_DRL_{water,A,i} = \frac{DIL_{organ,age,i} * \rho_{milk}}{AWDIR * FDC_W * TF_{Milk,A,i} * e^{-\lambda_i t_m}}$$

Assuming:

$\rho_{milk}$ = 1.04 $kg_{wet}$/l,
$AWDIR_{cow}$ = 60 l/d,
$FDC_W$ = 1.0,
$TF_{Milk,cow,60Co}$ = 3.0E-04 µCi/l per µCi/d,
$\lambda_{Co}$ = 3.60E-04 $d^{-1}$, and
$t_m$ = 2 days

The $Milk\_DRL_{water}$ for $^{60}$Co for cow milk equals:

$$Milk\_DRL_{water,cow,{}^{60}Co} = \frac{0.02\frac{\mu Ci}{kg_{wet}} * 1.04\frac{kg_{wet}}{l}}{60\frac{l}{d} * 1 * 3.0\text{E-}04\frac{\mu Ci/l}{\mu Ci/d} * e^{-3.6\text{E-}04*2}} = 1.15\frac{\mu Ci}{l}$$

Therefore cows that drink water with $^{60}$Co contamination greater than 1.15 µCi/l have the potential to produce milk that would exceed the DIL. Milk that exceeds the DIL could produce a dose that exceeds the PAG when consumed by a 3 month old.

# METHOD 4.4 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:

- Represents:
    1. $Meat\_DRL_{area,A,i}$: The ground concentration, or areal activity (μCi/m$^2$), of radionuclide *i* deposited over a grazing area that would result in a grazing animal's (*A*) meat exceeding the Derived Intervention Level (DIL) for that radionuclide;
    2. $Meat\_DRL_{mass,A,i}$: The mass concentration (μCi/kg$_{wet}$), of radionuclide *i* in animal feed that would result in the animal's (*A*) meat exceeding the Derived Intervention Level (DIL) for that radionuclide; or
    3. $Meat\_DRL_{water,A,i}$: The water concentration (μCi/l), of radionuclide *i* in an animal's drinking water that would result in the animal's (*A*) meat exceeding the Derived Intervention Level (DIL) for that radionuclide.

- 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 that the PAG has the potential to be exceeded.

- 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.

- 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).

- Is calculated using the DIL calculated in Method 4.1

## Discussion

The Meat_DRL predicts the amount of radioactivity deposited either on an animal's grazing area (μCi/m$^2$) or in an animal's feed or water (μCi/kg$_{wet}$ or μCi/l) that would cause the animal's meat to exceed 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 $^{103}$Ru and $^{106}$Ru).
2) Are based on the most restrictive DIL for each radionuclide based on age group and target organ. See Method 4.1 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 $kg_{wet}$/d for feed, 60 l/d for water, and 0.5 $kg_{soil}$/d for soil.
   - Goat – 6 $kg_{wet}$/d for feed, 8 l/d for water, and 0.06 $kg_{soil}$/d for soil.
5) Assume a forage yield of 0.7 $kg_{wet}/m^2$ for pastureland.
6) Assume a soil density of 1600 $kg_{soil}/m^3$.
7) Assume a mixing depth of 1.0E-03 m for the first growing season and 0.15 after plowing (EPA89).
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 5.2.

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., $^{134}Cs$+$^{137}Cs$) 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:

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).

Constants – Crop Retention Factor, Crop Yield, Animal Daily Intake Rates (Feed, Water, Soil), Transfer Factor for each type of Meat and for each radionuclide.

Other Factors – Decay of radionuclides during the time period under consideration, fraction of animals' diet contaminated, soil mixing depth.

Appropriate DIL for each radionuclide – Calculated using Method 4.1.

If incident-specific values have not been established, recommended default values for selected inputs are available in Appendix C.

**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

The final output of this method is the Meat_DRL value for a radionuclide contaminant for the growing area.

### Final

$Meat\_DRL_i$ = Ingestion Derived Response Level for Meat, expressed as one of the following:

1. $Meat\_DRL_{area,A,i}$: The ground concentration, or areal activity (µCi/m$^2$), of radionuclide *i* deposited over a grazing area that would result in a grazing animal's (*A*) meat exceeding the Derived Intervention Level (DIL) for that radionuclide;

2. $Meat\_DRL_{mass,A,i}$: The mass concentration (µCi/$kg_{wet}$) of radionuclide *i* in animal feed that would result in the animal's (*A*) meat exceeding the Derived Intervention Level (DIL) for that radionuclide; or
3. $Meat\_DRL_{water,A,i}$: The water concentration (µCi/l) of radionuclide *i* in an animal's drinking water that would result in the animal's (*A*) meat exceeding 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 4.4.1 Ingestion DRL for Meat based on areal activity (µCi/m$^2$) on forage

This method calculates the areal activity level (µCi/m$^2$) of a radionuclide deposited over a grazing area that would result in a grazing animal's meat exceeding the DIL for the radionuclide.

## Calculation

Equation 4.4-1 shows this $Meat\_DRL_{area}$ calculation.

$$Meat\_DRL_{area,A,i} = \frac{DIL_{organ,age,i}}{\left[\frac{\left(CRF * \left(\frac{1\text{-}e^{-\lambda_w t_g}}{\lambda_w * t_g}\right) * AFDIR\right)}{Y} + \frac{ASDIR}{\rho_{soil} * d_m}\right] * FDC_F * TF_{Meat,A,i} * \left(\frac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g}\right) * e^{-\lambda_i t_m}}$$

(Eq. 4.4-1)

$$\frac{\mu\text{Ci}}{\text{m}^2} = \frac{\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}}{\left[\frac{\left(\text{unitless} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \frac{\text{kg}_{\text{wet}}}{\text{d}}\right)}{\frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \frac{\frac{\text{kg}_{\text{soil}}}{\text{d}}}{\frac{\text{kg}_{\text{soil}}}{\text{m}^3} * \text{m}}\right] * \text{unitless} * \frac{\mu\text{Ci}/\text{kg}_{\text{wet}}}{\mu\text{Ci}/\text{d}} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \text{unitless}}$$

where:

$Meat\_DRL_{area,A,i}$ = Ingestion Derived Response Level for Meat, the ground concentration, or areal activity, of radionuclide *i* that will be expected to cause the meat from grazing animals ($A$) to exceed the Derived Intervention Level (DIL) for that radionuclide, µCi/m$^2$;

$DIL_{organ,\ age,\ i}$ = Derived Intervention Level, the activity concentration level of radionuclide $i$ at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to exceed the applicable ingestion PAG, µCi/kg$_{wet}$;

$CRF$ = 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 (default 4.62E-02, corresponds to a 15 day half life), d$^{-1}$;

$t_g$ = Grazing Time, time from deposition or sampling to the end of the grazing period, d;

$\left(\frac{1\text{-}e^{-\lambda_w t_g}}{\lambda_w * t_g}\right)$ = 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, kg$_{wet}$/d;

$Y$ = Crop Yield, the mass of crop grown per area of land, kg$_{wet}$/m$^2$;

$ASDIR$ = Animal Soil Daily Ingestion Rate, the daily rate at which an animal consumes soil, kg$_{soil}$/d;

$\rho_{soil}$ = Soil density, kg$_{soil}$/m$^3$;

$d_m$ = Mixing Depth, m;

$FDC_F$ = Fraction of Diet Contaminated (feed), the fraction of the animal's diet that is from contaminated feed (default 1.0), unitless;
**NOTE:** 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, µCi/kg$_{wet}$ per µCi/d;

$\lambda_i$ = Decay constant for the radionuclide $i$, d$^{-1}$;

$\left(\frac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g}\right)$ = 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 (default 20), d; and

$e^{-\lambda i t m}$ = Radioactive Decay adjustment for radionuclide $i$ over time $t_m$, unitless.

# Method 4.4.2 Ingestion DRL for Meat based on radionuclide concentration (µCi/kg$_{wet}$) in forage mass

This method calculates the mass concentration level (µCi/kg$_{wet}$) of a radionuclide in animal feed that would result in the animal's meat exceeding the DIL for the radionuclide.

## Calculation

Equation 4.4-2 shows this $Meat\_DRL_{mass}$ calculation.

$$Meat\_DRL_{mass,A,i} = \frac{DIL_{organ,age,i}}{AFDIR * FDC_F * TF_{Meat,A,i} * \left(\frac{1\text{-}e^{-\lambda_w t_g}}{\lambda_w * t_g}\right) * \left(\frac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g}\right) * e^{-\lambda_i t_m}}$$

(Eq. 4.4-2)

$$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} = \frac{\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}}{\frac{\text{kg}_{\text{wet}}}{\text{d}} * \text{unitless} * \frac{\mu\text{Ci}/\text{kg}_{\text{wet}}}{\mu\text{Ci}/\text{d}} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \text{unitless}}$$

where:

$Meat\_DRL_{mass,A,i}$ = Ingestion Derived Response Level for Meat, the mass concentration of radionuclide *i* that will be expected to cause the meat from grazing animals (*A*) to exceed the Derived Intervention Level (DIL) for that radionuclide, µCi/kg$_{wet}$;

$DIL_{organ,\ age,\ i}$ = Derived Intervention Level, the activity concentration level of radionuclide *i* at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to exceed the applicable ingestion PAG, µCi/kg$_{wet}$;

*AFDIR* = Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed, kg$_{wet}$/d;

$FDC_F$ = Fraction of Diet Contaminated (feed), the fraction of an animal's diet that is from contaminated feed (default 1.0), unitless;
**NOTE:** 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, µCi/kg$_{wet}$ per µCi/d;

$\lambda_w$ = Decay constant for weathering radioactive material off plants (default 4.62E-02, corresponds to a 15 day half life), d$^{-1}$;

$t_g$ = Grazing Time, time from deposition or sampling to the end of the grazing period, d;

$\lambda_i$ = Decay constant for the 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 (default 20), 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 4.4.3 Ingestion DRL for Meat based on radionuclide concentration (µCi/l) in water

This method calculates the concentration level (µCi/l) of a radionuclide in an animal's drinking water that would result in the animal's meat exceeding 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 4.4-3 shows this $Meat\_DRL_{water}$ calculation.

$$Meat\_DRL_{water,A,i} = \frac{DIL_{organ,age,i}}{AWDIR * FDC_W * TF_{Meat,A,i} * \left(\frac{1-e^{-\lambda_i t_g}}{\lambda_i * t_g}\right) * e^{-\lambda_i t_m}} \quad \text{(Eq. 4.4-3)}$$

$$\frac{\mu\text{Ci}}{\text{l}} = \frac{\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}}{\frac{\text{l}}{\text{d}} * \text{unitless} * \frac{\mu\text{Ci}/\text{kg}_{\text{wet}}}{\mu\text{Ci}/\text{d}} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \text{unitless}}$$

where:

$Meat\_DRL_{water,A,i}$ = Ingestion Derived Response Level for Meat, the water concentration of radionuclide *i* that will be expected to cause the meat from animals drinking contaminated water (*A*) to exceed the Derived Intervention Level (DIL) for that radionuclide, µCi/l;

$DIL_{organ,\ age,\ i}$ = Derived Intervention Level, the activity concentration level of radionuclide *i* at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to exceed the applicable ingestion PAG, µCi/$\text{kg}_{\text{wet}}$;

*AWDIR* = Animal Water Daily Ingestion Rate, the daily rate at which an animal consumes water, l/d;

$FDC_W$ = Fraction of Diet Contaminated (water), the fraction of an animal's diet that is from contaminated water (default 1.0), unitless;
**NOTE:** 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, µCi/$\text{kg}_{\text{wet}}$ per µCi/d;

$\lambda_i$ = Decay constant for the radionuclide *i*, $\text{d}^{-1}$;

$t_g$ = Grazing Time, time from deposition or sampling to the end of the grazing period, d;

$\left(\frac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g}\right)$ = 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 (default 20), 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 $^{60}$Co in units of areal activity (µCi/m$^2$)**

The most conservative DIL for $^{60}$Co is 0.02 µCi/kg$_{wet}$ (3 month old, whole body).

Assuming that the cow will continue to graze on the contaminated field for 90 days after deposition, Equation 4.4-1 can be used to calculate the DRL.

$$Meat\_DRL_{area,A,i} = \frac{DIL_{organ,age,i}}{\left[\frac{\left(CRF * \left(\frac{1\text{-}e^{-\lambda_w t_g}}{\lambda_w * t_g}\right) * AFDIR\right)}{Y} + \frac{ASDIR}{\rho_{soil} * d_m}\right] * FDC_F * TF_{Meat,A,i} * \left(\frac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g}\right) * e^{-\lambda_i t_m}}$$

Assuming:

$CRF$ = 0.5,
$\lambda_w$ = 4.62E-02 d$^{-1}$,
$t_g$ = 90 d,
$AFDIR_{cow}$ = 50 kg$_{wet}$/d,
$Y$ = 0.7 kg$_{wet}$/m$^2$,
$ASDIR_{cow}$ = 0.5 kg$_{soil}$/d,
$\rho_{soil}$ = 1600 kg$_{soil}$/m$^3$,
$d_m$ = 1.0E-03 m,
$FDC_F$ = 1.0,
$TF_{Meat,cow,60Co}$ = 1.0E-02 µCi/kg$_{wet}$ per µCi/d,
$\lambda_{Co}$ = 3.60E-04 d$^{-1}$, and
$t_m$ = 20 days

The $Meat\_DRL_{area}$ for $^{60}$Co for Beef equals:

$$Meat\_DRL_{area,cow,^{60}Co} = \frac{0.02\,\frac{\mu Ci}{kg_{wet}}}{\left[\frac{\left(0.5 * \frac{1\text{-}e^{-4.62E\text{-}02d^{-1} * 90d}}{4.62E\text{-}02d^{-1} * 90d} * 50\,\frac{kg_{wet}}{d}\right)}{0.7\,\frac{kg_{wet}}{m^2}} + \frac{0.5\,\frac{kg_{soil}}{d}}{1600\,\frac{kg_{soil}}{m^3} * 1.0E\text{-}03\text{ m}}\right] * 1 * 1.0E\text{-}02\,\frac{\mu Ci/kg_{wet}}{\mu Ci/d} * \frac{1\text{-}e^{-3.6E\text{-}04d^{-1} * 90d}}{3.6E\text{-}04d^{-1} * 90d} * e^{-3.6E\text{-}04 * 20}}$$

$$= 0.232\,\frac{\mu Ci}{m^2}$$

Therefore cows grazing for 90 days in areas with $^{60}$Co contamination on the ground greater than 0.232 µCi/m$^2$ at the start of the grazing period have the potential to produce meat (beef) that would exceed the DIL. Meat that exceeds the DIL could produce a dose that exceeds the PAG when consumed by a 3 month old.

## EXAMPLE 2

**Problem: Calculate the Meat (Beef) Ingestion DRL for $^{60}$Co in units of mass concentration (µCi/$kg_{wet}$)**

The most conservative DIL for $^{60}$Co is 0.02 µCi/$kg_{wet}$ (3 month old, whole body).

Assuming that the cow will continue to graze on the contaminated field for 90 days after deposition, Equation 4.4-2 can be used to calculate the DRL.

$$Meat\_DRL_{mass,A,i} = \frac{DIL_{organ,age,i}}{AFDIR * FDC_F * TF_{Meat,A,i} * \left(\frac{1\text{-}e^{-\lambda_w t_g}}{\lambda_w * t_g}\right) * \left(\frac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g}\right) * e^{-\lambda_i t_m}}$$

Assuming:

$AFDIR_{cow}$ = 50 $kg_{wet}$/d,
$FDC_F$ = 1.0,
$TF_{Meat,cow,60Co}$ = 1.0E-02 µCi/$kg_{wet}$ per µCi/d,
$\lambda_w$ = 4.62E-02 $d^{-1}$,
$t_g$ = 90 d,
$\lambda_{Co}$ = 3.60E-04 $d^{-1}$, and
$t_m$ = 20 days

The $Meat\_DRL_{mass}$ for $^{60}$Co for Beef equals:

$$Meat\_DRL_{mass,cow,^{60}Co} = \frac{0.02 \frac{\mu Ci}{kg_{wet}}}{50 \frac{kg_{wet}}{d} * 1 * 1.0E\text{-}02 \frac{\mu Ci / kg_{wet}}{\mu Ci / d} * \frac{1\text{-}e^{-4.62E\text{-}02 d^{-1} * 90d}}{4.62E\text{-}02 d^{-1} * 90d} * \frac{1\text{-}e^{-3.6E\text{-}04 d^{-1} * 90d}}{3.6E\text{-}04 d^{-1} * 90d} * e^{-3.6E\text{-}04 * 20}}$$

$$= 0.172 \frac{\mu Ci}{kg_{wet}}$$

Therefore cows that eat forage for 90 days with $^{60}$Co contamination greater than 0.172 µCi/$kg_{wet}$ at the start of the grazing period have the potential to produce meat (beef) that would exceed the DIL. Meat that exceeds the DIL could produce a dose that exceeds the PAG when consumed by a 3 month old.

# EXAMPLE 3

**Problem: Calculate the Meat (Beef) Ingestion DRL for $^{60}$Co in units of water concentration (µCi/l)**

The most conservative DIL for $^{60}$Co is 0.02 µCi/$kg_{wet}$ (3 month old, whole body).

Assuming that the cow will continue to drink the contaminated water for 90 days after deposition, Equation 4.4-3 can be used to calculate the DRL.

$$Meat\_DRL_{water,A,i} = \frac{DIL_{organ,age,i}}{AWDIR * FDC_W * TF_{Meat,A,i} * \left(\frac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g}\right) * e^{-\lambda_i t_m}}$$

Assuming:

$AWDIR_{cow}$ = 60 l/d,
$FDC_W$ = 1.0,
$TF_{Meat,cow,60Co}$ = 1.0E-02 µCi/$kg_{wet}$ per µCi/d,
$\lambda_{Co}$ = 3.60E-04 $d^{-1}$,
$t_g$ = 90 d, and
$t_m$ = 20 days

The $Meat\_DRL_{water}$ for $^{60}$Co for Beef equals:

$$Meat\_DRL_{water,cow,{}^{60}Co} = \frac{0.02\,\frac{\mu Ci}{kg_{wet}}}{60\,\frac{l}{d} * 1 * 1.0\text{E-}02\,\frac{\mu Ci / kg_{wet}}{\mu Ci / d} * e^{-3.6\text{E-}04*20}} = 3.39\text{E-}02\,\frac{\mu Ci}{l}$$

Therefore cows that drink water for 90 days with $^{60}$Co contamination greater than 3.39E-02 µCi/l at the start of the drinking period have the potential to produce meat (beef) that would exceed the DIL. Meat that exceeds the DIL could produce a dose that exceeds the PAG when consumed by a 3 month old.

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# METHOD 4.5 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:

- Can be applied to the whole body ($E_{50}$) or to a specific organ ($H_{T,50}$)
- 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.
- 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 (µCi/kg or µCi/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):

- Meat/Fish (Beef, Pork, Poultry, Fin Fish, Shell Fish, Other Meat);
- Crop/Produce (Leafy, Exposed, Protected, Other Produce, Breads, Cereals, Other Grains);
- Milk (Fresh Cow’s Milk, Other Dairy, Eggs); and
- 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 5.2.

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 4.7.

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:

- Data – Activity concentration (µCi/kg or µCi/l) from sample analysis data.
- Constants – Fraction of food contaminated, daily food intake rate, ingestion dose coefficient.
- 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).

If incident-specific values have not been established, recommended default values for selected inputs are available in Appendix C.

**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

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.

### Final

$E_{50}$ = Committed Effective Dose, the dose to the whole body, received by the receptor under consideration over the commitment period, from the ingestion of all radionuclides in contaminated food, mrem

$H_{T,50}$ = Committed Equivalent Dose, the dose to organ "t", received by the receptor under consideration over the commitment period, 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 the age group under consideration (mrem·d/$kg_{wet}$)

# Method 4.5.1 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 4.5-1 represents the final form of the Ingestion Dose calculation:

$$E_{50,Ing,age} = \sum_{Subgroup} \left( DFIR_{subgroup,age} * IngDP_{avg,age} \right) \qquad \text{(Eq. 4.5-1)}$$

$$\text{mrem} = \sum_{Subgroup} \left( \frac{\text{kg}_{\text{wet}}}{\text{d}} * \frac{\text{mrem·d}}{\text{kg}_{\text{wet}}} \right)$$

where:

$E_{50,Ing,age}$ = Committed Effective Dose from ingestion, the dose to the whole body, received by the age group under consideration over the commitment period, from ingestion of all radionuclides in all contaminated food types, mrem;

$DFIR_{subgroup,age}$ = Daily Food Intake Rate for a food subgroup for the age group under consideration (See Appendix C, Table 10), $kg_{wet}$/d;

$IngDP_{avg,age}$ = Average Ingestion Dose Parameter for a subgroup, the average of the individual $IngDP_{E,f,age}$ for each type of contaminated food in a subgroup for the age group under consideration, mrem·d/$kg_{wet}$.

### 4.5.1.1 Calculation of IngDP

Equation 4.5-2 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 $IngDP_{avg,age}$ 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.

**NOTE:** If detailed dietary intake amounts are available, individual food type intakes may be used instead of calculating an average for the subgroup, but this method does not assume that information is available.

$$IngDP_{E,f,age} = \sum_i C_{f,i} * FFC_{f,i} * IngDC_{E,age,i} * e^{-\lambda_i t_h} * \frac{1-e^{-\lambda_i t_c}}{\lambda_i} \quad \text{(Eq. 4.5-2)}$$

$$\frac{\text{mrem}\cdot\text{d}}{\text{kg}_{\text{wet}}} = \sum_i \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \text{unitless} * \frac{\text{mrem}}{\mu\text{Ci}} * \text{unitless} * \frac{\text{unitless}}{\text{d}^{-1}}$$

where:

$IngDP_{E,f,age}$ = Ingestion Dose Parameter, the committed effective dose received by the whole body (*E*) over the commitment period, from ingestion of all radionuclides in a specific food type (*f*) by a specific age group, mrem·d/$kg_{wet}$;

$C_{f,i}$ = Food Contamination, the level of contamination of radionuclide *i* in a specific food type (*f*), µCi/$kg_{wet}$ or µCi/l;

$FFC_{f,i}$ = Fraction of Food Type Contaminated, (default 1.0), unitless;
**NOTE:** If there is convincing local information that the actual *FFC* is considerably different, local authorities may decide to use a different *FFC*.

$IngDC_{E,age,i}$ = Ingestion Dose Coefficient, the ingestion pathway dose coefficient for the whole body (*E*) for the age group under consideration for radionuclide *i*, mrem/µCi;

$\lambda_i$ = Decay constant for radionuclide *i*, $d^{-1}$;

$t_h$ = Hold Time, the time elapsed from sample measurement to the beginning of the consumption period, d;

$e^{-\lambda ith}$ = Radioactive Decay adjustment for radionuclide *i* from sample measurement to the beginning of the consumption period, 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 4.5.2 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 $^{137}$Cs and $^{60}$Co for 1 year beginning 100 days after sampling.**

Assume food samples were collected for several food types with results as shown below:

**Table 4.5-E1**

| Food Type | $^{60}$Co ($\mu$Ci/kg$_{wet}$) | $^{137}$Cs ($\mu$Ci/kg$_{wet}$) |
|---|---|---|
| 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[a] | 3.00E-03[a] |
| Oranges | 6.50E-04 | 4.00E-05 |
| Water | 3.50E-03[a] | 5.00E-04[a] |
| [a] 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 4.5-2

Table 4.5-E2 shows the values needed to calculate the individual IngDP for each food type.

**Table 4.5-E2**

| Radionuclide | IngDC (mrem/µCi) | λ (days$^{-1}$) | $e^{-\lambda t_h}$ | $\frac{1-e^{-\lambda t_c}}{\lambda}$ (days) |
|---|---|---|---|---|
| $^{60}$Co | 12.7 | 3.6E-04 | 0.965 | 342 |
| $^{137}$Cs | 50.3 | 6.33E-05 | 0.993 | 361 |
| Time from sampling to start of consumption (hold time ($t_h$)): 100 days<br>Consumption period ($t_c$): 365 days<br>Fraction of Food Contaminated (FFC): 1.0 (default) | | | | |

Example IngDP calculation for Beef and IngDP values for the other contaminated food types (Table 4.5-E3):

$$IngDP_{E,Beef,Adult} = 2.5\text{E-}03\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * 1.0 * 1.0 * 12.7\frac{\text{mrem}}{\mu\text{Ci}} * 0.965 * 342\ \text{d}$$
$$+4.0\text{E-}03\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * 1.0 * 1.0 * 50.3\frac{\text{mrem}}{\mu\text{Ci}} * 0.993 * 361\ \text{d}$$
$$= 82.6\frac{\text{mrem}\cdot\text{d}}{\text{kg}_{\text{wet}}}$$

**Table 4.5-E3**

| Food Type | Sub-group | IngDP ($mrem \cdot d/kg_{wet}$) |
|---|---|---|
| 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 4.5-1

Obtain the Ingestion Dose for each subgroup by multiplying the IngDP for the subgroup by the associated Daily Food Intake Rate (DFIR), and then add up the subgroup doses to obtain the Committed Effective Dose ($E_{50}$) as shown in Table 4.5-E4.

**Table 4.5-E4**

| Food Type | Sub-group | IngDP ($mrem \cdot d/kg_{wet}$) | Daily Food Intake Rate ($kg_{wet}/d$)[a] | Subgroup Ingestion Dose (mrem) |
|---|---|---|---|---|
| Beef | Beef | 82.6 | 0.098 | 8.09 |
| Corn/Oranges | Protected Crop | 12.1[b] | 0.155 | 1.88 |
| Lettuce | Leafy Crop | 189 | 0.042 | 7.94 |
| Milk | Cow's Milk | 62.3 | 0.238 | 14.8 |
| Water | Tap Water | 23.7 | 0.679 | 16.1 |
| | | | $E_{50}$ (∑) | 48.8 |

[a] Assumes a density of 1.04 kg/l for milk and 1.0 kg/l for water.
[b] 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 ($H_{T,50}$) for a specific organ and/or different age group, use the appropriate IngDC for the organ/age group and calculate as demonstrated above.

# METHOD 4.6 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:

- Can be used to determine potential doses to individuals consuming the food when results from direct sampling of the food are not available.
- Uses deposition data to project potential contamination levels in crops, milk and meat.
- 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 ($\mu Ci/m^2$). 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 $kg_{wet}/m^2$ 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 5.2.

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 $kg_{wet}$/d for feed, 60 l/d for water, and 0.5 $kg_{soil}$/d for soil.
- Goat – 6 $kg_{wet}$/d for feed, 8 l/d for water, and 0.06 $kg_{soil}$/d for soil.

7) A forage yield of 0.7 $kg_{wet}/m^2$ 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 $kg_{soil}/m^3$.

10) Assume a mixing depth of 1.0E-03 m for the first growing season and 0.15 m after plowing (EPA89).

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:

- 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).
- 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.
- Other Factors – Decay of radionuclides during the time period under consideration, fraction of animals' diet contaminated, soil mixing depth.

If incident-specific values have not been established, recommended default values for selected inputs are available in Appendix C.

**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

The final output of this method is the projected contamination levels in foods that have been affected by a deposition of radioactive material.

### Final

$C_{crop}$ = Projected Contamination level in a food Crop (fresh produce), the level of activity per mass in a food type harvested from contaminated ground, $\mu Ci/kg_{wet}$;

$C_{milk}$ = Projected Contamination level in Milk, the level of activity per volume in milk produced from consuming radioactive material, μCi/l; and
$C_{meat}$ = Projected Contamination level in Meat, the level of activity per mass in meat produced from consuming radioactive material, μCi/$kg_{wet}$.

**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 4.5 to calculate ingestion dose when food samples are not available.

# Method 4.6.1 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 4.6-1 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:

$$C_{crop,i} = \frac{Dp_i * CRF}{Y} * e^{-\lambda_i t_m} \qquad \text{(Eq. 4.6-1)}$$

$$\frac{\mu\text{Ci}}{\text{kg}_\text{wet}} = \frac{\frac{\mu\text{Ci}}{\text{m}^2} * \text{unitless}}{\frac{\text{kg}_\text{wet}}{\text{m}^2}} * \text{unitless}$$

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, μCi/$kg_{wet}$;
$Dp_{i(m)}$ = Deposition, the areal activity of a marker radionuclide *i(m)* per unit area of ground at $t_0$ (deposition), μCi/$m^2$;
$CRF$ = 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, $kg_{wet}/m^2$; and
$\lambda_i$ = Decay constant for the radionuclide *i*, $d^{-1}$;
$t_m$ = Time to Market, the number of days from harvest to consumption (default 1), d; and
$e^{-\lambda itm}$ = Radioactive Decay adjustment for radionuclide *i* over time $t_m$, unitless.

## Method 4.6.2 Calculation of Contamination in Milk

Equation 4.6-2a 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.

$$C_{milk,i} = \left\{ \begin{array}{l} Dp_i * \left[ \dfrac{(CRF * AFDIR)}{Y} + \dfrac{ASDIR}{\rho_{soil} * d_m} \right] * FDC_F \\ + \left[ AWDIR * FDC_W * C_W \right] \end{array} \right\} * TF_{Milk,A,i} * e^{-\lambda_i t_m} \quad \text{(Eq. 4.6-2a)}$$

$$\frac{\mu\text{Ci}}{\text{l}} = \left\{ \begin{array}{l} \dfrac{\mu\text{Ci}}{\text{m}^2} * \left[ \dfrac{\left(\text{unitless} * \dfrac{\text{kg}_{\text{wet}}}{\text{d}}\right)}{\dfrac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \dfrac{\dfrac{\text{kg}_{\text{soil}}}{\text{d}}}{\dfrac{\text{kg}_{\text{soil}}}{\text{m}^3} * \text{m}} \right] * \text{unitless} \\ + \left[ \dfrac{\text{l}}{\text{d}} * \text{unitless} * \dfrac{\mu\text{Ci}}{\text{l}} \right] \end{array} \right\} * \frac{\mu\text{Ci}/\text{l}}{\mu\text{Ci}/\text{d}} * \text{unitless}$$

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, µCi/l;
- $CRF$ = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop (default 0.5 for pastureland), unitless;
- $AFDIR$ = Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed, $\text{kg}_{\text{wet}}$/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, $\text{kg}_{\text{soil}}$/d;
- $\rho_{soil}$ = Soil density, $\text{kg}_{\text{soil}}/\text{m}^3$;
- $d_m$ = Mixing Depth, m;
- $FDC_F$ = Fraction of the animals' Diet Contaminated (feed), unitless;
- $Dp_i$ = Deposition, the areal radioactivity of radionuclide *i* per unit area of ground, $\mu\text{Ci}/\text{m}^2$;
- $AWDIR$ = 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;
- $C_W$ = Contamination level in drinking water, µCi/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, µCi/l per µCi/d;
- $\lambda_i$ = Decay constant for the radionuclide *i*, $\text{d}^{-1}$;

$t_m$ = Time to Market, the number of days from harvest to consumption (default 2), d; and

$e^{-\lambda itm}$ = Radioactive Decay adjustment for radionuclide *i* over time $t_m$, unitless.

If the contamination level in the soil is known (µCi/$kg_{soil}$) the equation can be rewritten as shown in Equation 4.6-2b.

$$C_{milk,i} = \left\{ \begin{array}{l} \dfrac{\left(Dp_i * CRF * AFDIR * FDC_F\right)}{Y} + \left(ASDIR * C_S\right) \\ + \left(AWDIR * FDC_W * C_W\right) \end{array} \right\} * TF_{Milk,A,i} * e^{-\lambda_i t_m}$$

(Eq. 4.6-2b)

$$\frac{\mu Ci}{l} = \left\{ \begin{array}{l} \dfrac{\left(\dfrac{\mu Ci}{m^2} * unitless * \dfrac{kg_{wet}}{d} * unitless\right)}{\dfrac{kg_{wet}}{m^2}} + \left(\dfrac{kg_{soil}}{d} * \dfrac{\mu Ci}{kg_{soil}}\right) \\ + \left(\dfrac{l}{d} * unitless * \dfrac{\mu Ci}{l}\right) \end{array} \right\} * \frac{\mu Ci / l}{\mu Ci / d} * unitless$$

where:

$C_S$ = Contamination level in soil, µCi/$kg_{soil}$;

## Method 4.6.3 Calculation of Contamination in Meat

Equation 4.6-3a 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.

$$C_{meat,i} = \left\{ \begin{array}{l} Dp_i * \left[ \dfrac{\left( CRF * \left( \dfrac{1 - e^{-\lambda_w t_g}}{\lambda_w * t_g} \right) * AFDIR \right)}{Y} + \dfrac{ASDIR}{\rho_{soil} * d_m} \right] * FDC_F \\ + \left[ AWDIR * FDC_W * C_W \right] \end{array} \right\} * TF_{Meat,A,i} * \left( \frac{1 - e^{-\lambda_i t_g}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m}$$

(Eq. 4.6-3a)

$$\frac{\mu Ci}{kg_{wet}} = \left\{ \begin{array}{l} \dfrac{\mu Ci}{m^2} * \left[ \dfrac{\left( unitless * \dfrac{unitless}{d^{-1} * d} * \dfrac{kg_{wet}}{d} \right)}{\dfrac{kg_{wet}}{m^2}} + \dfrac{\dfrac{kg_{soil}}{d}}{\dfrac{kg_{soil}}{m^3} * m} \right] * unitless \\ + \left[ \dfrac{l}{d} * unitless * \dfrac{\mu Ci}{l} \right] \end{array} \right\} * \frac{\mu Ci / kg_{wet}}{\mu Ci / d} * \frac{unitless}{d^{-1} * d} * unitless$$

where:

$C_{meat,i}$ = Projected Contamination level in Meat, the level of activity of radionuclide *i* per mass in an animal's meat from consuming radioactive material, $\mu Ci/kg_{wet}$;
$CRF$ = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop (default 0.5 for pastureland), 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 (default 4.62E-02, corresponds to a 15 day half life), $d^{-1}$;
$\left(\frac{1-e^{-\lambda_w t_g}}{\lambda_w * t_g}\right)$ = 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, $kg_{wet}/d$;
$Y$ = Crop Yield, the mass of crop grown per area of land, $kg_{wet}/m^2$;
$ASDIR$ = Animal Soil Daily Ingestion Rate, the daily rate at which an animal consumes soil, $kg_{soil}/d$;
$\rho_{soil}$ = Soil density, $kg_{soil}/m^3$;
$d_m$ = Mixing Depth, m;
$FDC_F$ = Fraction of the animals' Diet Contaminated (feed), unitless;
$Dp_i$ = Deposition, the areal radioactivity of radionuclide *i* per unit area of ground, $\mu Ci/m^2$;
$AWDIR$ = 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;
$C_W$ = Contamination level in drinking water, µCi/l;
$TF_{Meat,A,i}$ = Transfer Factor for meat, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the meat of the animal, $\mu Ci/kg_{wet}$ per µCi/d;

$\lambda_i$ = Decay constant for the 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, 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 ($\mu Ci/kg_{soil}$) the equation can be rewritten as shown in Equation 4.6-3b.

$$C_{meat,i} = \left\{ \begin{array}{l} \dfrac{\left( Dp_i * CRF * \left( \dfrac{1\text{-}e^{-\lambda_w t_g}}{\lambda_w * t_g} \right) * AFDIR * FDC_F \right)}{Y} + \left( ASDIR * C_S \right) \\ + \left( AWDIR * FDC_W * C_W \right) \end{array} \right\} * TF_{Meat,A,i} * \left( \dfrac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m}$$

(Eq. 4.6-3b)

$$\frac{\mu\text{Ci}}{\text{l}} = \left\{ \begin{array}{l} \dfrac{\left( \dfrac{\mu\text{Ci}}{\text{m}^2} * \text{unitless} * \dfrac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \dfrac{\text{kg}_{\text{wet}}}{\text{d}} * \text{unitless} \right)}{\dfrac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \left( \dfrac{\text{kg}_{\text{soil}}}{\text{d}} * \dfrac{\mu\text{Ci}}{\text{kg}_{\text{soil}}} \right) \\ + \left( \dfrac{\text{l}}{\text{d}} * \text{unitless} * \dfrac{\mu\text{Ci}}{\text{l}} \right) \end{array} \right\} * \frac{\mu\text{Ci}/\text{l}}{\mu\text{Ci}/\text{d}} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \text{unitless}$$

where:

$C_S$ = Contamination level in soil, $\mu$Ci/kg$_{soil}$;

## EXAMPLE 1

**Problem: Calculate the projected contamination levels for a lettuce crop from an area with a deposition of $^{60}$Co.**

Assuming a deposition (areal activity) of $^{60}$Co of 4.0E-03 μCi/m$^2$, Equation 4.6-1 can be used to predict the contamination level in the lettuce crop.

$$C_{crop,i} = \frac{Dp_i * CRF}{Y} * e^{-\lambda_i t_m}$$

Assuming:

$CRF$ = 0.2 (fresh produce),
$Y$ = 2.0 kg$_{wet}$/m$^2$ (fresh produce),
$\lambda_{Co}$ = 3.60E-04 d$^{-1}$, and
$t_m$ = 1 day.

$$C_{lettuce,^{60}Co} = \frac{4.0\text{E-}03 \frac{\mu\text{Ci}}{\text{m}^2} * 0.2}{2.0 \frac{\text{kg}_{\text{wet}}}{\text{m}^2}} * e^{\text{-3.6E-04}*1} = 4.0\text{E-}04 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

# EXAMPLE 2

**Problem: Calculate the projected contamination levels for cow's milk from an area with a deposition of $^{60}$Co.**

Assume a deposition (areal activity) of $^{60}$Co of 4.0E-03 µCi/m$^2$ and a water concentration value of 3.0E-05 µCi/l.

Equation 4.6-2 can be used to calculate the contamination level in the cow's milk.

$$C_{milk,i} = \left\{ \begin{array}{l} Dp_i * \left[ \dfrac{(CRF * AFDIR)}{Y} + \dfrac{ASDIR}{\rho_{soil} * d_m} \right] * FDC_F \\ + \left[ AWDIR * FDC_W * C_W \right] \end{array} \right\} * TF_{Milk,A,i} * e^{-\lambda_i t_m}$$

Assuming:

$CRF$ = 0.5 (pasture),
$AFDIR_{cow}$ = 50 $kg_{wet}$/d,
$Y$ = 0.7 $kg_{wet}/m^2$ (pasture),
$ASDIR_{cow}$ = 0.5 $kg_{soil}$/d,
$\rho_{soil}$ = 1600 $kg_{soil}/m^3$,
$d_m$ = 1.0E-03 m,
$FDC_F$ = 1.0,
$AWDIR_{cow}$ = 60 l/d,
$FDC_W$ = 1.0,
$TF_{Milk,cow,60Co}$ = 3.0E-04 µCi/l per µCi/d,
$\lambda_{Co}$ = 3.60E-04 d$^{-1}$, and
$t_m$ = 2 days.

$$C_{milk,^{60}Co} = \left\{ \begin{array}{l} \left[ \dfrac{\left(0.5 * 50 \dfrac{kg_{wet}}{d}\right)}{0.7 \dfrac{kg_{wet}}{m^2}} + \dfrac{0.5 \dfrac{kg_{soil}}{d}}{1600 \dfrac{kg_{soil}}{m^3} * 1.0E\text{-}03m} \right] * 1 * 4.0E\text{-}03 \dfrac{\mu Ci}{m^2} \\ + \left[ 60 \dfrac{l}{d} * 1 * 3.0E\text{-}05 \dfrac{\mu Ci}{l} \right] \end{array} \right\} * 3.0E\text{-}04 \dfrac{\mu Ci/l}{\mu Ci/d} * e^{-3.6E\text{-}04*2}$$

$$= 4.4E\text{-}05 \frac{\mu Ci}{l}$$

# EXAMPLE 3

**Problem: Calculate the projected contamination levels for beef from an area with a deposition of $^{60}$Co.**

Assume a deposition (areal activity) of $^{60}$Co of 4.0E-03 µCi/m$^2$ and a water concentration value of 3.0E-05 µCi/l.

Assuming that the cow will continue to graze on the contaminated field for 90 days after deposition, Equation 4.6-3 can be used to calculate the contamination level in the cow's meat.

$$C_{meat,i} = \left\{ \begin{array}{l} Dp_i * \left[ \dfrac{\left( CRF * \left( \dfrac{1\text{-}e^{-\lambda_w t_g}}{\lambda_w * t_g} \right) * AFDIR \right)}{Y} + \dfrac{ASDIR}{\rho_{soil} * d_m} \right] * FDC_F \\ + \left[ AWDIR * FDC_W * C_W \right] \end{array} \right\} * TF_{Meat,A,i} * \left( \dfrac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m}$$

Assuming:

$CRF$ = 0.5 (pasture),
$\lambda_w$ = 4.62E-02 d$^{-1}$,
$t_g$ = 90 d,
$AFDIR_{cow}$ = 50 kg$_{wet}$/d,
$Y$ = 0.7 kg$_{wet}$/m$^2$ (pasture),
$ASDIR_{cow}$ = 0.5 kg$_{soil}$/d,
$\rho_{soil}$ = 1600 kg$_{soil}$/m$^3$,
$d_m$ = 1.0E-03 m,
$FDC_F$ = 1.0,
$AWDIR_{cow}$ = 60 l/d,
$FDC_W$ = 1.0,
$TF_{Meat,cow,60Co}$ = 1.0E-02 µCi/kg$_{wet}$ per µCi/d,
$\lambda_{Co}$ = 3.60E-04 d$^{-1}$, and
$t_m$ = 20 days.

$$C_{beef,{}^{60}Co} = \left\{ \begin{array}{l} \left[ \dfrac{\left( 0.5 * \dfrac{1\text{-}e^{-4.62\text{E-}02\text{d}^{-1} * 90\text{d}}}{4.62\text{E-}02\text{d}^{-1} * 90\text{d}} * 50 \dfrac{\text{kg}_{\text{wet}}}{\text{d}} \right)}{0.7 \dfrac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \dfrac{0.5 \dfrac{\text{kg}_{\text{soil}}}{\text{d}}}{1600 \dfrac{\text{kg}_{\text{soil}}}{\text{m}^3} * 1.0\text{E-}03\text{m}} \right] * 1 * 4.0\text{E-}03 \dfrac{\mu\text{Ci}}{\text{m}^2} \\ + \left[ 60 \dfrac{\text{l}}{\text{d}} * 1 * 3.0\text{E-}05 \dfrac{\mu\text{Ci}}{\text{l}} \right] \end{array} \right\}$$

$$* 1.0\text{E-}02 \frac{\mu\text{Ci}/\text{l}}{\mu\text{Ci}/\text{d}} * \frac{1\text{-}e^{-3.6\text{E-}04\text{d}^{-1} * 90\text{d}}}{3.6\text{E-}04\text{d}^{-1} * 90\text{d}} * \text{e}^{-3.6\text{E-}04 * 20}$$

$$= 3.6\text{E-}04 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

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# METHOD 4.7 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:

- Can be applied to the whole body ($E_{50}$) or to a specific organ ($H_{T,50}$)
- 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.
- 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 ($\mu Ci/m^2$). 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 5.0E-05 $kg_{soil}$/day for adults and 1.0E-04 $kg_{soil}$/day for children (EPA97a). This method uses the conservative value of 1.0E-04 $kg_{soil}$/day for all calculations. If specific intake rates are known, use those instead of defaults.
2) Soil density of 1600 $kg_{soil}/m^3$.

3) Mixing depth of 1.0E-03 m for the surface layer of contaminated soil and 1.0E-04 m for the layer of dust over pavement (EPA89). This method uses the conservative value of 1.0E-04 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:

- Data – Areal concentration ($\mu Ci/m^2$) from monitoring data.
- Constants – Daily Soil Intake Rate, Ingestion Dose Coefficient.
- 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).

If incident-specific values have not been established, recommended default values for selected inputs are available in Appendix C.

**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

The final output of this method is the Ingestion Dose for soils that have been contaminated by a deposition of radioactive material.

### Final

$E_{50,soil}$ = Committed Effective Dose, the dose to the whole body, received by the receptor under consideration over the commitment period, from the ingestion of all radionuclides in contaminated soil, mrem

$H_{T,50,soil}$ = Committed Equivalent Dose, the dose to organ “t”, received by the receptor under consideration over the commitment period, 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 4.7.1 Calculation of Committed Effective Dose from Inadvertent Soil Ingestion

Equation 4.7-1 shows the Ingestion Dose calculation:

$$E_{50,soil,age} = \frac{DSIR}{\rho_{soil} * d_m} * \sum_i \left( Dp_{i,t_0} * e^{-\lambda t_1} * WF_{t_1} * IngDC_{E,age,i} * CRP_{i,TP} \right) \quad \text{(Eq. 4.7-1)}$$

$$\text{mrem} = \frac{\frac{\text{kg}_{\text{soil}}}{\text{d}}}{\frac{\text{kg}_{\text{soil}}}{\text{m}^3} * \text{m}} * \sum_i \left( \frac{\mu\text{Ci}}{\text{m}^2} * \text{unitless} * \text{unitless} * \frac{\text{mrem}}{\mu\text{Ci}} * \text{d} \right)$$

where:

$E_{50,soil,age}$ = Committed Effective Dose from inadvertent soil ingestion, the dose to the whole body, received by the age group under consideration over the commitment period, from ingestion of all radionuclides in contaminated soil, mrem;

$DSIR$ = Daily Soil Intake Rate, $kg_{soil}/d$;

$\rho_{soil}$ = Soil density, $kg_{soil}/m^3$;

$d_m$ = Mixing Depth, m;

$Dp_{i,t0}$ = Deposition, the measured or predicted areal activity of radionuclide i per unit area of ground at the time of deposition ($t_0$), $\mu Ci/m^2$;

$e^{-\lambda t1}$ = Radioactive Decay adjustment from $t_0$ (deposition) to $t_1$ (start of the time phase), unitless;

$WF_{t1}$ = Weathering adjustment 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 the age group under consideration for radionuclide *i*, mrem/µCi; and

$CRP_{i,TP}$ = Combined Removal Parameter, value that adjusts for radioactive decay and weathering effects that decrease the amount of radionuclide i available to cause direct exposure or to be ingested over the time phase (*TP*, $t_1$ *to* $t_2$) under consideration, d;
**NOTE:** See Appendix F, Supplement 2 for details on calculating CRP.

## Method 4.7.2 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 specific organ when calculating the IngDP.

## EXAMPLE 1

**Problem: Calculate the Whole Body Ingestion Dose received by an adult from inadvertent consumption of soil contaminated with $^{60}$Co and $^{137}$Cs for 1 year, beginning 100 days after deposition.**

Assume monitoring results (at deposition) as shown below:

$Dp_{i,Co}$ = 2.5E-03 µCi/m$^2$
$Dp_{i,Cs}$ = 4.0E-03 µCi/m$^2$

Equation 4.7-1 can be used to calculate the dose:

$$E_{50,soil,age} = \frac{DSIR}{\rho_{soil} * d_m} * \sum_i \left( Dp_{i,t_0} * e^{-\lambda t_1} * WF_{t_1} * IngDC_{E,age,i} * CRP_{i,TP} \right)$$

Given:

$IngDC_{Co}$ = 12.7 mrem/µCi
$\lambda_{Co}$ = 3.6E-04 d$^{-1}$
$IngDC_{Cs}$ = 50.3 mrem/µCi
$\lambda_{Cs}$ = 6.33E-05 d$^{-1}$
$t_1$ = 100 d (Start of Time Phase – used in CRP calculation)
$t_2$ = 465 d (End of Time Phase – used in CRP calculation)
$WF_{100d}$ = 0.950

Assuming:

$DSIR$ = 1.0E-04 kg$_{soil}$/d
$\rho_{soil}$ = 1600 kg$_{soil}$/m$^3$
$d_m$ = 1.0E-04 m

Calculating CRP as in Appendix F, Supplement 2 yields:

$CRP_{Co}$ = 290 d
$CRP_{Cs}$ = 314 d

$$E_{50,soil,Adult} = \frac{1.0\text{E-04 } \frac{\text{kg}_{\text{soil}}}{\text{d}}}{1600 \frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 1.0\text{E-04 m}} * \left( \begin{array}{l} 2.5\text{E-03} \frac{\mu\text{Ci}}{\text{m}^2} * 0.965 * 0.950 * 12.7 \frac{\text{mrem}}{\mu\text{Ci}} * 290 \text{ d} \\ +4.0\text{E-03} \frac{\mu\text{Ci}}{\text{m}^2} * 0.994 * 0.950 * 50.3 \frac{\text{mrem}}{\mu\text{Ci}} * 314 \text{ d} \end{array} \right)$$

$$= 4.26\text{E-02 mrem}$$

To calculate an Committed Equivalent Dose ($H_{T,50}$) for a specific organ and/or different age group, use the appropriate IngDC for the organ/age group and calculate as demonstrated above.

# SECTION 5. SAMPLE MANAGEMENT METHODS

Effective Date

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# INTRODUCTION TO SAMPLE MANAGEMENT METHODS

These methods describe how to use sample data to perform various assessment activities. 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 5.1 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*):

- 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.

- Is used to calculate the Resuspension Parameter (*KP*) and Inhalation Dose Parameter for Deposition (*InhDP_Dp*) for each radionuclide in a deposition mixture.

## Discussion

**This calculation is presented as an alternative to the default, time dependent, formula from NCRP 129 shown in Appendix F, Supplement 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:

- It may be difficult to obtain accurate/representative sample-based values.
- Hot particles may significantly skew the air sample activity results.
- Samples are only representative of the resuspension factor for a specific point in time and space.
- Resuspension may change over the time phase of interest as the land use changes.
- Weathering processes and alpha-recoil energy can break apart contaminated particles creating smaller particle sizes over time potentially changing resuspension.
- 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

The final output of this method is the resuspension factor for a radionuclide contaminant.

### Final

$K_i$ = Resuspension Factor, the ratio of the activity level in the air to the level on the ground of radionuclide *i*, $m^{-1}$.

### Intermediate

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

None

# Calculation

Equation 5.1-1 shows the Resuspension Factor calculation.

$$K_i = \frac{\chi_i}{Dp_i} \qquad \text{(Eq. 5.1-1)}$$

$$\text{m}^{-1} = \frac{\mu\text{Ci}/\text{m}^3}{\mu\text{Ci}/\text{m}^2}$$

where:

$K_i$ = Resuspension Factor for radionuclide *i*, $\text{m}^{-1}$;
$\chi_i$ = Air Concentration of radionuclide *i*, $\mu\text{Ci/m}^3$; and
$Dp_i$ = Deposition (ground concentration) of radionuclide *i*, $\mu\text{Ci/m}^2$.

## EXAMPLE 1

**Problem: Calculate the Resuspension Factor from sample results**

At a particular sampling location, the average results for $^{137}Cs$ are:

Air Sampling: 2.74E-03 µCi/m$^3$
Ground Sampling: 2.74E+04 µCi/m$^2$

$$K = \frac{2.74\text{E-}03 \ \frac{\mu\text{Ci}}{\text{m}^3}}{2.74\text{E+}04 \ \frac{\mu\text{Ci}}{\text{m}^2}} = 1.00\text{E-}07 \, \text{m}^{-1}$$

# METHOD 5.2 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:

Data – Sampling Results from food products/fodder in terms of dry mass ($\mu Ci/kg_{dry}$).

Constants – Mass Conversion Factor for the food product/fodder.

If incident-specific values have not been established, recommended default values for selected inputs are available in Appendix C.

**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

The final output of this method is a sample analysis result in "wet mass" that may be directly compared to a DIL.

### Final

$C_{sample,i,wet}$ = Sample Contamination, the level of contamination of radionuclide *i* in a analytical sample in terms of wet mass, $\mu Ci/kg_{wet}$.

### Intermediate

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

None.

# Calculation

Equation 5.2-1 shows the wet mass Contamination calculation.

$$C_{sample,i,wet} = C_{sample,i,dry} * MCF_{D-W,subgroup} \qquad \text{(Eq. 5.2-1)}$$

$$\frac{\mu Ci}{kg_{wet}} = \frac{\mu Ci}{kg_{dry}} * \frac{kg_{dry}}{kg_{wet}}$$

where:

$C_{sample,i,wet}$ = Sample Contamination, the level of contamination of radionuclide *i* in an analytical sample in terms of wet mass, $\mu Ci/kg_{wet}$;
$C_{sample,i,dry}$ = Sample Contamination, the level of contamination of radionuclide *i* in an analytical sample in terms of dry mass, $\mu Ci/kg_{dry}$; 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), $kg_{dry}/kg_{wet}$.

**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 6.0E-02 µCi/kg of $^{137}$Cs. The crop of apples is intended to be consumed as fresh produce (i.e., not dried or dehydrated).

The DIL for $^{137}$Cs is 3.7E-02 µCi/kg; does the sample exceed the DIL?

Because this apple crop's "as prepared for consumption" form will be wet mass, Equation 5.2-1 should be used to calculate the wet mass Concentration.

$$C_{sample,i,wet} = C_{sample,i,dry} * MCF_{D-W,subgroup}$$

Given:

$MCF_{D\text{-}W,\ \mathrm{apples}} = 0.18\ \mathrm{kg_{dry}/kg_{wet}}$

$$C_{sample,i,wet} = 6.0\text{E-}02\,\frac{\mu\mathrm{Ci}}{\mathrm{kg_{dry}}} * 0.18\,\frac{\mathrm{kg_{dry}}}{\mathrm{kg_{wet}}} = 1.08\text{E-}02\,\frac{\mu\mathrm{Ci}}{\mathrm{kg_{wet}}}$$

Since:

$$1.08\text{E-}02\,\frac{\mu\mathrm{Ci}}{\mathrm{kg_{wet}}} < 3.7\text{E-}02\,\frac{\mu\mathrm{Ci}}{\mathrm{kg_{wet}}}$$

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 5.3 NORMALIZING SAMPLES

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

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# METHOD 5.4 DETERMINING MDA REQUIREMENTS

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

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# GLOSSARY

| | |
|---|---|
| **Acute Health Effects** | See Early Health Effects. |
| **Cloud Shine** | Gamma radiation from radioactive materials in the air (plume). |
| **Committed Effective Dose ($E_{50}$)** | The sum of the committed equivalent doses for 50 years following intake (inhalation or ingestion) of a radionuclide to each organ multiplied by a tissue weighting factor. |
| **Committed Equivalent Dose ($H_{T,50}$)** | The equivalent dose to a specific organ for 50 years following intake (inhalation or ingestion). It does not include contributions from external dose. |
| **Delayed Health Effects** | A wide range of cancers and hereditary effects that usually occur many years after exposure. In contrast to early health effects, it is assumed there are no dose thresholds below which these effects do not occur. |
| **Deposition** | The contamination found on the surface of the ground. |
| **Derived Intervention Level (DIL)** | The concentration of a radionuclide in food derived from the protective action guide and at which introduction of protective measures should be considered. |
| **Derived Response Level (DRL)** | 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. |
| **Early Health Effects** | Health effects that are likely to occur shortly after exposure (hours, weeks) resulting from high doses over a short period (acute doses) to specific organs and involve thresholds below which these health effects are not expected to occur. |
| **Early Phase** | The period of time that extends from the time the threat of a major release is identified until the release or threat of major release has ended and areas of major deposition have been identified. |
| **Effective Dose (E)** | The sum of the equivalent dose from each organ multiplied by a tissue weighting factor. |
| **Equivalent Dose ($H_T$)** | The dose to an organ multiplied by the radiation weighting factor. |
| **Emergency Worker Guidance** | Guidance on the external dose and Committed Effective Dose incurred by workers (other than a pregnant woman) while performing emergency services. |
| **External Dose** | The dose of radiation received by an individual from a source of ionizing radiation outside the body. |
| **Facility Operator** | The organization that operates the facility. |
| **Groundshine** | Gamma radiation from radioactive materials deposited on the ground. |
| **ICRP 60+** | ICRP Publication 60 and the collection of ICRP documents relating to the ICRP 60 dosimetry model published subsequently. |
| **Submersion** | To be surrounded or engulfed by the radioactive cloud. |

| | |
|---|---|
| **Intermediate Phase** | The period beginning after the release and potential for further major release is over and reliable environmental data are available for use as a basis for relocation and ingestion protective actions. Usually one year of deposition and 30 days of ingestion calculation. |
| **Light-Water Reactor (LWR)** | A nuclear reactor that uses natural water as a coolant and moderator. All U.S. commercial power reactors in the United States are LWRs, as are the Russian-constructed VVERs. |
| **Marker Radionuclide** | A nuclide contained in deposition or samples that is easily identified in the field or laboratory. It is used to determine areas of concern before performing a comprehensive nuclide analysis. |
| **Mixture** | The nuclide ratio (relative abundance) of the radionuclides in a sample or deposition. |
| **Pathways** | The paths radionuclides follow from the source through the environment, including vegetation and animals, to reach an individual or a population. |
| **Protective Action Guide (PAG)** | The projected dose, from an accidental release of radioactive material, where specific actions to reduce or avoid dose are warranted. |
| **Quality Factor (QF)** | 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. |
| **Relative Biological Effectiveness (RBE)** | 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. |
| **Resuspension** | Reintroduction to the atmosphere of material originally deposited onto surfaces. |
| **Stability Class** | A class that describes conditions of atmospheric turbulence. Classes are generally grouped into six classes ranging from class A, very unstable, through class F, very stable. |
| **Total Effective Dose (TED)** | The sum of the effective dose (for external exposures) and the committed effective dose. |
| **Total Equivalent Dose – Organ (TEDO)** | The sum of the equivalent dose (for external exposure) and the committed equivalent dose to a specific organ. |
| **Transfer Factor** | 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. |

**Turn-Back Guidance** 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[1] | 0.05 |
| Whole body[2] | 1.00 |

Source: ICRP90, Table 2.

[1] "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 ($H_{remainder}$) 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.

[2] 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 |
|---|---|---|---|
| *AFDIR* | $\frac{kg_{wet}}{d}$ | Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed (forage or stored): (Cow default 50, Goat default 6). | 4.3, 4.4, 4.6, Table 10 |
| *ASDIR* | $\frac{kg_{soil}}{d}$ | Animal Soil Daily Ingestion Rate, the daily rate at which an animal consumes soil: (Cow default 0.5, Goat default 0.06). | 4.3, 4.4, 4.6, Table 10 |
| *AvCRP* | | (RESERVED) | |
| *AWDIR* | $\frac{L}{d}$ | Animal Water Daily Ingestion Rate, the daily rate at which an animal consumes water: (Cow default 60, Goat default 8). | 4.3, 4.4, 4.6, Table 10 |
| *BR* | $\frac{m^3}{s}$ | Breathing Rate, the activity-weighted average volume of air breathed per unit time by an adult male (ICRP94, Table B.16B), 2.56E-04. | 2.1 |
| $\chi_i$ | $\frac{\mu Ci}{m^3}$ | Air concentration of radionuclide i. | 5.1 |
| $C_{crop,i}$ | $\frac{\mu Ci}{kg_{wet}}$ | 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. | 4.6 |
| $C_{f,i}$ | $\frac{\mu Ci}{kg_{wet}}$ or $\frac{\mu Ci}{L}$ | Food Contamination, the level of contamination of radionuclide i in a specific food type (f). | 4.5 |
| $C_{meat,i}$ | $\frac{\mu Ci}{kg_{wet}}$ | Projected Contamination level in meat, the level of activity of radionuclide i per mass in an animal's meat from consuming radioactive material. | 4.6 |
| $C_{milk,i}$ | $\frac{\mu Ci}{L}$ | Projected Contamination level in milk, the level of activity of radionuclide i per volume in milk produced from animals consuming radioactive material. | 4.6 |
| $C_{S,i}$ | $\frac{\mu Ci}{kg_{soil}}$ | Measured Contamination level of radionuclide i in soil. | 4.6 |

| TERM | UNITS | DEFINITION | METHODS |
|---|---|---|---|
| $C_{sample,i,dry}$ | $\frac{\mu Ci}{kg_{dry}}$ | Sample Contamination, the level of contamination of radionuclide i in an analytical sample in terms of dry mass. | 5.2 |
| $C_{sample,i,wet}$ | $\frac{\mu Ci}{kg_{wet}}$ | Sample Contamination, the level of contamination of radionuclide i in an analytical sample in terms of wet mass. | 5.2 |
| $C_{W,i}$ | $\frac{\mu Ci}{L}$ | Measured Contamination level of radionuclide i in drinking water. | 4.6 |
| *CRF* | unitless | Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop (default 0.5 for pastureland and 0.2 (1.0 for iodine) for fresh produce). | 4.2, 4.3, 4.4, 4.6, Table 10 |
| $Crop\_DRL_{mat,i}$ | $\frac{\mu Ci}{m^2}$ | Ingestion Derived Response Level for mature Crop/Produce, the ground concentration, or areal activity, of radionuclide i that will be expected to cause the crop/produce growing in that area to exceed the applicable Derived Intervention Level (DIL). | 4.2 |
| $Crop\_DRL_{imm,i}$ | $\frac{\mu Ci}{m^2}$ | Ingestion Derived Response Level for immature Crop/Produce, the ground concentration, or areal activity, of radionuclide i that will be expected to cause the crop/produce growing in that area to exceed the applicable Derived Intervention Level (DIL). | 4.2 |
| $CRP_{i,\ TP}$ | s, d | Combined Removal Parameter, value that adjusts for radioactive decay and weathering effects that decrease the amount of radionuclide i available to cause direct exposure or to be ingested over the time phase (TP) under consideration. | 2.1, 4.7 |
| $DFIR_{age}$ | $\frac{kg_{wet}}{d}$ | Daily Food Intake Rate, the daily intake rate (as prepared for consumption, i.e. wet mass) for the age group under consideration. | 4.1 |
| $DFIR_{subgroup,age}$ | $\frac{kg_{wet}}{d}$ | Daily Food Intake Rate for a food subgroup (as prepared for consumption, i.e. wet mass) for the age group under consideration. | 4.5 |
| $DIL_{organ,age,i}$ | $\frac{\mu Ci}{kg_{wet}}$ | Derived Intervention Level, the activity concentration level of radionuclide i at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to exceed the applicable ingestion PAG. | 4.1, 4.2, 4.3, 4.4 |
| $d_m$ | m | Mixing Depth (default 1.0E-03 for the first growing season and 0.15 after plowing). | 4.2, 4.3, 4.4, 4.6, |

| TERM | UNITS | DEFINITION | METHODS |
|---|---|---|---|
| $Dp\_DRL_{\alpha,tn}$ | $\frac{\mu Ci_\alpha}{m^2}$ | Deposition Alpha Derived Response Level, the areal alpha activity of the mixture, at time $t_n$ (time of measurement, prediction or evaluation), at which the dose from all radionuclides in a deposition mixture would result in a dose equal to the PAG for the time phase under consideration. | 2.3 |
| $Dp\_DRL_{\beta-,tn}$ | $\frac{\mu Ci_\beta}{m^2}$ | Deposition Beta Derived Response Level, the areal beta activity of the mixture, at time $t_n$ (time of measurement, prediction or evaluation), at which the dose from all radionuclides in a deposition mixture would result in a dose equal to the PAG for the time phase under consideration. | 2.4 |
| $Dp\_DRL_{DR,\ E,\ tn}$ | $\frac{mrem}{hr}$ | Deposition Dose Rate Derived Response Level, the external dose rate, at time $t_n$, at which the dose from all radionuclides in a deposition mixture would result in a dose equal to the PAG for the time phase under consideration. | 2.2 |
| $Dp\_DRL_{organ,i,tn}$ | $\frac{\mu Ci}{m^2}$ | Deposition Derived Response Level, the areal activity (radioactivity per unit area) at time $t_n$ of radionuclide i, at which the dose to the organ of interest from all radionuclides in a deposition mixture would result in a dose equal to the PAG for the time phase under consideration. | 2.1, 2.3, 2.4 |
| $Dp\_DRL_{XR,\ E,tn}$ | $\frac{mR}{hr}$ | Deposition Exposure Rate Derived Response Level, the external exposure rate at time $t_n$ at which the dose from all radionuclides in a deposition mixture would result in a dose to the whole body (E) equal to the PAG for the time phase under consideration. | 2.2, 2.5 |
| $Dp_i$ | $\frac{\mu Ci}{m^2}$ | Deposition of radionuclide *i* | 5.1 |
| $Dp_{i,tn}$ | $\frac{\mu Ci}{m^2}$ | Deposition, the measured or predicted areal activity of radionuclide i per unit area of ground at time $t_n$. | 2.1, 2.5, 3.2, 4.6 |
| $Dp_{i\ (m)}$ | $\frac{\mu Ci}{m^2}$ | Deposition of the marker radionuclide. | 2.1, 4.6 |
| $Dp\_PPD_{DR,E,TP}$ | mrem | Deposition Dose Rate Projected Public Dose, the projected dose to the whole body (E), over the time phase (TP) under consideration from a measured external dose rate. | 2.5 |
| $Dp\_PPD_{Dp,E,TP}$ | mrem | Deposition Projected Public Dose, the projected dose to the whole body (E), over the time phase (TP) under consideration from a deposition of radioactive material. | 2.5 |
| $DRCF_{skin,i,TP}$ | | (RESERVED) | |

| TERM | UNITS | DEFINITION | METHODS |
|---|---|---|---|
| $DSIR$ | $\frac{kg_{soil}}{d}$ | Daily Soil Intake Rate, the amount of soil inadvertently ingested by humans in a day (default of 1.0E-04). | 4.7 |
| $E_{50,Ing,age}$ | mrem | Committed Effective Dose from ingestion, the dose to the whole body, received by the age group under consideration over the commitment period, from ingestion of all radionuclides in all contaminated food types. | 4.5 |
| $E_{50,soil}$ | mrem | Committed Effective Dose from ingestion of soil. | 4.7 |
| $EDI_i$ | d | Effective Days of Intake, the number of days required for the radionuclide to decay to <1% of its initial activity (set to 365 if value is greater). | 4.1 |
| $ExDC\_Dp_{E,i}$ | $\frac{mrem \cdot m^2}{hr \cdot \mu Ci}$ | External Dose Coefficient for Deposition, the effective dose rate to the whole body (E) from the external exposure to radionuclide i per unit activity deposited on the ground, (values using DCFPAK from ICRP 60+ dosimetry models). | 2.1, 2.2 |
| $ExDF\_Dp_{E,i}$ | $\frac{mrem \cdot m^2}{hr \cdot \mu Ci}$ | External Dose Factor for Deposition, the effective dose rate to the whole body (E) from the external exposure to radionuclide i per unit activity deposited on the surface and adjusted for the ground roughness factor. | 2.2 |
| $ExDP\_Dp_{E,i,TP}$ | $\frac{mrem \cdot m^2}{\mu Ci}$ | External Dose Parameter for Deposition, the groundshine dose received by the whole body (*E*), over the time phase under consideration (*TP*), per unit of areal activity of radionuclide *i* deposited on the ground and adjusted for the ground roughness factor. | 2.1, 3.2 |
| $ExDR$ | $\frac{mrem}{hr}$ | External dose rate, the external dose rate from materials deposited on the ground. | 2.5, 2.8, 3.1 |
| $ExDR_a$ | $\frac{mrem}{hr}$ | Dose rate at time $t_a$ (hours after detonation). | 2.8 |
| $ExDR_b$ | $\frac{mrem}{hr}$ | Dose rate at time $t_b$ (hours after detonation). | 2.8 |
| $ExDR_r$ | $\frac{mrem}{hr}$ | Reference dose rate at 1 hour after nuclear detonation. | 2.8 |
| $ExDR_{r,PAG}$ | $\frac{mrem}{hr}$ | Reference dose rate at 1 hour after nuclear detonation which would produce a dose for the time phase equal to the PAG. | 2.8 |

| TERM | UNITS | DEFINITION | METHODS |
|---|---|---|---|
| $ExDR_t$ | $\frac{\text{mrem}}{\text{hr}}$ | Dose rate at time t (hours after detonation). | 2.8 |
| $ExTDCF_{TP}$ | $\frac{\text{mrem}_{\text{inh+external}}}{\text{mrem}_{\text{external}}}$ | 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 (TP) of interest<br>**NOTE:** This value is used to convert a measurement from a self reading dosimeter into a dose which includes the effects of inhalation of resuspended material. | 3.2 |
| $FDC_{age,i}$ | unitless | Fraction of Diet Contaminated, the fraction of a human's diet that is contaminated; default value of 0.3 (except for $^{132}$Te, $^{131}$I, $^{133}$I and $^{239}$Np in the diet of an infant where it is 1.0).<br>**NOTE:** If there is convincing local information that the actual FDC is considerably different, local authorities may decide to use a different FDC. | 4.1 |
| $FDC_F$ | unitless | Fraction of Diet Contaminated (feed), the fraction of the animal's diet that is from contaminated feed (default 1.0).<br>**NOTE:** If there is convincing local information that the actual FDC is considerably different, local authorities may decide to use a different FDC. | 4.3, 4.4, 4.6 |
| $FDC_W$ | unitless | Fraction of Diet Contaminated (water), the fraction of an animal's diet that is from contaminated water (default 1.0).<br>N**OTE:** If there is convincing local information that the actual FDC is considerably different, local authorities may decide to use a different FDC. | 4.3, 4.4, 4.6 |
| $FFC_{f,\,i}$ | unitless | Fraction of Food Type Contaminated, (default 1.0).<br>**NOTE:** If there is convincing local information that the actual FFC is considerably different, local authorities may decide to use a different FFC. | 4.5 |
| $GRF$ | unitless | Ground Roughness Factor, a unitless constant (0.82) that compensates for the fact that the external exposure is not coming from an infinite flat plane (An02). | 2.1, 2.2 |
| $H_{Skin,TP}$ | | (RESERVED) | |
| $H_{T,50}$ | mrem | Committed Equivalent Dose, the dose to organ "T", received by the receptor under consideration over the commitment period, from the ingestion of all radionuclides in contaminated food. | 4.5 |
| $H_{T,50,soil}$ | mrem | Committed Equivalent Dose, the dose to organ "T" from the ingestion of soil. | 4.7 |

| TERM | UNITS | DEFINITION | METHODS |
|---|---|---|---|
| *ICRF* | | (RESERVED) | |
| $IND\_DRL_{DR}$ | $\frac{\text{mrem}}{\text{hr}}$ | Improvised Nuclear Device Derived Response Level, the external dose rate, at time $t_n$, at which the dose from all radionuclides in a fallout deposition mixture would result in a dose equal to the PAG for the time phase under consideration. | 2.8 |
| $IngDC_{organ,\ age,\ i}$ | $\frac{\text{mrem}}{\mu\text{Ci}}$ | Ingestion Dose Coefficient, the ingestion pathway dose coefficient for the target organ for a specific age group for radionuclide i. | 4.1, 4.5 |
| $IngDP_{avg,age}$ | $\frac{\text{mrem} \cdot \text{d}}{\text{kg}_{\text{wet}}}$ | Average Ingestion Dose Parameter for a subgroup, the average of the individual $\text{IngDP}_{\text{E,f,age}}$ for each type of contaminated food in a subgroup for the age group under consideration. | 4.5 |
| $IngDP_{E,f,age}$ | $\frac{\text{mrem} \cdot \text{d}}{\text{kg}_{\text{wet}}}$ | Ingestion Dose Parameter, the committed effective dose received by the whole body (E) over the commitment period, from ingestion of all radionuclides in a specific food type (f) by a specific age group. | 4.5 |
| $InhDC_{E\ ,i}$ | $\frac{\text{Sv}}{\text{Bq}}$ | Inhalation Dose Coefficient, the committed effective dose coefficient for the whole body (E), for radionuclide i (values from ICRP 60+ dosimetry models, DCFPAK). | 2.1 |
| $InhDP\_Dp_{E,\ i,\ TP}$ | $\frac{\text{mrem} \cdot \text{m}^2}{\mu\text{Ci}}$ | Inhalation Dose Parameter for Deposition, the committed effective dose received by the whole body (*E*), from the inhalation of resuspended radionuclide *i* over the time phase under consideration (*TP*), per unit of areal activity of the radionuclide deposited on the ground. | 2.1, 3.2 |
| *K* | $\text{m}^{-1}$ | Resuspension Factor, value based on the time-varying formula from NCRP Report No. 129, (NCRP99). | 2.1, 5.1 |
| *KIPF* | unitless | Potassium Iodide Protection Factor, which defaults to 1 for all non-iodine isotopes or when no KI is administered.<br>**NOTE:** Consult Health and Safety personnel for appropriate values for KIPF. | 3.2 |
| $KP_{i,\ TP}$ | s/m | Resuspension Parameter, value that adjusts the airborne radioactivity level of radionuclide i over the time phase (TP) under consideration for radioactive decay and the time-dependent resuspension factor (K) (value obtained via numerical integration from Turbo FRMAC). | 2.1 |
| $\lambda_i$ | $\text{s}^{-1}$ | Decay constant for radionuclide i. | 2.1, 2.2, 3.2, 4.2, 4.3, 4.4, 4.5, 4.6 |

| TERM | UNITS | DEFINITION | METHODS |
|---|---|---|---|
| $\lambda_w$ | $d^{-1}$ | Decay constant for weathering radioactive material off plants. (Corresponds to a 15 day half life, default 4.62E-02). | 4.2, 4.4, 4.6 |
| $MCF_{D\text{-}W,subgroup}$ | $\frac{kg_{dry}}{kg_{wet}}$ | Mass Conversion Factor (dry to wet) – the ratio of dry mass to wet mass for a food subgroup (See Appendix C, Table 9). | 4.2, 4.5, 5.2 |
| $Meat\_DRL_{area,A,i}$ | $\frac{\mu Ci}{m^2}$ | Ingestion Derived Response Level for meat, the ground concentration, or areal activity, of radionuclide i that will be expected to cause the meat from grazing animals (A) to exceed the Derived Intervention Level (DIL) for that radionuclide. | 4.4 |
| $Meat\_DRL_{mass,A,i}$ | $\frac{\mu Ci}{kg_{wet}}$ | Ingestion Derived Response Level for meat, the mass concentration of radionuclide i that will be expected to cause the meat from grazing animals (A) to exceed the Derived Intervention Level (DIL) for that radionuclide. | 4.4 |
| $Meat\_DRL_{water,A,i}$ | $\frac{\mu Ci}{L}$ | Ingestion Derived Response Level for meat, the water concentration of radionuclide i that will be expected to cause the meat from drinking animals (A) to exceed the Derived Intervention Level (DIL) for that radionuclide. | 4.4 |
| *MExDF_Dp* | $\frac{mrem}{hr}$ | Mixture External Dose Factor for all radionuclides in the mixture of interest. | 2.2, 2.5 |
| $Milk\_DRL_{area,A,i}$ | $\frac{\mu Ci}{m^2}$ | Ingestion Derived Response Level for milk, the ground concentration, or areal activity, of radionuclide i that will be expected to cause the milk produced by grazing animals (A) to exceed the Derived Intervention Level (DIL) for that radionuclide. | 4.3 |
| $Milk\_DRL_{mass,A,i}$ | $\frac{\mu Ci}{kg_{wet}}$ | Ingestion Derived Response Level for milk, the mass concentration in feed of radionuclide i that will be expected to cause the milk produced by grazing animals (A) to exceed the Derived Intervention Level (DIL) for that radionuclide. | 4.3 |
| $Milk\_DRL_{water,A,i}$ | $\frac{\mu Ci}{L}$ | Ingestion Derived Response Level for Milk, the water concentration of radionuclide i that will be expected to cause the milk produced by drinking animals (A) to exceed the Derived Intervention Level (DIL) for that radionuclide. | 4.3 |
| $MTDP\_Dp_{E\ TP}$ | mrem | Mixture Total Dose Parameter for Deposition, the sum of the external dose from groundshine and the internal dose from inhalation of resuspended material received by the whole body (E), over the time phase under consideration (TP), from the areal activity level of the mixture. | 2.1, 2.2, 2.5 |
| *PAG* | mrem | Protective Action Guide, the dose limits specified by federal or local authorities at which protective actions may be warranted. | 2.1, 2.2, 2.5, 2.8, 4.1 |

| TERM | UNITS | DEFINITION | METHODS |
|---|---|---|---|
| $\rho_{milk}$ | $\frac{kg_{wet}}{L}$ | Milk density (default 1.04). | 4.3 |
| $\rho_{soil}$ | $\frac{kg_{soil}}{m^3}$ | Soil Density (default 1600). | 4.2, 4.3, 4.4, 4.6 |
| *RPF* | unitless | Respiratory Protection Factor, which defaults to 1 when no respirators are used. **NOTE:** Consult Health and Safety personnel for appropriate values for RPF. | 3.2 |
| *SF* | | (RESERVED) | |
| *SSF* | | (RESERVED) | |
| *SkinDP* | | (RESERVED) | |
| *ST* | hr | Stay Time | 3.1 |
| $t_0$ | NA | Time of Deposition | 2.1 |
| $t_1$ | s | The start of the time phase (integration period) under consideration. | 2.1, 2.8 |
| $t_2$ | s | The end of the time phase (integration period) under consideration. | 2.1, 2.8 |
| $t_a$, $t_b$ | hr | Time after a nuclear detonation at which a measurement is made. | 2.8 |
| $t_c$ | d | Consumption Time, the length of the consumption period (default 365 days). | 4.5 |
| $t_f$ | d | Field Time, the time the crop spends growing in the field from deposition or sampling to harvest, d; | 4.2 |
| $t_g$ | d | Grazing Time, time from deposition or sampling to the end of the grazing period. | 4.4, 4.6 |
| $t_h$ | d | Hold Time, the time elapsed from sample measurement to the beginning of the consumption period. | 4.5 |
| $t_{In}$ | | (RESERVED) | |
| $t_m$ | d | Time to Market, the number of days from harvest to consumption (Default 1 for crops, 2 for milk and 20 for meat). | 4.2, 4.3, 4.4, 4.6, Table 10 |
| $t_n$ | s | Evaluation Time, the point in time, relative to the start of the event, at which the measurement, prediction or evaluation is performed. | 2.1, 2.2, 2.5, 2.8 (in hours) |
| $t_{Out}$ | | (RESERVED) | |

| TERM | UNITS | DEFINITION | METHODS |
|---|---|---|---|
| $TBL$ | $\frac{mrem}{hr}$ or $\frac{mR}{hr}$ | Worker Turn-Back Limit, the Integrated Turn-Back Limit divided by the Stay Time in the contaminated area. | 3.1 |
| $TBL\_D_{TP}$ | $mrem_{external}$ | 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 (TP) that would result in the worker receiving their dose limit. | 3.2 |
| $TBL\_X_{TP}$ | mR | Worker 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 (TP) that would result in the worker receiving their dose limit. | 3.2 |
| $TDP\_Dp_{E,\, i,\, TP}$ | $\frac{mrem \cdot m^2}{\mu Ci}$ | Total Dose Parameter for Deposition, the sum of the external dose from groundshine and the internal (committed effective) dose from inhalation of resuspended material received, by the whole body (E), over the time phase under consideration (TP), per unit of areal activity of radionuclide i deposited on the ground. | 2.1, 2.5 |
| $TF_{crop,i}$ | $\frac{\mu Ci / kg_{dry}}{\mu Ci / kg_{soil}}$ | 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. Transfer Factors for plants are in terms of edible dry plants (PNNL03). | 4.2 |
| $TF_{Meat,A,i}$ | $\frac{\mu Ci / kg_{wet}}{\mu Ci / d}$ | Transfer Factor for meat, the fraction of radionuclide i consumed by an animal (A) that is transferred to the meat of the animal. | 4.4, 4.6 |
| $TF_{Milk,A,i}$ | $\frac{\mu Ci / L}{\mu Ci / d}$ | Transfer Factor for milk, the fraction of radionuclide i consumed by an animal (A) that is transferred to the milk produced by the animal. | 4.3, 4.6 |
| $WF$ | unitless | Weathering Factor, value that adjusts the groundshine dose for weathering forces that reduce the radionuclide activity near the surface and thereby decrease the external dose rate (An02). | 2.1, 2.2, 3.2, 4.7 |
| $WF_{tn}$ | unitless | Weathering adjustment from $t_0$ (deposition) to $t_n$ (time of measurement, prediction or evaluation). | 2.1, 2.2, 3.2, 4.7 |

| TERM | UNITS | DEFINITION | METHODS |
|---|---|---|---|
| $x$ | unitless | Power function exponent, the value that represents the decay of fallout radioactivity at a given location. Default =1.2. | 2.8 |
| $XDCF_A$ | $\frac{\text{mrem}}{\text{mR}}$ | Exposure to Dose Conversion Factor (acute), the constant used to convert external exposure (mR) to midline (bone marrow) dose (mrem), 0.7. | 3.2 |
| $XDCF_C$ | $\frac{\text{mrem}}{\text{mR}}$ | Exposure to Dose Conversion Factor (chronic), the constant used to convert external exposure (mR) to deep tissue (1 cm) dose (mrem), 1.0. | 2.2, 3.2 |
| $Y$ | $\frac{\text{kg}_{\text{wet}}}{\text{m}^2}$ | Crop Yield, the mass of crop grown per area of land (default 2.0 for produce and 0.7 for pastureland). | 4.2, 4.3, 4.4, 4.6, Table 10 |
| $Y_{\alpha\, i}$ | $\frac{\mu\text{Ci}_\alpha}{\mu\text{Ci}_{\text{nt}}}$ | Yield, the alpha activity per total (nuclear transformation) activity of radionuclide i. | 2.3 |
| $Y_{\beta\, i}$ | $\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}_{\text{nt}}}$ | Yield, the beta activity per total (nuclear transformation) activity of radionuclide i. | 2.4 |

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| # | Radionuclide | $t_{1/2}$ (d) | λ ($d^{-1}$) | Branching Ratio |
|---|---|---|---|---|
| 1 | **Am-241** | **1.58E+05** | **4.36E-06** | **NA** |
| 2 | **Ba-140/La-140** | | | |
| | Ba-140 | 1.27E+01 | 5.44E-02 | 1 |
| | La-140 | 1.68E+00 | 4.13E-01 | 1 |
| 3 | **Ce-141** | **3.25E+01** | **2.13E-02** | **NA** |
| 4 | **Ce-144/Pr-144/Pr-144m** | | | |
| | Ce-144 | 2.84E+02 | 2.44E-03 | 1 |
| | Pr-144 | 1.20E-02 | 5.78E+01 | 0.982 |
| | Pr-144m | 5.00E-03 | 1.39E+02 | 1.78E-02 |
| | Pr-144 | 1.20E-02 | 5.78E+01 | 0.999 |
| 5 | **Cf-252** | **9.64E+02** | **7.19E-04** | **NA** |
| 6 | **Cm-242** | **1.63E+02** | **4.26E-03** | **NA** |
| 7 | **Cm-244** | **6.61E+03** | **1.05E-04** | **NA** |
| 8 | **Co-60** | **1.93E+03** | **3.60E-04** | **NA** |
| 9 | **Cs-134** | **7.53E+02** | **9.20E-04** | **NA** |
| 10 | **Cs-136** | **1.31E+01** | **5.29E-02** | **NA** |
| 11 | **Cs-137/Ba-137m** | | | |
| | Cs-137 | 1.10E+04 | 6.33E-05 | 1 |
| | Ba-137m | 1.77E-03 | 3.91E+02 | 0.946 |
| 12 | **Gd-153** | **2.42E+02** | **2.86E-03** | **NA** |
| 13 | **I-129** | **5.73E+09** | **1.21E-10** | **NA** |
| 14 | **I-131** | **8.04E+00** | **8.62E-02** | **NA** |
| 15 | **I-132** | **9.58E-02** | **7.23E+00** | **NA** |
| 16 | **I-133** | **8.67E-01** | **8.00E-01** | **NA** |
| 17 | **I-134** | **3.65E-02** | **1.90E+01** | **NA** |
| 18 | **I-135/Xe-135m** | | | |
| | I-135 | 2.75E-01 | 2.52E+00 | 1 |
| | Xe-135m | 1.06E-02 | 6.53E+01 | 0.154 |
| 19 | **Ir-192** | **7.40E+01** | **9.36E-03** | **NA** |
| 20 | **Kr-87** | **5.30E-02** | **1.31E+01** | **NA** |
| 21 | **Kr-88/Rb-88** | | | |
| | Kr-88 | 1.18E-01 | 5.86E+00 | 1 |
| | Rb-88 | 1.24E-02 | 5.61E+01 | 1 |
| 22 | **La-140** | **1.68E+00** | **4.13E-01** | **NA** |
| 23 | **Mo-99/Tc-99m** | | | |
| | Mo-99 | 2.75E+00 | 2.52E-01 | 1 |
| | Tc-99m | 2.51E-01 | 2.76E+00 | 0.876 |
| 24 | **Nb-95** | **3.52E+01** | **1.97E-02** | **NA** |
| 25 | **Np-237/Pa-233** | | | |
| | Np-237 | 7.82E+08 | 8.87E-10 | 1 |
| | Pa-233 | 2.70E+01 | 2.57E-02 | 1 |
| 26 | **Np-239** | **2.36E+00** | **2.94E-01** | **NA** |
| 27 | **Pm-147** | **9.58E+02** | **7.23E-04** | **NA** |
| 28 | **Pu-238** | **3.20E+04** | **2.16E-05** | **NA** |
| 29 | **Pu-239** | **8.79E+06** | **7.89E-08** | **NA** |
| 30 | **Pu-241/U-237** | | | |
| | Pu-241 | 5.26E+03 | 1.32E-04 | 1 |
| | U-237 | 6.75E+00 | 1.03E-01 | 2.45E-05 |

| # | Radionuclide | $t_{1/2}$ (d) | λ ($d^{-1}$) | Branching Ratio |
|---|---|---|---|---|
| 31 | **Ra-226/Rn-222…** | | | |
| | Ra-226 | 5.84E+05 | 1.19E-06 | 1 |
| | Rn-222 | 3.82E+00 | 1.81E-01 | 1 |
| | Po-218 | 2.12E-03 | 3.27E+02 | 1 |
| | At-218 | 2.31E-05 | 2.99E+04 | 2.00E-04 |
| | Bi-214 | 1.38E-02 | 5.02E+01 | 1 |
| | Po-214 | 1.90E-09 | 3.65E+08 | 1 |
| | Pb-214 | 1.86E-02 | 3.72E+01 | 1 |
| | Bi-214 | 1.38E-02 | 5.02E+01 | 1 |
| | Po-214 | 1.90E-09 | 3.64E+08 | 1 |
| 32 | **Ru-103/Rh-103m** | | | |
| | Ru-103 | 3.93E+01 | 1.76E-02 | 1 |
| | Rh-103m | 3.90E-02 | 1.78E+01 | 0.997 |
| 33 | **Ru-106/Rh-106** | | | |
| | Ru-106 | 3.68E+02 | 1.88E-03 | 1 |
| | Rh-106 | 3.46E-04 | 2.00E+03 | 1 |
| 34 | **Sb-127/Te-127** | | | |
| | Sb-127 | 3.85E+00 | 1.80E-01 | 1 |
| | Te-127 | 3.90E-01 | 1.78E+00 | 0.824 |
| 35 | **Sb-129/Te-129** | | | |
| | Sb-129 | 1.80E-01 | 3.85E+00 | 1 |
| | Te-129 | 4.83E-02 | 1.43E+01 | 0.775 |
| 36 | **Se-75** | **1.20E+02** | **5.79E-03** | **NA** |
| 37 | **Sr-89** | **5.05E+01** | **1.37E-02** | **NA** |
| 38 | **Sr-90/Y-90** | | | |
| | Sr-90 | 1.06E+04 | 6.52E-05 | 1 |
| | Y-90 | 2.67E+00 | 2.60E-01 | 1 |
| 39 | **Sr-91/Y-91m** | | | |
| | Sr-91 | 3.96E-01 | 1.75E+00 | 1 |
| | Y-91m | 3.45E-02 | 2.01E+01 | 0.578 |
| 40 | **Te-129m/Te-129** | | | |
| | Te-129m | 3.36E+01 | 2.06E-02 | 1 |
| | Te-129 | 4.83E-02 | 1.43E+01 | 0.65 |
| 41 | **Te-131m/Te-131** | | | |
| | Te-131m | 1.25E+00 | 5.55E-01 | 1 |
| | Te-131 | 1.74E-02 | 3.99E+01 | 0.222 |
| 42 | **Te-132/I-132** | | | |
| | Te-132 | 3.26E+00 | 2.13E-01 | 1 |
| | I-132 | 9.58E-02 | 7.23E+00 | 1 |
| 43 | **Tm-170** | **1.29E+02** | **5.39E-03** | **NA** |
| 44 | **Xe-133** | **5.24E+00** | **1.32E-01** | **NA** |
| 45 | **Xe-135** | **3.79E-01** | **1.83E+00** | **NA** |
| 46 | **Xe-138** | **9.84E-03** | **7.04E+01** | **NA** |
| 47 | **Y-91** | **5.85E+01** | **1.18E-02** | **NA** |
| 48 | **Yb-169** | **3.20E+01** | **2.16E-02** | **NA** |
| 49 | **Zr-95/Nb-95m/Nb-95** | | | |
| | Zr-95 | 6.40E+01 | 1.08E-02 | 1 |
| | Nb-95m | 3.61E+00 | 1.92E-01 | 6.98E-03 |
| | Nb-95 | 3.52E+01 | 1.97E-02 | 1 |
| | Nb-95 | 3.52E+01 | 1.97E-02 | 0.993 |

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**Table 2-1 Dose Limits for Workers Performing Emergency Services**

| TED [a] (rem) | Lens of Eye (rem) | Other Organ, Thyroid, Skin (rem) | Activity | Condition |
|---|---|---|---|---|
| 5 | 15 | 50 | All. | |
| 10 | 30 | 100 | Protecting valuable property. | Lower dose not practicable. |
| 25 | 75 | 250 | Life saving or protection of large populations. | Lower dose not practicable. |
| >25 | >75 | >250 | Life saving 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

[a] 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**

| Time Phase | Protective Action | Limit (rem) | Comments |
|---|---|---|---|
| Early | Evacuation or Sheltering | TED 1-5 [a]<br>Thyroid 5-25<br>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 | 25 | Equivalent Dose to the thyroid from radioiodine. Requires approval of state medical officials. |
| 1st Year | Relocation [b] | 2 [a] | Or 100 rem skin dose. |
| | Apply dose reduction techniques | <2 | Should be taken to reduce doses to ALARA.<br>(Scrubbing and/or flushing hard surfaces, soaking or plowing soil, minor removal of soil from areas of concentration, limiting outdoor time, etc.) |
| 2nd Year | Relocation [b] | 0.5 [a] | Any single year after the 1st. |
| 50 Years | Relocation [b] | 5 [a] | Total for 50 years. |
| Ingestion | See Table 2-3 | 0.5 CED<br>5 $H_T$ | Due to ingestion of contaminated food in one year.<br>Whichever is more limiting (Whole Body or Organ). |

Source: EPA92, FDA98

[a] 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.

[b] 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 Ingestion Protective Actions**

| | |
|---|---|
| **Animals** | Move to shelter and/or corral, provide protected feed and water. |
| **All foods** | Isolate by temporary embargo until survey and initial sampling is completed. Determine whether condemnation or other disposition is appropriate. |
| **Milk** | Hold for decay or divert to other products involving adequate decay during processing (e.g., cheese, butter, dry milk solids, or evaporated milk). |
| **Fruits and Vegetables** | Wash, brush, scrub or peel to remove surface contamination. Preserve by canning, freezing, dehydration, or storage to permit decay. |
| **Grains** | 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 is 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 [a, b] (percent) |
|---|---|
| 140 | 5 |
| 200 | 15 |
| 300 | 50 |
| 400 | 85 |
| 460 | 95 |

| Whole-Body Absorbed Dose (rad) | Prodromal Effects [a, c] (percent affected) |
|---|---|
| 50 | 2 |
| 100 | 15 |
| 150 | 50 |
| 200 | 85 |
| 250 | 98 |

Source: EPA92, Table 2-3

[a] Risks will be lower for protracted exposure periods.

[b] Supportive medical treatment may increase the dose where these frequencies occur by approximately 50 percent.

[c] 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<br>100<br>800 | Vomiting<br>Diarrhea<br>Lethality |
| Skin | 200 | Transient erythema |
| Thyroid | 300 | Hypothyroidism |
| Lung [a] | 600 | Pneumonitis |
| Bone | 1000 | Osteonecrosis |

Source Me95

[a] The lung dose includes an RBE of 10 applied to the high LET (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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This Table contains the Deposition and Dose Rate DRLs and the intermediate products necessary to calculate the DRLs for the Assessment Working Group's list of radionuclides. Values are provided for the 4 standard Time Phases (Early, 1st Year, 2nd Year and 50 Year.)

These values are **only appropriate** when the:

- mixture of interest contains only 1 radionuclide (and any included daughters),
- Exposure to Dose Conversion Factor is 1.0,
- start of the Time Phase ($t_1$) is equal to the time of Deposition ($t_0$), and
- time of interest ($t_n$) is equal to the time of Deposition ($t_0$).

The terms contained in this table are defined below:

| DRLs | | |
|---|---|---|
| $Dp\_DRL_{organ,i,tn}$ | $\frac{\mu Ci}{m^2}$ | Deposition Derived Response Level, the areal activity (radioactivity per unit area) at time $t_n$ of radionuclide i, at which the dose to the organ of interest from all radionuclides in mixture would result in a dose equal to the PAG for the time phase under consideration. |
| $Dp\_DRL_{XR,E,tn}$ | $\frac{mR}{hr}$ | Deposition Exposure Rate Derived Response Level, the external exposure rate, at time $t_n$, at which the dose from all radionuclides in a deposition mixture would result in a dose to the whole body (E) equal to the PAG for the time phase under consideration. |
| Intermediate Values | | |
| $ExDP\_Dp_{E,\,i,\,TP}$ | $\frac{mrem \cdot m^2}{\mu Ci}$ | External Dose Parameter for Deposition, the groundshine dose received by the whole body (E), over the time phase under consideration (TP), per unit of radioactivity of radionuclide *i* deposited on the ground and adjusted for the ground roughness factor. |
| $ExDF_{E,i}$ | $\frac{mrem \cdot m^2}{hr \cdot \mu Ci}$ | External Dose Factor for deposition, the external dose rate to the whole body (E) per unit activity deposited on the ground from radionuclide *i* and adjusted for the ground roughness factor. |
| $InhDP\_Dp_{E,\,i,\,TP}$ | $\frac{mrem \cdot m^2}{\mu Ci}$ | Inhalation Dose Parameter for Deposition, the committed effective dose received by the whole body (E), over the time phase under consideration (TP), per unit activity of radionuclide *i* deposited on the ground from the inhalation of the resuspended radionuclide. |
| $TDP\_Dp_{E,\,i,\,TP}$ | $\frac{mrem \cdot m^2}{\mu Ci}$ | Total Dose Parameter for Deposition, the sum of the external dose from groundshine and the internal (committed effective) dose from inhalation of resuspended material received, by the whole body (E), over the time phase under consideration (TP), per unit of areal activity of radionuclide *i* deposited on the ground. |

**Notes:**

Dp_DRLs apply to individual (marker) radionuclides. If a radionuclide is formed from multiple pathways in a chain (e.g., $^{144}$Pr is formed by two separate branches from the decay of $^{144}$Ce), the Dp_DRL values have been summed to indicate the total contribution from that radionuclide for all branches.

$Dp\_DRL_{XR}$ apply to the mixture of radionuclides. (In this case, a single parent and the included daughters.)

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| # | Radionuclide | ExDP_Dp (mrem·m²)/µCi | InhDP_Dp (mrem·m²)/µCi | TDP_Dp (mrem·m²)/µCi | ExDF (mrem·m²)/(hr·µCi) | Dp_DRL µCi/m² | $Dp\_DRL_{XR}$ mR/hr |
|---|---|---|---|---|---|---|---|
| 1 | **Am-241** | **2.28E-02** | **1.89E+01** | **1.89E+01** | **2.38E-04** | **5.29E+01** | **1.26E-02** |
| 2 | **Ba-140/La-140** | **2.20E+00** | **1.27E-03** | **2.20E+00** | **2.56E-02** | **-** | **1.16E-02** |
| | Ba-140 | 1.80E-01 | 1.06E-03 | 1.81E-01 | 2.09E-03 | 4.53E+02 | - |
| | La-140 | 2.02E+00 | 2.07E-04 | 2.02E+00 | 2.35E-02 | 4.53E+02 | - |
| 3 | **Ce-141** | **7.00E-02** | **7.12E-04** | **7.07E-02** | **7.63E-04** | **1.41E+04** | **1.08E-02** |
| 4 | **Ce-144/Pr-144/Pr-144m** | **1.86E-01** | **1.03E-02** | **1.96E-01** | **1.95E-03** | **-** | **9.94E+00** |
| | Ce-144 | 1.80E-02 | 1.03E-02 | 2.83E-02 | 1.89E-04 | 5.09E+03 | - |
| | Pr-144m | 1.14E-02 | NA | 1.14E-02 | 1.19E-04 | 9.06E+01 | - |
| | Pr-144 | 1.68E-01 | 3.57E-06 | 1.68E-01 | 1.76E-03 | 5.09E+03 | - |
| 5 | **Cf-252** | **4.52E-01** | **7.24E+00** | **7.69E+00** | **4.72E-03** | **1.30E+02** | **6.13E-01** |
| 6 | **Cm-242** | **6.94E-04** | **1.15E+00** | **1.15E+00** | **7.28E-06** | **8.67E+02** | **6.33E-03** |
| 7 | **Cm-244** | **6.14E-04** | **1.12E+01** | **1.12E+01** | **6.39E-06** | **8.96E+01** | **5.73E-04** |
| 8 | **Co-60** | **2.41E+00** | **6.01E-03** | **2.41E+00** | **2.51E-02** | **4.14E+02** | **1.04E+01** |
| 9 | **Cs-134** | **1.55E+00** | **3.99E-03** | **1.55E+00** | **1.62E-02** | **6.44E+02** | **1.04E+01** |
| 10 | **Cs-136** | **1.88E+00** | **5.05E-04** | **1.88E+00** | **2.18E-02** | **5.32E+02** | **1.16E+01** |
| 11 | **Cs-137/Ba-137m** | **5.75E-01** | **7.68E-03** | **5.82E-01** | **6.00E-03** | **-** | **1.03E+01** |
| | Cs-137 | 3.28E-03 | 7.68E-03 | 1.10E-02 | 3.42E-05 | 1.72E+03 | - |
| | Ba-137m | 6.04E-01 | NA | 6.04E-01 | 6.31E-03 | 1.62E+03 | - |
| 12 | **Gd-153** | **9.59E-02** | **4.68E-04** | **9.64E-02** | **1.01E-03** | **1.04E+04** | **1.04E+01** |
| 13 | **I-129** | **2.08E-02** | **7.03E-03** | **2.79E-02** | **2.18E-04** | **3.59E+04** | **7.77E+00** |
| 14 | **I-131** | **3.23E-01** | **1.28E-03** | **3.25E-01** | **3.99E-03** | **3.08E+03** | **1.23E+01** |
| 15 | **I-132** | **7.90E-02** | **1.29E-06** | **7.90E-02** | **2.38E-02** | **1.27E+04** | **3.02E+02** |
| 16 | **I-133** | **1.95E-01** | **1.19E-04** | **1.96E-01** | **6.80E-03** | **5.11E+03** | **3.47E+01** |
| 17 | **I-134** | **3.44E-02** | **2.42E-07** | **3.44E-02** | **2.72E-02** | **2.91E+04** | **7.91E+02** |
| 18 | **I-135/Xe-135m** | **1.60E-01** | **1.03E-05** | **1.60E-01** | **1.67E-02** | **-** | **1.05E+02** |
| | I-135 | 1.53E-01 | 1.03E-05 | 1.53E-01 | 1.60E-02 | 6.26E+03 | - |
| | Xe-135m | 4.32E-02 | NA | 4.32E-02 | 4.54E-03 | 9.65E+02 | - |
| 19 | **Ir-192** | **7.97E-01** | **1.28E-03** | **7.98E-01** | **8.47E-03** | **1.25E+03** | **1.06E+01** |
| 20 | **Kr-87** | **1.68E-02** | **NA** | **1.68E-02** | **9.17E-03** | **5.95E+04** | **5.45E+02** |
| 21 | **Kr-88/Rb-88** | **1.11E-01** | **3.87E-07** | **1.11E-01** | **2.70E-02** | **-** | **2.44E+02** |
| | Kr-88 | 7.70E-02 | NA | 7.70E-02 | 1.88E-02 | 9.05E+03 | - |
| | Rb-88 | 3.35E-02 | 3.87E-07 | 3.35E-02 | 8.19E-03 | 9.05E+03 | - |
| 22 | **La-140** | **1.10E+00** | **1.33E-04** | **1.10E+00** | **2.35E-02** | **9.07E+02** | **2.35E-02** |
| 23 | **Mo-99/Tc-99m** | **1.83E-01** | **1.41E-04** | **1.83E-01** | **3.02E-03** | **-** | **1.65E+01** |
| | Mo-99 | 1.17E-01 | 1.39E-04 | 1.17E-01 | 1.93E-03 | 5.47E+03 | - |
| | Tc-99m | 7.53E-02 | 2.81E-06 | 7.53E-02 | 1.25E-03 | 4.79E+03 | - |
| 24 | **Nb-95** | **7.31E-01** | **3.33E-04** | **7.32E-01** | **7.91E-03** | **1.37E+03** | **1.09E+01** |
| 25 | **Np-237/Pa-233** | **2.38E-01** | **9.74E+00** | **9.97E+00** | **2.47E-03** | **-** | **2.48E-01** |
| | Np-237 | 2.56E-02 | 9.74E+00 | 9.76E+00 | 2.67E-04 | 1.00E+02 | - |
| | Pa-233 | 2.12E-01 | 7.56E-04 | 2.12E-01 | 2.21E-03 | 1.00E+02 | - |
| 26 | **Np-239** | **9.98E-02** | **1.37E-04** | **9.99E-02** | **1.77E-03** | **1.00E+04** | **1.77E+01** |
| 27 | **Pm-147** | **2.94E-05** | **1.37E-03** | **1.40E-03** | **3.07E-07** | **7.17E+05** | **2.20E-01** |
| 28 | **Pu-238** | **6.28E-04** | **2.12E+01** | **2.12E+01** | **6.55E-06** | **4.73E+01** | **3.09E-04** |
| 29 | **Pu-239** | **3.21E-04** | **2.33E+01** | **2.33E+01** | **3.35E-06** | **4.29E+01** | **1.44E-04** |
| 30 | **Pu-241/U-237** | **4.66E-06** | **4.49E-01** | **4.49E-01** | **4.85E-08** | **-** | **1.09E-04** |
| | Pu-241 | 1.50E-06 | 4.49E-01 | 4.49E-01 | 1.56E-08 | 2.23E+03 | - |
| | U-237 | 1.29E-01 | 3.68E-04 | 1.29E-01 | 1.34E-03 | 5.46E-02 | - |

| # | Radionuclide | ExDP_Dp (mrem·m²)/µCi | InhDP_Dp (mrem·m²)/µCi | TDP_Dp (mrem·m²)/µCi | ExDF (mrem·m²)/(hr·µCi) | Dp_DRL µCi/m² | $Dp\_DRL_{XR}$ mR/hr |
|---|---|---|---|---|---|---|---|
| 31 | **Ra-226/Rn-222…** | **1.75E+00** | **1.87E+00** | **3.62E+00** | **1.83E-02** | **-** | **5.04E+00** |
| | Ra-226 | 7.00E-03 | 1.86E+00 | 1.87E+00 | 7.28E-05 | 2.76E+02 | - |
| | Rn-222 | 3.90E-04 | NA | 3.90E-04 | 4.07E-06 | 2.76E+02 | - |
| | Po-218 | 6.97E-09 | NA | 6.97E-09 | 7.28E-11 | 2.76E+02 | - |
| | At-218 | 1.31E-04 | NA | 1.31E-04 | 1.37E-06 | 5.53E-02 | - |
| | Pb-214 | 2.55E-01 | 2.88E-03 | 2.57E-01 | 2.65E-03 | 2.76E+02 | - |
| | Bi-214 | 1.49E+00 | 3.02E-03 | 1.49E+00 | 1.55E-02 | 2.76E+02 | - |
| | Po-214 | 8.25E-05 | NA | 8.25E-05 | 8.61E-07 | 2.76E+02 | - |
| 32 | **Ru-103/Rh-103m** | **4.81E-01** | **5.64E-04** | **4.81E-01** | **5.19E-03** | **-** | **1.08E+01** |
| | Ru-103 | 4.80E-01 | 5.63E-04 | 4.80E-01 | 5.18E-03 | 2.08E+03 | - |
| | Rh-103m | 8.36E-04 | 5.21E-07 | 8.36E-04 | 9.03E-06 | 2.07E+03 | - |
| 33 | **Ru-106/Rh-106** | **3.61E-01** | **1.29E-02** | **3.74E-01** | **3.78E-03** | **-** | **1.01E+01** |
| | Ru-106 | NA | 1.29E-02 | 1.29E-02 | 0.00E+00 | 2.67E+03 | - |
| | Rh-106 | 3.61E-01 | NA | 3.61E-01 | 3.78E-03 | 2.67E+03 | - |
| 34 | **Sb-127/Te-127** | **5.14E-01** | **3.06E-04** | **5.14E-01** | **7.51E-03** | **-** | **1.46E+01** |
| | Sb-127 | 5.08E-01 | 2.88E-04 | 5.08E-01 | 7.42E-03 | 1.94E+03 | - |
| | Te-127 | 7.84E-03 | 2.14E-05 | 7.86E-03 | 1.15E-04 | 1.60E+03 | - |
| 35 | **Sb-129/Te-129** | **1.01E-01** | **5.96E-06** | **1.01E-01** | **1.62E-02** | **-** | **1.60E+02** |
| | Sb-129 | 9.46E-02 | 5.31E-06 | 9.46E-02 | 1.52E-02 | 9.92E+03 | - |
| | Te-129 | 7.90E-03 | 8.35E-07 | 7.90E-03 | 1.27E-03 | 7.69E+03 | - |
| 36 | **Se-75** | **3.69E-01** | **2.60E-04** | **3.69E-01** | **3.89E-03** | **2.71E+03** | **1.06E+01** |
| 37 | **Sr-89** | **7.01E-02** | **1.52E-03** | **7.17E-02** | **7.49E-04** | **1.40E+04** | **1.05E+01** |
| 38 | **Sr-90/Y-90** | **1.17E-01** | **3.11E-02** | **1.49E-01** | **1.22E-03** | **-** | **8.26E+00** |
| | Sr-90 | 1.72E-03 | 3.08E-02 | 3.25E-02 | 1.79E-05 | 6.76E+03 | - |
| | Y-90 | 1.15E-01 | 2.94E-04 | 1.16E-01 | 1.20E-03 | 6.76E+03 | - |
| 39 | **Sr-91/Y-91m** | **1.54E-01** | **1.84E-05** | **1.54E-01** | **1.13E-02** | **-** | **7.28E+01** |
| | Sr-91 | 1.10E-01 | 1.81E-05 | 1.10E-01 | 8.05E-03 | 6.50E+03 | - |
| | Y-91m | 7.60E-02 | 5.06E-07 | 7.60E-02 | 5.55E-03 | 3.76E+03 | - |
| 40 | **Te-129m/Te-129** | **1.35E-01** | **1.51E-03** | **1.36E-01** | **1.46E-03** | **-** | **1.07E+01** |
| | Te-129m | 5.86E-02 | 1.51E-03 | 6.01E-02 | 6.37E-04 | 7.35E+03 | - |
| | Te-129 | 1.17E-01 | 7.47E-06 | 1.17E-01 | 1.27E-03 | 4.78E+03 | - |
| 41 | **Te-131m/Te-131** | **6.17E-01** | **1.09E-04** | **6.17E-01** | **1.60E-02** | **-** | **2.60E+01** |
| | Te-131m | 5.73E-01 | 1.08E-04 | 5.73E-01 | 1.48E-02 | 1.62E+03 | - |
| | Te-131 | 1.99E-01 | 2.88E-06 | 1.99E-01 | 5.16E-03 | 3.60E+02 | - |
| 42 | **Te-132/I-132** | **1.69E+00** | **3.18E-04** | **1.69E+00** | **2.61E-02** | **-** | **1.55E+01** |
| | Te-132 | 1.50E-01 | 3.01E-04 | 1.51E-01 | 2.32E-03 | 5.92E+02 | - |
| | I-132 | 1.54E+00 | 1.67E-05 | 1.54E+00 | 2.38E-02 | 5.92E+02 | - |
| 43 | **Tm-170** | **2.58E-02** | **1.81E-03** | **2.76E-02** | **2.72E-04** | **3.62E+04** | **9.87E+00** |
| 44 | **Xe-133** | **3.30E-02** | **NA** | **3.30E-02** | **4.44E-04** | **3.03E+04** | **1.34E+01** |
| 45 | **Xe-135** | **3.58E-02** | **NA** | **3.58E-02** | **2.73E-03** | **2.79E+04** | **7.63E+01** |
| 46 | **Xe-138** | **3.98E-03** | **NA** | **3.98E-03** | **1.17E-02** | **2.51E+05** | **2.93E+03** |
| 47 | **Y-91** | **7.60E-02** | **1.72E-03** | **7.77E-02** | **8.12E-04** | **1.29E+04** | **1.04E+01** |
| 48 | **Yb-169** | **2.96E-01** | **5.66E-04** | **2.97E-01** | **3.22E-03** | **3.37E+03** | **1.09E+01** |
| 49 | **Zr-95/Nb-95m/Nb-95** | **1.46E+00** | **1.47E-03** | **1.46E+00** | **1.55E-02** | **-** | **1.06E+01** |
| | Zr-95 | 7.14E-01 | 1.13E-03 | 7.15E-01 | 7.63E-03 | 6.85E+02 | - |
| | Nb-95m | 6.41E-02 | 1.70E-04 | 6.43E-02 | 6.83E-04 | 4.78E+00 | - |
| | Nb-95 | 7.44E-01 | 3.37E-04 | 7.45E-01 | 7.91E-03 | 6.85E+02 | - |

| # | Radionuclide | ExDP_Dp (mrem·m$^2$)/µCi | InhDP_Dp (mrem·m$^2$)/µCi | TDP_Dp (mrem·m$^2$)/µCi | ExDF (mrem·m$^2$)/(hr·µCi) | Dp_DRL µCi/m$^2$ | Dp_DRL$_{XR}$ mR/hr |
|---|---|---|---|---|---|---|---|
| 1 | **Am-241** | **1.91E+00** | **5.46E+01** | **5.65E+01** | **2.38E-04** | **3.54E+01** | **8.40E-03** |
| 2 | **Ba-140/La-140** | **1.12E+01** | **1.93E-03** | **1.12E+01** | **2.56E-02** | **-** | **2.29E-03** |
| | Ba-140 | 9.12E-01 | 1.61E-03 | 9.13E-01 | 2.09E-03 | 1.79E+02 | - |
| | La-140 | 1.03E+01 | 3.15E-04 | 1.03E+01 | 2.35E-02 | 1.79E+02 | - |
| 3 | **Ce-141** | **8.37E-01** | **1.32E-03** | **8.38E-01** | **7.63E-04** | **2.39E+03** | **9.10E-04** |
| 4 | **Ce-144/Pr-144/Pr-144m** | **1.05E+01** | **2.67E-02** | **1.05E+01** | **1.95E-03** | **-** | **3.70E-01** |
| | Ce-144 | 1.02E+00 | 2.67E-02 | 1.04E+00 | 1.89E-04 | 1.90E+02 | - |
| | Pr-144m | 6.41E-01 | 0.00E+00 | 6.41E-01 | 1.19E-04 | 3.38E+00 | - |
| | Pr-144 | 9.47E+00 | 9.28E-06 | 9.47E+00 | 1.76E-03 | 1.90E+02 | - |
| 5 | **Cf-252** | **3.34E+01** | **2.02E+01** | **5.37E+01** | **4.72E-03** | **3.73E+01** | **1.76E-01** |
| 6 | **Cm-242** | **3.04E-02** | **2.81E+00** | **2.85E+00** | **7.28E-06** | **7.03E+02** | **5.13E-03** |
| 7 | **Cm-244** | **5.04E-02** | **3.21E+01** | **3.22E+01** | **6.39E-06** | **6.22E+01** | **3.98E-04** |
| 8 | **Co-60** | **1.89E+02** | **1.71E-02** | **1.89E+02** | **2.51E-02** | **1.06E+01** | **2.65E-01** |
| 9 | **Cs-134** | **1.11E+02** | **1.10E-02** | **1.11E+02** | **1.62E-02** | **1.81E+01** | **2.92E-01** |
| 10 | **Cs-136** | **9.77E+00** | **7.73E-04** | **9.77E+00** | **2.18E-02** | **2.05E+02** | **4.45E+00** |
| 11 | **Cs-137/Ba-137m** | **4.76E+01** | **2.21E-02** | **4.76E+01** | **6.00E-03** | **-** | **2.52E-01** |
| | Cs-137 | 2.71E-01 | 2.21E-02 | 2.94E-01 | 3.42E-05 | 4.20E+01 | - |
| | Ba-137m | 5.00E+01 | 0.00E+00 | 5.00E+01 | 6.31E-03 | 3.97E+01 | - |
| 12 | **Gd-153** | **5.08E+00** | **1.20E-03** | **5.08E+00** | **1.01E-03** | **3.93E+02** | **3.96E-01** |
| 13 | **I-129** | **1.75E+00** | **2.03E-02** | **1.77E+00** | **2.18E-04** | **1.13E+03** | **2.46E-01** |
| 14 | **I-131** | **1.10E+00** | **1.77E-03** | **1.11E+00** | **3.99E-03** | **1.81E+03** | **7.21E+00** |
| 15 | **I-132** | **7.90E-02** | **1.29E-06** | **7.90E-02** | **2.38E-02** | **2.53E+04** | **6.03E+02** |
| 16 | **I-133** | **2.04E-01** | **1.21E-04** | **2.04E-01** | **6.80E-03** | **9.81E+03** | **6.66E+01** |
| 17 | **I-134** | **3.44E-02** | **2.42E-07** | **3.44E-02** | **2.72E-02** | **5.81E+04** | **1.58E+03** |
| 18 | **I-135/Xe-135m** | **1.60E-01** | **1.03E-05** | **1.60E-01** | **1.67E-02** | **-** | **2.10E+02** |
| | I-135 | 1.53E-01 | 1.03E-05 | 1.53E-01 | 1.60E-02 | 1.25E+04 | - |
| | Xe-135m | 4.32E-02 | 0.00E+00 | 4.32E-02 | 4.54E-03 | 1.93E+03 | - |
| 19 | **Ir-192** | **2.00E+01** | **2.77E-03** | **2.00E+01** | **8.47E-03** | **9.98E+01** | **8.47E-01** |
| 20 | **Kr-87** | **1.68E-02** | **0.00E+00** | **1.68E-02** | **9.17E-03** | **1.19E+04** | **1.09E+03** |
| 21 | **Kr-88/Rb-88** | **1.11E-01** | **3.87E-07** | **1.11E-01** | **2.70E-02** | **-** | **4.88E+02** |
| | Kr-88 | 7.70E-02 | 0.00E+00 | 7.70E-02 | 1.88E-02 | 1.81E+04 | - |
| | Rb-88 | 3.35E-02 | 3.87E-07 | 3.35E-02 | 8.19E-03 | 1.81E+04 | - |
| 22 | **La-140** | **1.36E+00** | **1.40E-04** | **1.36E+00** | **2.35E-02** | **1.47E+03** | **2.35E-02** |
| 23 | **Mo-99/Tc-99m** | **2.87E-01** | **1.60E-04** | **2.87E-01** | **3.02E-03** | **-** | **2.11E+01** |
| | Mo-99 | 1.84E-01 | 1.57E-04 | 1.84E-01 | 1.93E-03 | 6.95E+03 | - |
| | Tc-99m | 1.18E-01 | 3.17E-06 | 1.18E-01 | 1.25E-03 | 6.09E+03 | - |
| 24 | **Nb-95** | **9.40E+00** | **6.26E-04** | **9.40E+00** | **7.91E-03** | **2.13E+02** | **1.69E+00** |
| 25 | **Np-237/Pa-233** | **1.98E+01** | **2.82E+01** | **4.80E+01** | **2.47E-03** | **-** | **1.03E-01** |
| | Np-237 | 2.14E+00 | 2.82E+01 | 3.03E+01 | 2.67E-04 | 4.17E+01 | - |
| | Pa-233 | 1.77E+01 | 2.19E-03 | 1.77E+01 | 2.21E-03 | 4.17E+01 | - |
| 26 | **Np-239** | **1.44E-01** | **1.51E-04** | **1.44E-01** | **1.77E-03** | **1.39E+04** | **2.46E+01** |
| 27 | **Pm-147** | **2.17E-03** | **3.81E-03** | **5.99E-03** | **3.07E-07** | **3.34E+05** | **1.03E-01** |
| 28 | **Pu-238** | **5.32E-02** | **6.11E+01** | **6.12E+01** | **6.55E-06** | **3.27E+01** | **2.14E-04** |
| 29 | **Pu-239** | **2.68E-02** | **6.74E+01** | **6.74E+01** | **3.35E-06** | **2.97E+01** | **9.94E-05** |
| 30 | **Pu-241/U-237** | **3.81E-04** | **1.29E+00** | **1.29E+00** | **4.85E-08** | **-** | **7.59E-05** |
| | Pu-241 | 1.24E-04 | 1.29E+00 | 1.29E+00 | 1.56E-08 | 1.55E+03 | - |
| | U-237 | 1.05E+01 | 1.06E-03 | 1.05E+01 | 1.34E-03 | 3.80E-02 | - |

| # | Radionuclide | ExDP_Dp (mrem·m²)/µCi | InhDP_Dp (mrem·m²)/µCi | TDP_Dp (mrem·m²)/µCi | ExDF (mrem·m²)/(hr·µCi) | Dp_DRL µCi/m² | Dp_DRL$_{XR}$ mR/hr |
|---|---|---|---|---|---|---|---|
| 31 | **Ra-226/Rn-222…** | **1.47E+02** | **5.41E+00** | **1.52E+02** | **1.83E-02** | **-** | **2.40E-01** |
| | Ra-226 | 5.86E-01 | 5.39E+00 | 5.97E+00 | 7.28E-05 | 1.32E+01 | - |
| | Rn-222 | 3.26E-02 | 0.00E+00 | 3.26E-02 | 4.07E-06 | 1.32E+01 | - |
| | Po-218 | 5.83E-07 | 0.00E+00 | 5.83E-07 | 7.28E-11 | 1.32E+01 | - |
| | At-218 | 1.10E-02 | 0.00E+00 | 1.10E-02 | 1.37E-06 | 2.63E-03 | - |
| | Pb-214 | 2.13E+01 | 8.33E-03 | 2.13E+01 | 2.65E-03 | 1.32E+01 | - |
| | Bi-214 | 1.25E+02 | 8.72E-03 | 1.25E+02 | 1.55E-02 | 1.32E+01 | - |
| | Po-214 | 6.90E-03 | 0.00E+00 | 6.90E-03 | 8.61E-07 | 1.32E+01 | - |
| 32 | **Ru-103/Rh-103m** | **6.85E+00** | **1.08E-03** | **6.85E+00** | **5.19E-03** | **-** | **1.51E+00** |
| | Ru-103 | 6.84E+00 | 1.08E-03 | 6.84E+00 | 5.18E-03 | 2.92E+02 | - |
| | Rh-103m | 1.19E-02 | 1.00E-06 | 1.19E-02 | 9.03E-06 | 2.91E+02 | - |
| 33 | **Ru-106/Rh-106** | **2.22E+01** | **3.42E-02** | **2.22E+01** | **3.78E-03** | **-** | **3.41E-01** |
| | Ru-106 | 0.00E+00 | 3.42E-02 | 3.42E-02 | 0.00E+00 | 9.01E+01 | - |
| | Rh-106 | 2.22E+01 | 0.00E+00 | 2.22E+01 | 3.78E-03 | 9.01E+01 | - |
| 34 | **Sb-127/Te-127** | **1.00E+00** | **3.64E-04** | **1.00E+00** | **7.51E-03** | **-** | **1.51E+01** |
| | Sb-127 | 9.87E-01 | 3.43E-04 | 9.88E-01 | 7.42E-03 | 2.00E+03 | - |
| | Te-127 | 1.52E-02 | 2.56E-05 | 1.53E-02 | 1.15E-04 | 1.65E+03 | - |
| 35 | **Sb-129/Te-129** | **1.01E-01** | **5.96E-06** | **1.01E-01** | **1.62E-02** | **-** | **3.21E+02** |
| | Sb-129 | 9.46E-02 | 5.31E-06 | 9.46E-02 | 1.52E-02 | 1.98E+04 | - |
| | Te-129 | 7.90E-03 | 8.35E-07 | 7.90E-03 | 1.27E-03 | 1.54E+04 | - |
| 36 | **Se-75** | **1.34E+01** | **6.09E-04** | **1.34E+01** | **3.89E-03** | **1.50E+02** | **5.82E-01** |
| 37 | **Sr-89** | **1.26E+00** | **3.07E-03** | **1.26E+00** | **7.49E-04** | **1.58E+03** | **1.19E+00** |
| 38 | **Sr-90/Y-90** | **9.68E+00** | **8.94E-02** | **9.77E+00** | **1.22E-03** | **-** | **2.50E-01** |
| | Sr-90 | 1.42E-01 | 8.86E-02 | 2.31E-01 | 1.79E-05 | 2.05E+02 | - |
| | Y-90 | 9.54E+00 | 8.47E-04 | 9.54E+00 | 1.20E-03 | 2.05E+02 | - |
| 39 | **Sr-91/Y-91m** | **1.54E-01** | **1.84E-05** | **1.54E-01** | **1.13E-02** | **-** | **1.46E+02** |
| | Sr-91 | 1.10E-01 | 1.81E-05 | 1.10E-01 | 8.05E-03 | 1.30E+04 | - |
| | Y-91m | 7.60E-02 | 5.07E-07 | 7.60E-02 | 5.55E-03 | 7.51E+03 | - |
| 40 | **Te-129m/Te-129** | **1.66E+00** | **2.81E-03** | **1.66E+00** | **1.46E-03** | **-** | **1.76E+00** |
| | Te-129m | 7.23E-01 | 2.80E-03 | 7.26E-01 | 6.37E-04 | 1.20E+03 | - |
| | Te-129 | 1.44E+00 | 1.39E-05 | 1.44E+00 | 1.27E-03 | 7.83E+02 | - |
| 41 | **Te-131m/Te-131** | **6.92E-01** | **1.12E-04** | **6.93E-01** | **1.60E-02** | **-** | **4.63E+01** |
| | Te-131m | 6.42E-01 | 1.11E-04 | 6.43E-01 | 1.48E-02 | 2.89E+03 | - |
| | Te-131 | 2.23E-01 | 2.96E-06 | 2.23E-01 | 5.16E-03 | 6.42E+02 | - |
| 42 | **Te-132/I-132** | **2.94E+00** | **3.68E-04** | **2.94E+00** | **2.61E-02** | **-** | **1.78E+01** |
| | Te-132 | 2.62E-01 | 3.49E-04 | 2.62E-01 | 2.32E-03 | 6.80E+02 | - |
| | I-132 | 2.68E+00 | 1.94E-05 | 2.68E+00 | 2.38E-02 | 6.80E+02 | - |
| 43 | **Tm-170** | **9.80E-01** | **4.27E-03** | **9.84E-01** | **2.72E-04** | **2.03E+03** | **5.53E-01** |
| 44 | **Xe-133** | **8.02E-02** | **0.00E+00** | **8.02E-02** | **4.44E-04** | **2.49E+04** | **1.11E+01** |
| 45 | **Xe-135** | **3.58E-02** | **0.00E+00** | **3.58E-02** | **2.73E-03** | **5.59E+04** | **1.53E+02** |
| 46 | **Xe-138** | **3.98E-03** | **0.00E+00** | **3.98E-03** | **1.17E-02** | **5.02E+05** | **5.87E+03** |
| 47 | **Y-91** | **1.56E+00** | **3.56E-03** | **1.56E+00** | **8.12E-04** | **1.28E+03** | **1.04E+00** |
| 48 | **Yb-169** | **3.49E+00** | **1.04E-03** | **3.49E+00** | **3.22E-03** | **5.73E+02** | **1.85E+00** |
| 49 | **Zr-95/Nb-95m/Nb-95** | **3.23E+01** | **3.08E-03** | **3.23E+01** | **1.55E-02** | **-** | **9.59E-01** |
| | Zr-95 | 1.58E+01 | 2.37E-03 | 1.58E+01 | 7.63E-03 | 6.18E+01 | - |
| | Nb-95m | 1.42E+00 | 3.58E-04 | 1.42E+00 | 6.83E-04 | 4.31E-01 | - |
| | Nb-95 | 1.65E+01 | 7.11E-04 | 1.65E+01 | 7.91E-03 | 6.18E+01 | - |

| # | Radionuclide | ExDP_Dp (mrem·m$^2$)/µCi | InhDP_Dp (mrem·m$^2$)/µCi | TDP_Dp (mrem·m$^2$)/µCi | ExDF (mrem·m$^2$)/(hr·µCi) | Dp_DRL µCi/m$^2$ | Dp_DRL$_{XR}$ mR/hr |
|---|---|---|---|---|---|---|---|
| 1 | **Am-241** | **1.64E+00** | **5.47E+00** | **7.12E+00** | **2.38E-04** | **7.02E+01** | **1.67E-02** |
| 2 | **Ba-140/La-140** | **2.24E-08** | **6.54E-14** | **2.24E-08** | **2.56E-02** | **-** | **5.70E+08** |
| | Ba-140 | 1.83E-09 | 5.47E-14 | 1.83E-09 | 2.09E-03 | 2.23E+10 | - |
| | La-140 | 2.06E-08 | 1.07E-14 | 2.06E-08 | 2.35E-02 | 2.23E+10 | - |
| 3 | **Ce-141** | **2.96E-04** | **1.47E-08** | **2.96E-04** | **7.63E-04** | **1.69E+06** | **1.29E+03** |
| 4 | **Ce-144/Pr-144/Pr-144m** | **3.70E+00** | **8.57E-04** | **3.70E+00** | **1.95E-03** | **-** | **2.63E-01** |
| | Ce-144 | 3.59E-01 | 8.57E-04 | 3.60E-01 | 1.89E-04 | 1.39E+03 | - |
| | Pr-144m | 2.26E-01 | 0.00E+00 | 2.26E-01 | 1.19E-04 | 2.47E+01 | - |
| | Pr-144 | 3.34E+00 | 2.98E-07 | 3.34E+00 | 1.76E-03 | 1.39E+03 | - |
| 5 | **Cf-252** | **2.22E+01** | **1.45E+00** | **2.36E+01** | **4.72E-03** | **2.12E+01** | **1.00E-01** |
| 6 | **Cm-242** | **5.50E-03** | **3.93E-02** | **4.48E-02** | **7.28E-06** | **1.12E+04** | **8.13E-02** |
| 7 | **Cm-244** | **4.18E-02** | **3.07E+00** | **3.11E+00** | **6.39E-06** | **1.61E+02** | **1.03E-03** |
| 8 | **Co-60** | **1.43E+02** | **1.45E-03** | **1.43E+02** | **2.51E-02** | **3.50E+00** | **8.79E-02** |
| 9 | **Cs-134** | **6.82E+01** | **7.18E-04** | **6.82E+01** | **1.62E-02** | **7.33E+00** | **1.19E-01** |
| 10 | **Cs-136** | **3.39E-08** | **4.61E-14** | **3.39E-08** | **2.18E-02** | **1.47E+10** | **3.21E+08** |
| 11 | **Cs-137/Ba-137m** | **4.01E+01** | **2.16E-03** | **4.01E+01** | **6.00E-03** | **-** | **7.48E-02** |
| | Cs-137 | 2.29E-01 | 2.16E-03 | 2.31E-01 | 3.42E-05 | 1.25E+01 | - |
| | Ba-137m | 4.21E+01 | 0.00E+00 | 4.21E+01 | 6.31E-03 | 1.18E+01 | - |
| 12 | **Gd-153** | **1.53E+00** | **3.16E-05** | **1.54E+00** | **1.01E-03** | **3.25E+02** | **3.27E-01** |
| 13 | **I-129** | **1.50E+00** | **2.04E-03** | **1.51E+00** | **2.18E-04** | **3.31E+02** | **7.21E-02** |
| 14 | **I-131** | **2.01E-14** | **4.03E-19** | **2.01E-14** | **3.99E-03** | **2.49E+16** | **9.93E+13** |
| 15 | **I-132** | **0.00E+00** | **0.00E+00** | **0.00E+00** | **2.38E-02** | **NA** | **NA** |
| 16 | **I-133** | **2.86E-128** | **6.84E-134** | **2.86E-128** | **6.80E-03** | **1.75E+130** | **1.19E+128** |
| 17 | **I-134** | **0.00E+00** | **0.00E+00** | **0.00E+00** | **2.72E-02** | **NA** | **NA** |
| 18 | **I-135/Xe-135m** | **0.00E+00** | **0.00E+00** | **0.00E+00** | **1.67E-02** | **-** | **NA** |
| | I-135 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.60E-02 | NA | - |
| | Xe-135m | 0.00E+00 | 0.00E+00 | 0.00E+00 | 4.54E-03 | NA | - |
| 19 | **Ir-192** | **5.61E-01** | **4.12E-06** | **5.61E-01** | **8.47E-03** | **8.91E+02** | **7.55E+00** |
| 20 | **Kr-87** | **0.00E+00** | **0.00E+00** | **0.00E+00** | **9.17E-03** | **NA** | **NA** |
| 21 | **Kr-88/Rb-88** | **0.00E+00** | **0.00E+00** | **0.00E+00** | **2.70E-02** | **-** | **NA** |
| | Kr-88 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.88E-02 | NA | - |
| | Rb-88 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 8.19E-03 | NA | - |
| 22 | **La-140** | **3.81E-66** | **2.04E-72** | **3.81E-66** | **2.35E-02** | **1.31E+68** | **3.09E+66** |
| 23 | **Mo-99/Tc-99m** | **1.14E-41** | **9.89E-47** | **2.69E-41** | **3.02E-03** | **-** | **5.62E+40** |
| | Mo-99 | 1.72E-42 | 9.72E-47 | 1.72E-41 | 1.93E-03 | 1.86E+43 | - |
| | Tc-99m | 1.11E-41 | 1.98E-48 | 1.11E-41 | 1.25E-03 | 1.63E+43 | - |
| 24 | **Nb-95** | **5.98E-03** | **1.33E-08** | **5.98E-03** | **7.91E-03** | **8.36E+04** | **6.61E+02** |
| 25 | **Np-237/Pa-233** | **1.71E+01** | **2.83E+00** | **2.00E+01** | **2.47E-03** | **-** | **6.21E-02** |
| | Np-237 | 1.84E+00 | 2.83E+00 | 4.67E+00 | 2.67E-04 | 2.51E+01 | - |
| | Pa-233 | 1.53E+01 | 2.20E-04 | 1.53E+01 | 2.21E-03 | 2.51E+01 | - |
| 26 | **Np-239** | **2.68E-48** | **1.72E-53** | **2.68E-48** | **1.77E-03** | **1.87E+50** | **3.30E+47** |
| 27 | **Pm-147** | **1.44E-03** | **2.72E-04** | **1.71E-03** | **3.07E-07** | **2.92E+05** | **8.99E-02** |
| 28 | **Pu-238** | **4.48E-02** | **6.08E+00** | **6.12E+00** | **6.55E-06** | **8.17E+01** | **5.35E-04** |
| 29 | **Pu-239** | **2.31E-02** | **6.77E+00** | **6.79E+00** | **3.35E-06** | **7.36E+01** | **2.46E-04** |
| 30 | **Pu-241/U-237** | **3.13E-04** | **1.22E-01** | **1.22E-01** | **4.85E-08** | **-** | **1.99E-04** |
| | Pu-241 | 1.01E-04 | 1.22E-01 | 1.22E-01 | 1.56E-08 | 4.10E+03 | - |
| | U-237 | 8.66E+00 | 9.98E-05 | 8.66E+00 | 1.34E-03 | 1.00E-01 | - |

| # | Radionuclide | ExDP_Dp (mrem·m²)/µCi | InhDP_Dp (mrem·m²)/µCi | TDP_Dp (mrem·m²)/µCi | ExDF (mrem·m²)/(hr·µCi) | Dp_DRL µCi/m² | $Dp\_DRL_{XR}$ mR/hr |
|---|---|---|---|---|---|---|---|
| 31 | **Ra-226/Rn-222…** | **1.26E+02** | **5.43E-01** | **1.27E+02** | **1.83E-02** | **-** | **7.19E-02** |
| | Ra-226 | 5.05E-01 | 5.41E-01 | 1.05E+00 | 7.28E-05 | 3.94E+00 | - |
| | Rn-222 | 2.81E-02 | 0.00E+00 | 2.81E-02 | 4.07E-06 | 3.94E+00 | - |
| | Po-218 | 5.02E-07 | 0.00E+00 | 5.02E-07 | 7.28E-11 | 3.94E+00 | - |
| | At-218 | 9.44E-03 | 0.00E+00 | 9.44E-03 | 1.37E-06 | 7.87E-04 | - |
| | Pb-214 | 1.84E+01 | 8.36E-04 | 1.84E+01 | 2.65E-03 | 3.94E+00 | - |
| | Bi-214 | 1.07E+02 | 8.76E-04 | 1.07E+02 | 1.55E-02 | 3.94E+00 | - |
| | Po-214 | 5.95E-03 | 0.00E+00 | 5.95E-03 | 8.61E-07 | 3.94E+00 | - |
| 32 | **Ru-103/Rh-103m** | **9.29E-03** | **5.26E-08** | **9.29E-03** | **5.19E-03** | **-** | **2.79E+02** |
| | Ru-103 | 9.27E-03 | 5.26E-08 | 9.27E-03 | 5.18E-03 | 5.39E+04 | - |
| | Rh-103m | 1.61E-05 | 4.87E-11 | 1.61E-05 | 9.03E-06 | 5.37E+04 | - |
| 33 | **Ru-106/Rh-106** | **9.59E+00** | **1.42E-03** | **9.59E+00** | **3.78E-03** | **-** | **1.97E-01** |
| | Ru-106 | 0.00E+00 | 1.42E-03 | 1.42E-03 | 0.00E+00 | 5.21E+01 | - |
| | Rh-106 | 9.59E+00 | 0.00E+00 | 9.59E+00 | 3.78E-03 | 5.21E+01 | - |
| 34 | **Sb-127/Te-127** | **2.44E-29** | **7.10E-35** | **2.44E-29** | **7.51E-03** | **-** | **1.53E+29** |
| | Sb-127 | 2.41E-29 | 6.69E-35 | 2.41E-29 | 7.42E-03 | 2.05E+31 | - |
| | Te-127 | 3.72E-31 | 4.98E-36 | 3.72E-31 | 1.15E-04 | 1.69E+31 | - |
| 35 | **Sb-129/Te-129** | **0.00E+00** | **0.00E+00** | **0.00E+00** | **1.62E-02** | **-** | **NA** |
| | Sb-129 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.52E-02 | NA | - |
| | Te-129 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.27E-03 | NA | - |
| 36 | **Se-75** | **1.38E+00** | **4.30E-06** | **1.38E+00** | **3.89E-03** | **3.62E+02** | **1.41E+00** |
| 37 | **Sr-89** | **7.16E-03** | **7.37E-07** | **7.16E-03** | **7.49E-04** | **6.98E+04** | **5.23E+01** |
| 38 | **Sr-90/Y-90** | **8.15E+00** | **8.71E-03** | **8.16E+00** | **1.22E-03** | **-** | **7.46E-02** |
| | Sr-90 | 1.20E-01 | 8.63E-03 | 1.28E-01 | 1.79E-05 | 6.13E+01 | - |
| | Y-90 | 8.03E+00 | 8.25E-05 | 8.03E+00 | 1.20E-03 | 6.13E+01 | - |
| 39 | **Sr-91/Y-91m** | **3.41E-279** | **1.39E-285** | **3.41E-279** | **1.13E-02** | **-** | **1.65E+279** |
| | Sr-91 | 2.44E-279 | 1.37E-285 | 2.44E-279 | 8.05E-03 | 1.47E+281 | - |
| | Y-91m | 1.68E-279 | 3.83E-287 | 1.68E-279 | 5.55E-03 | 8.48E+280 | - |
| 40 | **Te-129m/Te-129** | **7.55E-04** | **4.15E-08** | **7.56E-04** | **1.46E-03** | **-** | **9.68E+02** |
| | Te-129m | 3.29E-04 | 4.14E-08 | 3.30E-04 | 6.37E-04 | 6.61E+05 | - |
| | Te-129 | 6.56E-04 | 2.05E-10 | 6.56E-04 | 1.27E-03 | 4.30E+05 | - |
| 41 | **Te-131m/Te-131** | **7.35E-89** | **5.46E-95** | **7.35E-89** | **1.60E-02** | **-** | **1.09E+89** |
| | Te-131m | 6.82E-89 | 5.43E-95 | 6.82E-89 | 1.48E-02 | 6.81E+90 | - |
| | Te-131 | 2.37E-89 | 1.45E-96 | 2.37E-89 | 5.16E-03 | 1.51E+90 | - |
| 42 | **Te-132/I-132** | **4.72E-34** | **4.29E-40** | **4.72E-34** | **2.61E-02** | **-** | **2.77E+34** |
| | Te-132 | 4.20E-35 | 4.06E-40 | 4.20E-35 | 2.32E-03 | 1.06E+36 | - |
| | I-132 | 4.30E-34 | 2.26E-41 | 4.30E-34 | 2.38E-02 | 1.06E+36 | - |
| 43 | **Tm-170** | **1.17E-01** | **3.59E-05** | **1.17E-01** | **2.72E-04** | **4.27E+03** | **1.16E+00** |
| 44 | **Xe-133** | **7.63E-23** | **0.00E+00** | **7.63E-23** | **4.44E-04** | **6.55E+24** | **2.91E+21** |
| 45 | **Xe-135** | **2.39E-292** | **0.00E+00** | **2.39E-292** | **2.73E-03** | **2.09E+294** | **5.71E+291** |
| 46 | **Xe-138** | **0.00E+00** | **0.00E+00** | **0.00E+00** | **1.17E-02** | **NA** | **NA** |
| 47 | **Y-91** | **1.76E-02** | **1.86E-06** | **1.76E-02** | **8.12E-04** | **2.84E+04** | **2.31E+01** |
| 48 | **Yb-169** | **1.09E-03** | **1.03E-08** | **1.09E-03** | **3.22E-03** | **4.59E+05** | **1.48E+03** |
| 49 | **Zr-95/Nb-95m/Nb-95** | **5.29E-01** | **2.47E-06** | **5.29E-01** | **1.55E-02** | **-** | **1.47E+01** |
| | Zr-95 | 2.59E-01 | 1.90E-06 | 2.59E-01 | 7.63E-03 | 9.45E+02 | - |
| | Nb-95m | 2.33E-02 | 2.86E-07 | 2.33E-02 | 6.83E-04 | 6.60E+00 | - |
| | Nb-95 | 2.70E-01 | 5.68E-07 | 2.70E-01 | 7.91E-03 | 9.45E+02 | - |

| # | Radionuclide | ExDP_Dp (mrem·m$^2$)/µCi | InhDP_Dp (mrem·m$^2$)/µCi | TDP_Dp (mrem·m$^2$)/µCi | ExDF (mrem·m$^2$)/(hr·µCi) | Dp_DRL µCi/m$^2$ | Dp_DRL$_{XR}$ mR/hr |
|---|---|---|---|---|---|---|---|
| 1 | **Am-241** | **4.53E+01** | **1.94E+02** | **2.39E+02** | **2.38E-04** | **2.09E+01** | **4.98E-03** |
| 2 | **Ba-140/La-140** | **1.12E+01** | **1.93E-03** | **1.12E+01** | **2.56E-02** | **-** | **2.29E-03** |
| | Ba-140 | 9.12E-01 | 1.61E-03 | 9.13E-01 | 2.09E-03 | 4.47E+02 | - |
| | La-140 | 1.03E+01 | 3.15E-04 | 1.03E+01 | 2.35E-02 | 4.47E+02 | - |
| 3 | **Ce-141** | **8.37E-01** | **1.32E-03** | **8.38E-01** | **7.63E-04** | **5.97E+03** | **9.10E-04** |
| 4 | **Ce-144/Pr-144/Pr-144m** | **1.64E+01** | **2.79E-02** | **1.64E+01** | **1.95E-03** | **-** | **5.94E-01** |
| | Ce-144 | 1.59E+00 | 2.79E-02 | 1.62E+00 | 1.89E-04 | 3.04E+02 | - |
| | Pr-144m | 1.00E+00 | 0.00E+00 | 1.00E+00 | 1.19E-04 | 5.42E+00 | - |
| | Pr-144 | 1.48E+01 | 9.69E-06 | 1.48E+01 | 1.76E-03 | 3.04E+02 | - |
| 5 | **Cf-252** | **1.13E+02** | **2.42E+01** | **1.37E+02** | **4.72E-03** | **3.65E+01** | **1.72E-01** |
| 6 | **Cm-242** | **3.72E-02** | **2.86E+00** | **2.90E+00** | **7.28E-06** | **1.73E+03** | **1.26E-02** |
| 7 | **Cm-244** | **6.41E-01** | **7.01E+01** | **7.08E+01** | **6.39E-06** | **7.06E+01** | **4.66E-04** |
| 8 | **Co-60** | **1.06E+03** | **2.40E-02** | **1.06E+03** | **2.51E-02** | **4.73E+00** | **1.19E-01** |
| 9 | **Cs-134** | **3.14E+02** | **1.27E-02** | **3.14E+02** | **1.62E-02** | **1.59E+01** | **2.58E-01** |
| 10 | **Cs-136** | **9.77E+00** | **7.73E-04** | **9.77E+00** | **2.18E-02** | **5.12E+02** | **1.11E+01** |
| 11 | **Cs-137/Ba-137m** | **7.60E+02** | **5.70E-02** | **7.60E+02** | **6.00E-03** | **-** | **3.94E-02** |
| | Cs-137 | 4.34E+00 | 5.70E-02 | 4.39E+00 | 3.42E-05 | 6.57E+00 | - |
| | Ba-137m | 7.99E+02 | 0.00E+00 | 7.99E+02 | 6.31E-03 | 6.22E+00 | - |
| 12 | **Gd-153** | **7.33E+00** | **1.24E-03** | **7.34E+00** | **1.01E-03** | **6.82E+02** | **6.86E-01** |
| 13 | **I-129** | **4.28E+01** | **7.42E-02** | **4.28E+01** | **2.18E-04** | **1.17E+02** | **2.54E-02** |
| 14 | **I-131** | **1.10E+00** | **1.77E-03** | **1.11E+00** | **3.99E-03** | **4.52E+03** | **1.81E+01** |
| 15 | **I-132** | **7.90E-02** | **1.29E-06** | **7.90E-02** | **2.38E-02** | **6.33E+04** | **1.51E+03** |
| 16 | **I-133** | **2.04E-01** | **1.21E-04** | **2.04E-01** | **6.80E-03** | **2.45E+04** | **1.67E+02** |
| 17 | **I-134** | **3.44E-02** | **2.42E-07** | **3.44E-02** | **2.72E-02** | **1.45E+05** | **3.96E+03** |
| 18 | **I-135/Xe-135m** | **1.60E-01** | **1.03E-05** | **1.60E-01** | **1.67E-02** | **-** | **5.24E+02** |
| | I-135 | 1.53E-01 | 1.03E-05 | 1.53E-01 | 1.60E-02 | 3.13E+04 | - |
| | Xe-135m | 4.32E-02 | 0.00E+00 | 4.32E-02 | 4.54E-03 | 4.82E+03 | - |
| 19 | **Ir-192** | **2.06E+01** | **2.77E-03** | **2.06E+01** | **8.47E-03** | **2.42E+02** | **2.05E+00** |
| 20 | **Kr-87** | **1.68E-02** | **0.00E+00** | **1.68E-02** | **9.17E-03** | **2.98E+04** | **2.72E+03** |
| 21 | **Kr-88/Rb-88** | **1.11E-01** | **3.87E-07** | **1.11E-01** | **2.70E-02** | **-** | **1.22E+03** |
| | Kr-88 | 7.70E-02 | 0.00E+00 | 7.70E-02 | 1.88E-02 | 4.53E+04 | - |
| | Rb-88 | 3.35E-02 | 3.87E-07 | 3.35E-02 | 8.19E-03 | 4.53E+04 | - |
| 22 | **La-140** | **1.36E+00** | **1.40E-04** | **1.36E+00** | **2.35E-02** | **3.67E+02** | **2.35E-02** |
| 23 | **Mo-99/Tc-99m** | **2.87E-01** | **1.60E-04** | **2.87E-01** | **3.02E-03** | **-** | **5.26E+01** |
| | Mo-99 | 1.84E-01 | 1.57E-04 | 1.84E-01 | 1.93E-03 | 1.74E+04 | - |
| | Tc-99m | 1.18E-01 | 3.17E-06 | 1.18E-01 | 1.25E-03 | 1.52E+04 | - |
| 24 | **Nb-95** | **9.41E+00** | **6.26E-04** | **9.41E+00** | **7.91E-03** | **5.31E+02** | **4.21E+00** |
| 25 | **Np-237/Pa-233** | **4.86E+02** | **1.03E+02** | **5.89E+02** | **2.47E-03** | **-** | **2.10E-02** |
| | Np-237 | 5.24E+01 | 1.03E+02 | 1.55E+02 | 2.67E-04 | 8.49E+00 | - |
| | Pa-233 | 4.34E+02 | 7.98E-03 | 4.34E+02 | 2.21E-03 | 8.49E+00 | - |
| 26 | **Np-239** | **1.44E-01** | **1.51E-04** | **1.44E-01** | **1.77E-03** | **3.47E+04** | **6.14E+01** |
| 27 | **Pm-147** | **7.29E-03** | **4.57E-03** | **1.18E-02** | **3.07E-07** | **4.22E+05** | **1.30E-01** |
| 28 | **Pu-238** | **1.09E+00** | **1.95E+02** | **1.96E+02** | **6.55E-06** | **2.55E+01** | **1.67E-04** |
| 29 | **Pu-239** | **6.57E-01** | **2.46E+02** | **2.46E+02** | **3.35E-06** | **2.03E+01** | **6.78E-05** |
| 30 | **Pu-241/U-237** | **4.26E-03** | **2.58E+00** | **2.59E+00** | **4.85E-08** | **-** | **9.38E-05** |
| | Pu-241 | 1.37E-03 | 2.58E+00 | 2.59E+00 | 1.56E-08 | 1.93E+03 | - |
| | U-237 | 1.18E+02 | 2.12E-03 | 1.18E+02 | 1.34E-03 | 4.73E-02 | - |

| # | Radionuclide | ExDP_Dp (mrem·m$^2$)/µCi | InhDP_Dp (mrem·m$^2$)/µCi | TDP_Dp (mrem·m$^2$)/µCi | ExDF (mrem·m$^2$)/(hr·µCi) | Dp_DRL µCi/m$^2$ | Dp_DRL$_{XR}$ mR/hr |
|---|---|---|---|---|---|---|---|
| 31 | **Ra-226/Rn-222…** | **3.55E+03** | **1.96E+01** | **3.57E+03** | **1.83E-02** | **-** | **2.55E-02** |
| | Ra-226 | 1.42E+01 | 1.95E+01 | 3.37E+01 | 7.28E-05 | 1.40E+00 | - |
| | Rn-222 | 7.92E-01 | 0.00E+00 | 7.92E-01 | 4.07E-06 | 1.40E+00 | - |
| | Po-218 | 1.42E-05 | 0.00E+00 | 1.42E-05 | 7.28E-11 | 1.40E+00 | - |
| | At-218 | 2.66E-01 | 0.00E+00 | 2.66E-01 | 1.37E-06 | 2.80E-04 | - |
| | Pb-214 | 5.17E+02 | 3.01E-02 | 5.17E+02 | 2.65E-03 | 1.40E+00 | - |
| | Bi-214 | 3.02E+03 | 3.16E-02 | 3.02E+03 | 1.55E-02 | 1.40E+00 | - |
| | Po-214 | 1.68E-01 | 0.00E+00 | 1.68E-01 | 8.61E-07 | 1.40E+00 | - |
| 32 | **Ru-103/Rh-103m** | **6.86E+00** | **1.08E-03** | **6.86E+00** | **5.19E-03** | **-** | **3.78E+00** |
| | Ru-103 | 6.85E+00 | 1.08E-03 | 6.85E+00 | 5.18E-03 | 7.29E+02 | - |
| | Rh-103m | 1.19E-02 | 1.00E-06 | 1.19E-02 | 9.03E-06 | 7.27E+02 | - |
| 33 | **Ru-106/Rh-106** | **3.99E+01** | **1.81E-03** | **3.99E+01** | **3.78E-03** | **-** | **4.73E-01** |
| | Ru-106 | 0.00E+00 | 1.81E-03 | 3.62E-02 | 0.00E+00 | 1.25E+02 | - |
| | Rh-106 | 3.99E+01 | 0.00E+00 | 3.99E+01 | 3.78E-03 | 1.25E+02 | - |
| 34 | **Sb-127/Te-127** | **1.00E+00** | **3.64E-04** | **1.00E+00** | **7.51E-03** | **-** | **3.76E+01** |
| | Sb-127 | 9.87E-01 | 3.43E-04 | 9.88E-01 | 7.42E-03 | 5.00E+03 | - |
| | Te-127 | 1.52E-02 | 2.56E-05 | 1.53E-02 | 1.15E-04 | 4.12E+03 | - |
| 35 | **Sb-129/Te-129** | **1.01E-01** | **5.96E-06** | **1.01E-01** | **1.62E-02** | **-** | **8.05E+02** |
| | Sb-129 | 9.46E-02 | 5.31E-06 | 9.46E-02 | 1.52E-02 | 4.96E+04 | - |
| | Te-129 | 7.90E-03 | 8.35E-07 | 7.90E-03 | 1.27E-03 | 3.85E+04 | - |
| 36 | **Se-75** | **1.49E+01** | **6.14E-04** | **1.49E+01** | **3.89E-03** | **3.35E+02** | **1.30E+00** |
| 37 | **Sr-89** | **1.27E+00** | **3.08E-03** | **1.27E+00** | **7.49E-04** | **3.93E+03** | **2.95E+00** |
| 38 | **Sr-90/Y-90** | **1.53E+02** | **2.28E-01** | **1.53E+02** | **1.22E-03** | **-** | **3.98E-02** |
| | Sr-90 | 2.25E+00 | 2.26E-01 | 2.47E+00 | 1.79E-05 | 3.27E+01 | - |
| | Y-90 | 1.51E+02 | 2.16E-03 | 1.51E+02 | 1.20E-03 | 3.27E+01 | - |
| 39 | **Sr-91/Y-91m** | **1.54E-01** | **1.84E-05** | **1.54E-01** | **1.13E-02** | **-** | **3.65E+02** |
| | Sr-91 | 1.10E-01 | 1.81E-05 | 1.10E-01 | 8.05E-03 | 3.25E+04 | - |
| | Y-91m | 7.60E-02 | 5.07E-07 | 7.60E-02 | 5.55E-03 | 1.88E+04 | - |
| 40 | **Te-129m/Te-129** | **1.66E+00** | **2.81E-03** | **1.66E+00** | **1.46E-03** | **-** | **4.40E+00** |
| | Te-129m | 7.23E-01 | 2.80E-03 | 7.26E-01 | 6.37E-04 | 3.01E+03 | - |
| | Te-129 | 1.44E+00 | 1.39E-05 | 1.44E+00 | 1.27E-03 | 1.96E+03 | - |
| 41 | **Te-131m/Te-131** | **6.92E-01** | **1.12E-04** | **6.93E-01** | **1.60E-02** | **-** | **1.16E+02** |
| | Te-131m | 6.42E-01 | 1.11E-04 | 6.43E-01 | 1.48E-02 | 7.22E+03 | - |
| | Te-131 | 2.23E-01 | 2.96E-06 | 2.23E-01 | 5.16E-03 | 1.60E+03 | - |
| 42 | **Te-132/I-132** | **2.94E+00** | **3.68E-04** | **2.94E+00** | **2.61E-02** | **-** | **4.45E+01** |
| | Te-132 | 2.62E-01 | 3.49E-04 | 2.62E-01 | 2.32E-03 | 1.70E+03 | - |
| | I-132 | 2.68E+00 | 1.94E-05 | 2.68E+00 | 2.38E-02 | 1.70E+03 | - |
| 43 | **Tm-170** | **1.11E+00** | **4.31E-03** | **1.12E+00** | **2.72E-04** | **4.47E+03** | **1.22E+00** |
| 44 | **Xe-133** | **8.02E-02** | **0.00E+00** | **8.02E-02** | **4.44E-04** | **6.23E+04** | **2.77E+01** |
| 45 | **Xe-135** | **3.58E-02** | **0.00E+00** | **3.58E-02** | **2.73E-03** | **1.40E+05** | **3.82E+02** |
| 46 | **Xe-138** | **3.98E-03** | **0.00E+00** | **3.98E-03** | **1.17E-02** | **1.26E+06** | **1.47E+04** |
| 47 | **Y-91** | **1.58E+00** | **3.57E-03** | **1.58E+00** | **8.12E-04** | **3.16E+03** | **2.57E+00** |
| 48 | **Yb-169** | **3.49E+00** | **1.04E-03** | **3.49E+00** | **3.22E-03** | **1.43E+03** | **4.61E+00** |
| 49 | **Zr-95/Nb-95m/Nb-95** | **3.29E+01** | **3.08E-03** | **3.29E+01** | **1.55E-02** | **-** | **2.36E+00** |
| | Zr-95 | 1.61E+01 | 2.37E-03 | 1.61E+01 | 7.63E-03 | 1.52E+02 | - |
| | Nb-95m | 1.45E+00 | 3.58E-04 | 1.45E+00 | 6.83E-04 | 1.06E+00 | - |
| | Nb-95 | 1.68E+01 | 7.12E-04 | 1.68E+01 | 7.91E-03 | 1.52E+02 | - |

This Table is RESERVED for the future inclusion of Skin Dose Data.

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**Table 6-1 Gamma Cloud Source Shielding Factors**

| Structure or Location | Shielding Factor [a] |
|---|---|
| Outside | 1.0 |
| Vehicles | 1.0 |
| Wood frame house [b] (no basement) | 0.9 |
| Basement of wood frame house | 0.6 |
| Masonry house (no basement) | 0.6 |
| Basement of masonry house | 0.4 |
| Large office or industrial building | 0.2 |

Source: EGG75

[a] Ratio of the interior dose to the exterior dose.

[b] 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**

| Structure or Location | Representative Shielding Factor [a] |
|---|---|
| Cars on fully contaminated road | 0.5 |
| Cars on fully decontaminated 50-foot road | 0.25 |
| Trains | 0.4 |
| One- and two-story wood-frame house (no basement) | 0.4 [b] |
| One- and two-story block and brick house (no basement) | 0.2 [b] |
| House basement, one or two walls fully exposed | 0.1 [b] |
| One story, less than two feet of basement, wall exposed | 0.05 [b] |
| Two stories, less than two feet of basement, wall exposed | 0.03 [b] |
| Three- or four-story structures, 5,000 to 10,000 square feet per floor | |
| First and second floors | 0.05 [b] |
| Basement | 0.01 [b] |
| Multi-story structures, greater than 10,000 square feet per floor | |
| Upper floors | 0.01 [b] |
| Basement | 0.005 [b] |

Source: EGG75

[a] Ratio of the interior dose to the exterior dose.

[b] Away from doors and windows.

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The default breathing rate used in the Methods in Volume 1 is the average breathing rate for an adult male. This table lists the breathing rates for all age groups from ICRP Publication 66 (ICRP94).

| Age Group | Activity | | | | | | | | Total Volume | Activity Avg. Rate |
|---|---|---|---|---|---|---|---|---|---|---|
| | Sleeping | | Sitting | | Light Activity | | Heavy Activity | | | |
| | Rate $m^3$/hr | Time hr/day | Rate $m^3$/hr | Time hr/day | Rate $m^3$/hr | Time hr/day | Rate $m^3$/hr | Time hr/day | $m^3$/day | $m^3$/hr |
| **Newborn (3 month)** | 0.09 | 17.0 | NA | NA | 0.19 | 7.0 | NA | NA | **2.86** | **0.12** |
| **Infant (1 year)** | 0.15 | 14.0 | 0.22 | 3.33 | 0.35 | 6.67 | NA | NA | **5.17** | **0.22** |
| **5 yr old** | 0.24 | 12.0 | 0.32 | 4.0 | 0.57 | 8.0 | NA | NA | **8.72** | **0.36** |
| **10 yr old** | 0.31 | 10.0 | 0.38 | 4.67 | 1.12 | 9.33 | NA | NA | **15.33** | **0.64** |
| **15 yr old (f)** | 0.35 | 10.0 | 0.4 | 7.0 | 1.3 | 6.75 | 2.57 | 0.25 | **15.72** | **0.65** |
| **15 yr old (m)** | 0.42 | 10.0 | 0.48 | 5.5 | 1.38 | 7.5 | 2.92 | 1.0 | **20.11** | **0.84** |
| **Adult (f) (Sedentary)** | 0.32 | 8.5 | 0.39 | 5.5 | 1.25 | 9.75 | 2.7 | 0.25 | **17.73** | **0.74** |
| **Adult (m) (Sedentary)** | 0.45 | 8.5 | 0.54 | 5.5 | 1.5 | 9.75 | 3.0 | 0.25 | **22.17** | **0.92** |
| See ICRP94, Tables 8, B.16A, and B.16B for methods to calculate breathing rates. | | | | | | | | | | |

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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 | FDA Listed | DIL[a] (μCi/kg) | Mature Crop_DRL[b] (μCi/m$^2$) | Leafy TF ($kg_{soil}$/kg) | Fruit TF ($kg_{soil}$/kg) | Root TF ($kg_{soil}$/kg) | Grain TF ($kg_{soil}$/kg) | Milk_DRL[c] (area) (μCi/m$^2$) | Milk_DRL[c] (mass) (μCi/$kg_{wet}$) | Milk_DRL[c] (water) (μCi/l) | Milk TF[c] (d/l) | Meat TF[d] (d/kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Am-241 | Y[e] | 5.4E-05 | 5.4E-04 | 4.7E-04 | 2.5E-04 | 3.5E-04 | 2.2E-05 | 1.0E+00 | 7.2E-01 | 6.0E-01 | 1.5E-06 | 4.0E-05 |
| Ba-140 | Y | 1.9E-01 | 1.9E+00 | 1.5E-01 | 1.5E-02 | 1.5E-02 | 1.5E-02 | 1.1E+01 | 7.9E+00 | 6.6E+00 | 4.8E-04 | 2.0E-04 |
| Ce-141 | Y | 1.9E-01 | 1.9E+00 | 2.0E-02 | 2.0E-02 | 2.0E-02 | 2.0E-02 | 1.8E+02 | 1.3E+02 | 1.1E+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[f] | 2.5E-04 | 3.5E-04 | 2.2E-05 | 1.9E+00 | 1.3E+00 | 1.1E+00 | 1.5E-06 | 4.0E-05 |
| Cm-242 | Y | 5.1E-04 | 5.1E-03 | 7.7E-04 | 1.5E-05 | 4.3E-04 | 2.1E-05 | 7.1E-01 | 5.1E-01 | 4.3E-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 | 7.5E-02 | 5.4E-02 | 4.5E-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 | 1.3E+00 | 1.1E+00 | 3.0E-04 | 1.0E-02 |
| Cs-134 | Y[g] | 2.5E-02 | 2.5E-01 | 4.6E-01 | 2.2E-01 | 1.3E-01 | 2.6E-02 | 8.8E-02 | 6.3E-02 | 5.3E-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 | 1.2E+00 | 8.7E-01 | 7.3E-01 | 7.9E-03 | 5.0E-02 |
| Cs-137 | Y[g] | 3.7E-02 | 3.7E-01 | 4.6E-01 | 2.2E-01 | 1.3E-01 | 2.6E-02 | 1.3E-01 | 9.4E-02 | 7.8E-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 | 3.3E+02 | 2.4E+02 | 2.0E+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 | 2.3E-03 | 3.3E-03 | 2.8E-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 | 8.5E-03 | 1.2E-02 | 1.0E-02 | 9.0E-03 | 4.0E-02 |
| I-133 | Y | 1.9E-01 | 8.5E-01 | 4.0E-02 | 4.0E-02 | 4.0E-02 | 4.0E-02 | 1.5E+00 | 2.1E+00 | 1.7E+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 | 7.7E+02 | 1.1E+03 | 9.2E+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 | 1.1E+03 | 8.0E+02 | 6.7E+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 | 5.7E+03 | 4.1E+03 | 3.4E+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 | 7.8E+01 | 6.5E+01 | 1.7E-03 | 1.0E-03 |
| Nb-95 | Y | 3.2E-01 | 3.3E+00 | 2.5E-02 | 2.5E-02 | 2.5E-02 | 2.5E-02 | 2.3E+04 | 1.6E+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 | 1.6E+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 | 6.1E-01 | 4.4E-01 | 3.7E-01 | 5.0E-06 | 1.0E-03 |

| Radionuclide | FDA Listed | DIL[a] (µCi/kg) | Mature Crop_DRL[b] (µCi/m$^2$) | Leafy TF ($kg_{soil}$/kg) | Fruit TF ($kg_{soil}$/kg) | Root TF ($kg_{soil}$/kg) | Grain TF ($kg_{soil}$/kg) | Milk_DRL[c] (area) (µCi/m$^2$) | Milk_DRL[c] (mass) (µCi/$kg_{wet}$) | Milk_DRL[c] (water) (µCi/l) | Milk TF[c] (d/l) | Meat TF[d] (d/kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Np-239 | Y | 7.6E-01 | 1.0E+01 | 3.2E-02 | 1.0E-02 | 1.3E-02 | 2.7E-03 | 7.6E+03 | 5.5E+03 | 4.6E+03 | 5.0E-06 | 1.0E-03 |
| Pa-233 | | 1.9E-01 | 1.9E+00 | 4.7E-04 | 2.5E-04 | 3.5E-04 | 2.2E-05 | 1.1E+03 | 8.0E+02 | 6.7E+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 | 2.0E+02 | 1.7E+02 | 3.0E-05 | 2.0E-05 |
| Pu-238 | Y[e] | 6.8E-05 | 6.8E-04 | 6.0E-05 | 4.5E-05 | 1.1E-03 | 8.6E-06 | 1.7E+00 | 1.2E+00 | 1.0E+00 | 1.1E-06 | 1.0E-05 |
| Pu-239 | Y[e] | 6.0E-05 | 6.0E-04 | 6.0E-05 | 4.5E-05 | 1.1E-03 | 8.6E-06 | 1.5E+00 | 1.1E+00 | 9.1E-01 | 1.1E-06 | 1.0E-05 |
| Pu-241 | Y | 3.2E-03 | 3.2E-02 | 6.0E-05 | 4.5E-05 | 1.1E-03 | 8.6E-06 | 8.1E+01 | 5.8E+01 | 4.8E+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 | 8.5E-04 | 7.1E-04 | 1.3E-03 | 9.0E-04 |
| Ru-103 | Y[h] | 1.8E-01 | 1.8E+00 | 4.0E-02 | 4.0E-02 | 4.0E-02 | 5.0E-03 | 1.6E+03 | 1.1E+03 | 9.4E+02 | 3.3E-06 | 5.0E-02 |
| Ru-106 | Y[h] | 1.2E-02 | 1.2E-01 | 4.0E-02 | 4.0E-02 | 4.0E-02 | 5.0E-03 | 1.0E+02 | 7.3E+01 | 6.1E+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 | 9.7E+02 | 8.1E+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 | 3.9E-01 | 2.8E-01 | 2.3E-01 | 4.0E-03 | 1.5E-02 |
| Sr-89 | Y | 3.8E-02 | 3.9E-01 | 3.0E+00 | 2.0E-01 | 5.0E-01 | 2.1E-01 | 3.9E-01 | 2.8E-01 | 2.3E-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 | 4.3E-02 | 3.1E-02 | 2.6E-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 | 9.5E+03 | 6.9E+03 | 5.7E+03 | 2.8E-03 | 8.0E-03 |
| Tc-99m | | 1.2E+03 | 1.9E+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 | 5.9E+03 | 2.5E-02 | 4.0E-03 | 4.0E-03 | 4.0E-03 | 2.2E+05 | 1.6E+05 | 1.3E+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 | 2.6E+00 | 1.9E+00 | 1.5E+00 | 4.5E-04 | 7.0E-03 |
| Te-131m | | 1.8E+00 | 3.1E+01 | 2.5E-02 | 4.0E-03 | 4.0E-03 | 4.0E-03 | 3.4E+02 | 2.4E+02 | 2.0E+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 | 1.1E+01 | 8.2E+00 | 6.8E+00 | 4.5E-04 | 7.0E-03 |
| Tm-170[i] | | 5.6E-02 | 5.6E-01 | 2.0E-02 | 2.0E-02 | 2.0E-02 | 2.0E-02 | 5.2E+01 | 3.8E+01 | 3.1E+01 | 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 | 7.8E+01 | 5.7E+01 | 4.7E+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 | 1.4E+03 | 1.0E+03 | 8.7E+02 | 2.0E-05 | 1.0E-03 |
| Y-91 | Y | 3.2E-02 | 3.2E-01 | 1.0E-02 | 1.0E-02 | 1.0E-02 | 1.0E-02 | 4.5E+01 | 3.3E+01 | 2.7E+01 | 2.0E-05 | 1.0E-03 |
| Yb-169[i] | | 2.4E-01 | 2.5E+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 |
| Zr-95 | Y | 1.1E-01 | 1.1E+00 | 1.0E-03 | 1.0E-03 | 1.0E-03 | 1.0E-03 | 5.7E+03 | 4.1E+03 | 3.4E+03 | 5.5E-07 | 1.0E-06 |

**Notes:**

[a] 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 $^{132}$Te, $^{131}$I, $^{133}$I and $^{239}$Np in the diet of an Infant, where it is assume to be 1.0. (See Volume 1, Method 4.1.)

[b] Assumes Crops are ready to harvest. (See Volume 1, Method 4.2 for assumptions and default inputs.)

[c] Values for Cow's Milk. See Volume 1, Method 4.3. Transfer Factors from PNNL-13421.

[d] Values for Beef. See Volume 1, Method 4.4. Transfer Factors from PNNL-13421.

[e] 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 µCi/kg.

[f] Two values for Cf are reported in the reference. The most conservative is in the table, the other is 2.5E-04.

[g] 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 µCi/kg.

[h] $^{103}$Ru and $^{106}$Ru DIL is based on Sum of Fractions ($^{103}$Ru /0.18) +($^{106}$Ru /0.012) <1. For the purposes of this table, we are assuming only ONE isotope is present.

[i] 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 [a]

| Plant Type | Mass Conversion Factor $kg_{dry}/kg_{wet}$ |
|---|---|
| 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 |

[a] Values from PNNL03, Table 2.1.

Inverse values for converting from wet to dry:

Table 9-2 Wet-to-Dry Mass

| Plant Type | Mass Conversion Factor $kg_{wet}/kg_{dry}$ |
|---|---|
| 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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This table lists the average DFIR for populations of various ages in the United States. All values except the total annual intake are given in grams per day. The annual intake is given in kilograms per year.

| Food Category | Daily Consumption (kg/day) | | | | | |
|---|---|---|---|---|---|---|
| | 3 months | 1 year | 5 years | 10 years | 15 years | Adult |
| Total Dairy | 5.7E-01 | 4.9E-01 | 4.6E-01 | 5.0E-01 | 4.8E-01 | 2.9E-01 |
| 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 |
| Fresh Eggs | 4.9E-03 | 1.2E-02 | 1.8E-02 | 1.8E-02 | 2.2E-02 | 2.9E-02 |
| Total Meat | 4.5E-02 | 6.9E-02 | 1.1E-01 | 1.4E-01 | 1.7E-01 | 1.9E-01 |
| 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 |
| Total Fish | 9.0E-04 | 3.8E-03 | 8.8E-03 | 1.2E-02 | 1.5E-02 | 1.9E-02 |
| 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 |
| Total Produce | 1.6E-01 | 1.6E-01 | 1.9E-01 | 2.4E-01 | 2.6E-01 | 2.9E-01 |
| 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 |
| Total Grains | 5.6E-02 | 1.1E-01 | 1.9E-01 | 2.3E-01 | 2.5E-01 | 2.1E-01 |
| 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 |
| Total Beverages | 3.1E-01 | 5.2E-01 | 8.0E-01 | 9.4E-01 | 1.1 | 1.5 |
| 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 |
| Miscellaneous | 5.5E-03 | 1.6E-02 | 3.1E-02 | 3.9E-02 | 3.9E-02 | 3.4E-02 |
| Total Daily Intake | 1.1 | 1.4 | 1.8 | 2.1 | 2.4 | 2.6 |
| Total Annual Intake (kg/yr) | 420 | 510 | 660 | 780 | 870 | 940 |

Sources: EPA84, FDA98 (Rounded to 2 significant figures.)

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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 [a] |
|---|---|---|
| Animal Feed Daily Ingestion Rate (AFDIR) | Milk Cow | 50 kg/d |
| | Beef Cattle | 50 kg/d |
| | Goat | 6 kg/d |
| Animal Soil Daily Ingestion Rate (ASDIR) | Milk Cow | 0.5 kg/d [b] |
| | Beef Cattle | 0.5 kg/d [b] |
| | Goat | 0.06 kg/d [b,c] |
| Animal Water Daily Ingestion Rate (AWDIR) | Milk Cow | 60 l/d |
| | Beef Cattle | 50 l/d |
| | Goat | 8 l/d |
| Crop Retention Factor (CRF) | Pastureland | 0.5 [d] |
| | Pastureland, Iodines | 1.0 |
| | Fresh produce, particulates | 0.2 |
| | Fresh produce, Iodines | 1.0 |
| | Crops planted AFTER deposition | 0.0 |
| Time to Market ($t_m$) | Crop/Produce | 1 d |
| | Milk | 2 d |
| | Meat | 20 d |
| Crop Yield (Y) | Produce | 2.0 $kg/m^2$ |
| | Pastureland | 0.7 $kg/m^2$ |
| Crop Weathering Half life ($t_{1/2}$) | | 15 d [e] |

[a] All values from NRC77 unless otherwise indicated.
[b] ANL01
[c] Goat value estimated based on ratio of Feed to Soil for Cows (100:1).
[d] Ng77 (Appendix B, page 113)
[e] NCRP07 (Page 165)

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Date:________________ Time:________________ Analyst:___________________________

☐ Predictive Analysis
Prediction Number:_________________________

☐ Sample-Based Analysis
Sample Number:___________________________
Sample Location:__________________________

Time Phase: ☐ Early ☐ 1st Year ☐ 2nd Year ☐ 50 Year

Evaluation Time ($t_n$):________________ (days after deposition, may be fractional)

Selected PAG Value:_________________ (mrem) PAG Authority:_____________________

Enter data in columns 1, 3, 4, and 5 Calculate column 6 by multiplying columns 4 and 5.
*(Column 3 values are found in Table 1. Column 5 values for each Time Phase are found in Table 4).*

| 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| Radionuclide | (m) | $\lambda_i$ ($d^{-1}$) | $Dp_i$ ($\mu Ci/m^2$) | $TDP\_Dp_i$ ($mrem \cdot m^2/\mu Ci$) | $Dp_i * TDP\_Dp_i$ (mrem) |
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Sum the values in the column 6: MTDP_Dp $\Sigma =$ ______

Select Marker Radionuclide (m), indicate in column 2.
Determine the decay effect for the marker radionuclide: $e^{-\lambda_{i(m)} t_n} =$ ______

Determine the weathering effect for $t_n$: $WF_{t_n} = 0.4e^{(-1.26E-03 * t_n)} + 0.6e^{(-3.84E-05 * t_n)} =$ ______

$$Dp\_DRL_{E,i(m),t_n} = \frac{PAG_{E,TP} * Dp_{i(m)} * e^{-\lambda_{i(m)} t_n} * WF_{t_n}}{MTDP\_Dp_{E,TP}} =$$ ______ ($\mu Ci/m^2$)

Date:_______________________ Time:_______________________ Analyst:___________________________________

☐ Predictive Analysis

Prediction Number:__________________________

☐ Sample-Based Analysis

Sample Number:_____________________

Sample Location:_____________________

Time Phase: ☐ Early ☐ 1st Year ☐ 2nd Year ☐ 50 Year Evaluation Time ($t_n$):________ (days after deposition, may be fractional)

Selected PAG Value:____________ (mrem) PAG Authority:_______________________ XDCF: ______________ (mrem/mR)

Enter data in columns 1, 2, 3, 5, and 7. Calculate column 4 by multiplying columns 2 and 3. Calculate column 8 by multiplying columns 2, 6, and 7.
*(Column 3 and 7 values for each Time Phase are found in Table 4. Column 5 values are found in Table 1.)*

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|
| Radionuclide | $Dp_i$ (µCi/m²) | $TDP\_Dp_i$ (mrem·m²/µCi) | $Dp_i * TDP\_Dp_i$ (mrem) | $\lambda_i$ ($d^{-1}$) | $e^{-\lambda_i t_n}$ | $ExDF_i$ (mrem·m²/hr·µCi) | $Dp_i * e^{-\lambda t} * ExDF_i$ (mrem/hr) |
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Sum values in column 4: MTDP_Dp = ______ Sum the values in column 8: ∑= ______

Determine the weathering effect for $t_n$: $WF_{t_n} = 0.4e^{(-1.26E\text{-}03 * t_n)} + 0.6e^{(-3.84E\text{-}05 * t_n)} =$ ______ Multiply WF by above ∑: $MExDF\_Dp_i$ = ______

$$Dp\_DRL_{XR_{E,t_n}} = \frac{Dp\_DRL_{DR_{E,t_n}}}{XDCF} = \text{\_\_\_\_\_\_ (mR/hr)}$$

$$Dp\_DRL_{DR_{E,t_n}} = PAG_{E,TP} * \frac{MExDF\_Dp_{E,t_n}}{MTDP\_Dp_{E,TP}} = \text{\_\_\_\_\_\_ (mrem/hr)}$$

**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 | $10^{-3}$ |

| | | |
|---|---|---|
| μ | 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 μCi/kg | = | 1000 pCi/g |
| Areal Activity: | 1 μCi/m$^2$ | = | 1 Ci/km$^2$ |
| | | = | 100 pCi/cm$^2$ |
| Volumetric Activity: | 1 Ci/m$^3$ | = | 1 mCi/L |
| | | = | 1 μCi/cm$^3$ |
| Dose Conversion: | 1 Sv/Bq | = | 3.7E+11 rem/Ci |
| Dose Rate Conversion: | 1 (mrem/yr)/( μCi/m$^2$) | = | 0.114 (rem/hr)/(Ci/m$^2$) |

**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**

°K = °C + 273
°F = (°C x 1.8) + 32
°C = (°F -32)/1.8

| | | lb/in$^2$ | atm | bar | kPa | mm (Hg) |
|---|---|---|---|---|---|---|
| 1 lb/in$^2$ | = | 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**

| | | $in^2$ | $ft^2$ | $yd^2$ | acre | $mi^2$ (s) | $cm^2$ | $m^2$ | ha | $km^2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 $in^2$ | = | 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 $ft^2$ | = | 144 | 1 | 0.111 | 2.30E-05 | 3.59E-08 | 929 | 9.29E-02 | 9.29E-06 | 9.29E-08 |
| 1 $yd^2$ | = | 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 $mi^2$ (statute) | = | 4.01E+09 | 2.79E+07 | 3.10E+06 | 640 | 1 | 2.59E+10 | 2.59E+06 | 259 | 2.59 |
| 1 $cm^2$ | = | 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 $m^2$ | = | 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 $km^2$ | = | 1.55E+09 | 1.08E+07 | 1.20E+06 | 247 | 0.386 | 1.0E+10 | 1.0E+06 | 100 | 1 |

**VOLUME**

| | | $in^3$ | fl oz | $ft^3$ | qt | gal | bu | mL | L |
|---|---|---|---|---|---|---|---|---|---|
| 1 $in^3$ | = | 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 $ft^3$ | = | 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 | $ft^3$/min | L/s | $m^3$/hr |
|---|---|---|---|---|---|
| 1 gal/min | = | 1 | 0.134 | 6.32E-02 | 0.227 |
| 1 $ft^3$/min | = | 7.48 | 1 | 0.472 | 1.70 |
| 1 L/s | = | 15.8 | 2.12 | 1 | 3.60 |
| 1 $m^3$/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/$in^3$ | lb/$ft^3$ | g/$cm^3$ | kg/$m^3$ |
|---|---|---|---|---|---|
| 1 lb/$in^3$ | = | 1 | 5.79E-04 | 27.7 | 2.77E+04 |
| 1 lb/$ft^3$ | = | 1.73E+03 | 1 | 1.60E-02 | 16.0 |
| 1 g/$cm^3$ | = | 3.61E-02 | 62.4 | 1 | 1.0E+03 |
| 1 kg/$m^3$ | = | 3.61E-05 | 6.24E-02 | 1.0E-03 | 1 |

## Misc

Water Density = (1 g/$cm^3$ at 4°C)

1 $ft^3$ = 7.48 gal = 62.4 lb

1 gal = 8.33 lb

Avogadro 's number

6.02E+23 per g-mole

Air Density = (0.001293 g/$cm^3$ at STP)

1 $ft^3$ = 0.0807 lb

1 $m^3$ = 1.29 kg

Molar Volume

22.4 L/g-mole

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# SUPPLEMENTS

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# SUPPLEMENT 1 – DECAY AND IN-GROWTH CALCULATIONS

The default assessment methods presented in this manual implement restrictive daughter inclusion rules and make the assumption that the radionuclide mixture is in transient/secular equilibrium. These assumptions simplify the calculation of each radionuclide's activity in the mixture at the evaluation time ($t_n$). Although these simplifying assumptions work well for many radionuclide chains, they are not ideal in all cases.

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:

$$A_{d_1,t_n} = A_{p,0} * \left(\lambda_{d_1} * BrR_{d_1}\right) * \left(\frac{e^{-\lambda_p t_n} - e^{-\lambda_{d_1} t_n}}{\lambda_{d_1} - \lambda_p}\right) \quad \text{(Eq. 2)}$$

The activity of its second generation daughter, including Branching Ratio ($BrR_{d2}$), at $t_n$ is:

$$A_{d_2,t_n} = A_{p,0} * \left(\lambda_{d_1} * BrR_{d_1} * \lambda_{d_2} * BrR_{d_2}\right) * \left[\frac{e^{-\lambda_p t_n}}{\left(\lambda_{d_1} - \lambda_p\right)\left(\lambda_{d_2} - \lambda_p\right)} + \frac{e^{-\lambda_{d_1} t_n}}{\left(\lambda_p - \lambda_{d_1}\right)\left(\lambda_{d_2} - \lambda_{d_1}\right)} + \frac{e^{-\lambda_{d_2} t_n}}{\left(\lambda_p - \lambda_{d_2}\right)\left(\lambda_{d_1} - \lambda_{d_2}\right)}\right] \quad \text{(Eq. 3)}$$

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:

$$A_{d_2,t_n} = A_{d_1,0} * \left(\lambda_{d_2} * BrR_{d_2}\right) * \left(\frac{e^{-\lambda_{d_1} t_n} - e^{-\lambda_{d_2} t_n}}{\lambda_{d_2} - \lambda_{d_1}}\right) \quad \text{(Eq. 4)}$$

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:

$$A_{d_2,t_n} = \left\{ \begin{array}{l} A_{p,0} * \left(\lambda_{d_1} * BrR_{d_1} * \lambda_{d_2} * BrR_{d_2}\right) \\ * \left[ \dfrac{e^{-\lambda_p t_n}}{\left(\lambda_{d_1} - \lambda_p\right)\left(\lambda_{d_2} - \lambda_p\right)} + \dfrac{e^{-\lambda_{d_1} t_n}}{\left(\lambda_p - \lambda_{d_1}\right)\left(\lambda_{d_2} - \lambda_{d_1}\right)} + \dfrac{e^{-\lambda_{d_2} t_n}}{\left(\lambda_p - \lambda_{d_2}\right)\left(\lambda_{d_1} - \lambda_{d_2}\right)} \right] \end{array} \right\}$$
$$+ \left[ A_{d_1,0} * \left(\lambda_{d_2} * BrR_{d_2}\right) * \left( \frac{e^{-\lambda_{d_1} t_n} - e^{-\lambda_{d_2} t_n}}{\lambda_{d_2} - \lambda_{d_1}} \right) \right] \quad \text{(Eq. 6)}$$
$$+ A_{d_2,0} * e^{-\lambda_{d_2} t_n}$$

In the general case, the activity of the "n$^{th}$" daughter (assuming an initial mix of parent only) at time $t_n$ would be:

$$A_{d_n,t_n} = A_{p,0} * \left( C_1 e^{-\lambda_p t_n} + C_2 e^{-\lambda_{d_1} t_n} + C_3 e^{-\lambda_{d_2} t_n} + \ldots + C_n e^{-\lambda_{d_n} t_n} \right)$$

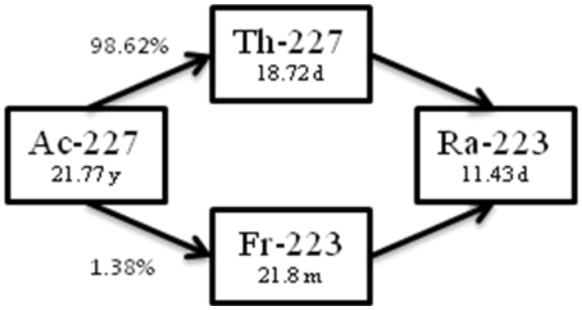
where:

$$C_1 = \frac{\lambda_{d_1}\lambda_{d_2}\ldots\lambda_{d_n}}{(\lambda_{d_1} - \lambda_p)(\lambda_{d_2} - \lambda_p)\ldots(\lambda_{d_n} - \lambda_p)}$$
$$C_2 = \frac{\lambda_{d_1}\lambda_{d_2}\ldots\lambda_{d_n}}{(\lambda_p - \lambda_{d_1})(\lambda_{d_2} - \lambda_{d_1})\ldots(\lambda_{d_n} - \lambda_{d_1})} \quad \text{(Eq. 7)}$$
$$\vdots$$
$$C_n = \frac{\lambda_{d_1}\lambda_{d_2}\ldots\lambda_{d_n}}{(\lambda_p - \lambda_{d_n})(\lambda_{d_1} - \lambda_{d_n})\ldots(\lambda_{d_{n-1}} - \lambda_{d_n})}$$

**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 $d^{-1}$

$\lambda_{Th} =$ 3.7E-02 $d^{-1}$ $BrR_{Ac,Th} = 0.9862$

$\lambda_{Fr} =$ 45.8 $d^{-1}$ $BrR_{Ac,Fr} = 0.0138$

$\lambda_{Ra} =$ 6.06E-02 $d^{-1}$ $BrR_{Th,Ra} = 1$ $BrR_{Fr,Ra} = 1$

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:

$$A_{\text{Ra, 100 days, Th}} = 1\text{ Ci} * \left(3.7\text{E-02 d}^{-1} * 0.9862 * 6.06\text{E-02 d}^{-1} * 1\right) * \left[ \begin{array}{l} \dfrac{e^{-8.72\text{E-05 d}^{-1} * 100\text{ d}}}{\left(3.7\text{E-02 d}^{-1} - 8.72\text{E-05 d}^{-1}\right)\left(6.06\text{E-02 d}^{-1} - 8.72\text{E-05 d}^{-1}\right)} \\ + \dfrac{e^{-3.7\text{E-02 d}^{-1} * 100\text{ d}}}{\left(8.72\text{E-05 d}^{-1} - 3.7\text{E-02 d}^{-1}\right)\left(6.06\text{E-02 d}^{-1} - 3.7\text{E-02 d}^{-1}\right)} \\ + \dfrac{e^{-6.06\text{E-02 d}^{-1} * 100\text{ d}}}{\left(8.72\text{E-05 d}^{-1} - 6.06\text{E-02 d}^{-1}\right)\left(3.7\text{E-02 d}^{-1} - 6.06\text{E-02 d}^{-1}\right)} \end{array} \right]$$

$$= 0.922\text{ Ci}$$

For the Fr-223 branch, from equation 4 above:

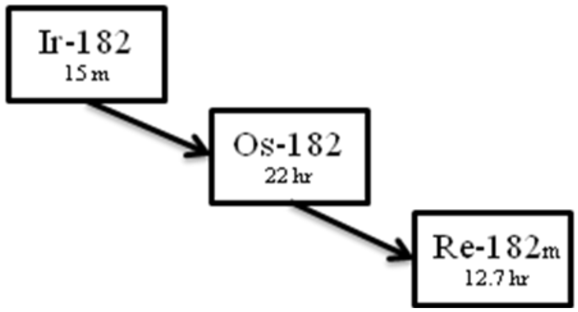
$$A_{\text{Ra, 100 days, Fr}} = 1\ \text{Ci} * \left(45.8\ \text{d}^{-1} * 0.0138 * 6.06\text{E-02}\ \text{d}^{-1} * 1\right) * \left[ \begin{array}{l} \dfrac{e^{-8.72\text{E-05 d}^{-1} * 100\ \text{d}}}{\left(45.8\ \text{d}^{-1} - 8.72\text{E-05 d}^{-1}\right)\left(6.06\text{E-02 d}^{-1} - 8.72\text{E-05 d}^{-1}\right)} \\ + \dfrac{e^{-3.7\text{E-02 d}^{-1} * 100\ \text{d}}}{\left(8.72\text{E-05 d}^{-1} - 45.8\ \text{d}^{-1}\right)\left(6.06\text{E-02 d}^{-1} - 45.8\ \text{d}^{-1}\right)} \\ + \dfrac{e^{-6.06\text{E-02 d}^{-1} * 100\ \text{d}}}{\left(8.72\text{E-05 d}^{-1} - 6.06\text{E-02 d}^{-1}\right)\left(45.8\ \text{d}^{-1} - 6.06\text{E-02 d}^{-1}\right)} \end{array} \right]$$

$$= 0.0137\ \text{Ci}$$

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 | $\lambda_{Ir} = 2.77\ hr^{-1}$ |
| Os-182 | 1.04E-02 Ci | $\lambda_{Os} = 3.15E\text{-}02\ hr^{-1}$ |
| Re-182m | 3.97E-04 Ci | $\lambda_{Re} = 5.46E\text{-}02\ hr^{-1}$ |

From equation 6 above:

$$A_{Re,\ 6hr} = \left\{ 6.25E\text{-}02\ Ci * \left(3.15E\text{-}02\ hr^{-1} * 1 * 5.46E\text{-}02hr^{-1} * 1\right) * \left[ \frac{e^{-2.77\ hr^{-1}*6\ hr}}{\left(3.15E\text{-}02\ hr^{-1} - 2.77\ hr^{-1}\right)\left(5.46E\text{-}02hr^{-1} - 2.77\ hr^{-1}\right)} + \frac{e^{-3.15E\text{-}02\ hr^{-1}*6\ hr}}{\left(2.77\ hr^{-1} - 3.15E\text{-}02\ hr^{-1}\right)\left(5.46E\text{-}02hr^{-1} - 3.15E\text{-}02\ hr^{-1}\right)} + \frac{e^{-5.46E\text{-}02hr^{-1}*6\ hr}}{\left(2.77\ hr^{-1} - 5.46E\text{-}02hr^{-1}\right)\left(3.15E\text{-}02\ hr^{-1} - 5.46E\text{-}02hr^{-1}\right)} \right] \right\}$$

$$+ \left[ 1.04E\text{-}02\ Ci * \left(5.46E\text{-}02hr^{-1} * 1\right) * \left( \frac{e^{-3.15E\text{-}02\ hr^{-1}*6\ hr} - e^{-5.46E\text{-}02hr^{-1}*6\ hr}}{5.46E\text{-}02hr^{-1} - 3.15E\text{-}02\ hr^{-1}} \right) \right]$$

$$+ 3.97E\text{-}04\ Ci * e^{-5.46E\text{-}02hr^{-1}*6\ hr}$$

$$= 3.10E\text{-}03\ Ci$$

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# SUPPLEMENT 2 – CALCULATION OF RESUSPENSION AND COMBINED REMOVAL PARAMETERS

Several assessment methods rely on the time-dependent integrated quantities which require complex math to calculate. In order to avoid lengthy diversions away from the health physics behind the methods (which would need to be repeated at several locations in the manual) the detailed derivations of these terms have been placed here.

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 (*TP*) under consideration for radioactive decay and the time-dependent resuspension factor (*K*) (value obtained numerically from Turbo FRMAC), s/m;

$CRP_{i,\,TP}$ = Combined Removal Parameter, value that adjusts for radioactive decay and weathering effects that decrease the amount of radionuclide i available to cause direct exposure or to be ingested over the time phase (*TP*) under consideration, s;

*WF* = Weathering Factor, value that adjusts the groundshine dose for weathering forces that reduce the radionuclide activity near the surface and thereby decrease the external dose rate, unitless;

**NOTE:** Weathering is used in this manual both as a contributor to the Combined Removal Parameter and as an independent factor. This Supplement treats Weathering as a contributor to the CRP. If a calculation involves weathering as an independent factor the section on Weathering may be performed as a stand-alone calculation.

## 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 weathering in the area under investigation.

The KP integral below does not have an exact solution when K is in a time-dependent form (as in the standard approach used here). Therefore the integral cannot be solved analytically and must be solved using a software program that is capable of numerical integration.

$$KP_{i,TP} = \int_{t_1}^{t_2} K * e^{-\lambda_i t} dt \qquad \text{(Eq. 1)}$$

$$\frac{s}{m} = \int_{s}^{s} \frac{1}{m} * e^{-\left(s^{-1} * s\right)} dt$$

where:

$KP_{i,\,TP}$ = Resuspension Parameter, value that adjusts the airborne radioactivity level of radionuclide *i* over the time phase (*TP*) under consideration for radioactive decay and the time-dependent resuspension factor (*K*) (value obtained numerically from Turbo FRMAC), s/m;

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

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

$K$ = Resuspension Factor, value based on the time-varying formula from NCRP Report No. 129, (NCRP99), $m^{-1}$:

- K = 1E-06 $m^{-1}$ for t < 1 day, or
- K = 1E-06 $m^{-1}$/t for t > 1 and ≤ 1,000 day, or
- K = 1E-09 $m^{-1}$ for t > 1,000 day.

The K model used here is the standard approach, but may not be appropriate for the environmental conditions existing in the area under investigation. An alternate K 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; and

$\lambda_i$ = Decay constant for radionuclide *i*, $s^{-1}$.

**Combined Removal Parameter**

In this Method, the Combined Removal Parameter (CRP) adjusts the external (groundshine) dose for radioactive decay ($e^{-\lambda t}$) and the time-dependent weathering factor (WF) over the time phase under consideration.

$$CRP_{i,TP} = \int_{t_1}^{t_2} \left( WF_{i,TP} * e^{-\lambda_i t} \right) dt \qquad \text{(Eq. 2)}$$

$$s = \int_{s}^{s} (\text{unitless} * e^{-\left(s^{-1} * s\right)})\, dt$$

where:

$CRP_{i,\,TP}$ = Combined Removal Parameter, value that adjusts for radioactive decay and weathering effects that decrease the amount of radionuclide i available to cause direct exposure or to be ingested over the time phase (*TP*) under consideration, s;

$WF_{i,\,TP}$ = Weathering Factor, value that adjusts the groundshine dose from radionuclide *i* for weathering forces that reduce the radionuclide activity near the surface over the time phase (*TP*) and thereby decreases the external dose rate, unitless (An02);

$\lambda_i$ = Decay Constant for radionuclide *i*, $s^{-1}$;

$t_1$ = the start of the time phase (integration period) under consideration, s; and
$t_2$ = the end of the time phase (integration period) under consideration, s.

## Weathering Factor

The Weathering Factor (WF) adjusts the external exposure rate for the decrease that occurs over time as the deposited material migrates deeper into the soil column. 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.

$$WF = 0.4 * e^{\left(\text{-1.46E-08}*t_n\right)} + 0.6 * e^{\left(\text{-4.44E-10}*t_n\right)} \qquad \text{(Eq. 3)}$$

$$\text{unitless} = \text{unitless} * \left( e^{-\left(s^{-1}*s\right)} \right) + \text{unitless} * \left( e^{-\left(s^{-1}*s\right)} \right)$$

where:

$WF$ = Weathering Factor, value that adjusts the groundshine dose for weathering forces that reduce the radionuclide activity near the surface and thereby decrease the external dose rate, unitless;
0.4 = Fraction of material that undergoes rapid weathering, unitless;
0.6 = Fraction of material that undergoes slow weathering, unitless;
1.46E-08 = Rate constant representing the removal rate for the fraction of material that is rapidly ($t_{1/2}$ = 1.5 y) weathered, $s^{-1}$;
4.44E-10 = Rate constant representing the removal rate for the fraction of material that is slowly ($t_{1/2}$ = 50 y) weathered, $s^{-1}$; and
$t_n$ = Evaluation Time, the point in time, relative to the start of the event, at which the measurement, prediction or evaluation is performed, 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 CRP to be simply a radioactive decay adjustment for each radionuclide over the time phase under consideration.

## Combining the Weathering Factor and Radioactive Decay to produce the Combined Removal 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.

Multiplying the WF by the radioactive decay yields:

$$CRP_{i,TP} = \int_{t_1}^{t_2} \left[ \left( 0.4 * e^{(-1.46\text{E-}08 * t_n)} + 0.6 * e^{(-4.44\text{E-}10 * t_n)} \right) * e^{(-\lambda_i * t_n)} \right] dt \quad \text{(Eq. 4a)}$$

This simplifies to:

$$CRP_{i,TP} = \int_{t_1}^{t_2} \left[ 0.4 * e^{(-t_n * (\lambda_i + 1.46\text{E-}08))} + 0.6 * e^{(-t_n * (\lambda_i + 4.44\text{E-}10))} \right] dt \quad \text{(Eq. 4b)}$$

Integrating over the time phase under consideration yields the following:

$$CRP_{i,TP} = \frac{0.4 * \left( e^{(-t_2 * (\lambda_i + 1.46\text{E-}08))} - e^{(-t_1 * (\lambda_i + 1.46\text{E-}08))} \right)}{-(\lambda_i + 1.46\text{E-}08)} + \frac{0.6 * \left( e^{(-t_2 * (\lambda_i + 4.44\text{E-}10))} - e^{(-t_1 * (\lambda_i + 4.44\text{E-}10))} \right)}{-(\lambda_i + 4.44\text{E-}10)} \quad \text{(Eq. 4c)}$$

$$s = \frac{\text{unitless} * \left( e^{(s * (s^{-1} + s^{-1})) - (s * (s^{-1} + s^{-1}))} \right)}{-(s^{-1} + s^{-1})} + \frac{\text{unitless} * \left( e^{(s * (s^{-1} + s^{-1})) - (s * (s^{-1} + s^{-1}))} \right)}{-(s^{-1} + s^{-1})}$$

| Reference | Title |
|---|---|
| 10 CFR 20 | *Standards for Protection Against Radiation*, Code of Federal Regulations, Title 10, Energy, Part 20. |
| An02 | Anspaugh, L. R., et al., "Movement of Radionuclides in Terrestrial Exosystems by Physical Processes" in *Health Physics*, Vol. 82, pp. 670-679, April 2002. |
| ANL01 | Yu, C., et al., *User's Manual for RESRAD*, ver. 6, Argonne National Laboratory, Argonne, IL, 2001. |
| DCFPAK | Eckerman, K., et al., Dose Coefficient Factor Package, Oak Ridge National Laboratory, Oak Ridge, TN, 1996 - current version. |
| DHS08 | *Planning Guidance for Protection and Recovery Following Radiological Dispersal Device and Improvised Nuclear Device Incidents*, U.S. Department of Homeland Security, Washington, DC, Federal Register, August 1, 2008. |
| DNA75 | Place, W. M., Cobb, F. C., and Defferding, C. G., *Palomares Summary Report*, AD-A955702, U.S. Defense Nuclear Agency, Washington, DC, January 1975. |
| DOE01 | *Radiological Emergency Response Health and Safety Manual*, DOE/NV/11718--440, U.S. Department of Energy, Washington, DC, May 2001. |
| DOE01a | *A Preliminary Review of the Flow and Characteristics of Recycled Uranium Throughout the DOE Complex 1952-1999*, U.S. Department of Energy, Washington, DC, March 2001. |
| DOE01b | *Guide of Good Practices for Occupational Radiological Protection in Uranium Facilities*, DOE-STD-1136-2000, rev. 2, U.S. Department of Energy, Washington, DC, March 2001. |
| DOE94 | Recommended Values and Technical Bases for Airborne Release Fractions (ARFs), Airborne Release Rates (ARRs), and Respirable Fractions (RFs) at DOE Non-Reactor Nuclear Facilities, DOE-HDBK-3010-94, U.S. Department of Energy, Washington, DC, 1994. |
| DOE99 | *Final Programmatic Environmental Impact Statement for Alternative Strategies for the Long-Term Management and Use of Depleted Uranium Hexafluoride*, DOE/EIS-0269, DOE-Office of Nuclear Facilities Management, Germantown, MD, April 1999. |
| EGG75 | Burson, Z.G., *Structural Shielding from Cloud and Fallout Gamma-Ray Sources for Assessing the Consequence of Reactor Accidents*, EGG-1183-1670, EG&G, Las Vegas, NV, 1975. |
| EPA84 | *An Estimation of the Daily Average Food Intake by Age and Sex for Use in Assessing the Radionuclide Intake of Individuals in the General Population*, EPA 520/1-84-021, U.S. Environmental Protection Agency, Washington, DC, 1984. |

EPA88 *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion*, Federal Guidance Report No. 11, EPA 520/1-88-020, U.S. Environmental Protection Agency, Washington, DC, 1988.

EPA89 *Evaluation of Skin and Ingestion Exposure Pathways*, EPA 520/1-89-016, U.S. Environmental Protection Agency, Washington, DC, 1989.

EPA92 *Manual of Protective Action Guides and Protective Actions for Nuclear Incidents*, EPA 400-R-92-001, U.S. Environmental Protection Agency, Washington, DC, 1992.

EPA94a *PAG Subcommittee Report on Implementation of EPA's Dose Limits for Emergency Workers,* U.S. Environmental Protection Agency, Washington, DC, 1994.

EPA97a *Exposure Factors Handbook*, EPA/600/P-95-002Fa, U.S. Environmental Protection Agency, Washington, DC, August 1997.

EPA00 *Guidance for the Data Quality Objectives Process,* EPA G/5, EPA/600/R-96/05, U.S. Environmental Protection Agency, Washington, DC, August 2000.

FDA98 *Accidental Radioactive Contamination of Human Foods and Animal Feeds: Recommendations for State and Local Agencies*, U.S. Food and Drug Administration, Washington, DC, August 13, 1998.

Gl77 Glasstone, S. and Dolan, P.J. *The Effects of Nuclear Weapons*. U.S. Department of Defense and U.S. Department of Energy, 1977 (3rd edition).

Ho94 Homann, S.G., *HOTSPOT Health Physics Codes for the PC*, UCRL-MA-106315, Version 6.5, Lawrence Livermore National Laboratory, Livermore, CA, 1994.

IAEA93 *Modeling of Weathering Decontamination and Activity Movement in Sewage System,* International Atomic Energy Agency, Vienna, Austria, 1993.

ICRP77 *Recommendations of the International Commission on Radiological Protection,* ICRP Publication 26, International Commission on Radiological Protection, Ottawa, Ontario, Canada, 1977.

ICRP80 *Limits for the Intake of Radionuclides by Worker,* Annals of the ICRP, ICRP Publication 30, International Commission on Radiological Protection, Ottawa, Ontario, Canada, 1979-80.

ICRP90 *1990 Recommendations of the International Commission on Radiological Protection,* ICRP Publication 60, International Commission on Radiological Protection, Ottawa, Ontario, Canada, 1990.

ICRP94 *Human Respiratory Tract Model for Radiological Protection,* ICRP Publication 66, International Commission on Radiological Protection, Ottawa, Ontario, Canada, 1994.

Me95 Mettler, F. A. and Upton, A. C., *Medical Effects of Ionizing Radiation*, 2nd ed., W. B. Saunders & Co., Philadelphia, PA, 1995.

NCRP99 *Recommended Screening Limits for Contaminated Surface Soil and Review of Factors Relevant to Site-Specific Studies*, NCRP Report 129, National Council on Radiation Protection and Measurements, Bethesda, MD, 1999.

NCRP07 *Cs-137 in the Environment: Radioecology and Approaches to Assessment and Management*, NCRP Report No. 154, National Council on Radiation Protection and Measurements, Bethesda, MD, 2007.

Ng77 Ng, Y. C., Colsher, C. S., Quinn, D. J., and Thompson, S. E., *Transfer Coefficients for the Prediction of the Dose to Man via the Forage-Cow-Milk Pathway from Radionuclides Released to the Biosphere*, UCRL-51939, Lawrence Livermore National Laboratory, Livermore, California, 1977.

NRC01 Sjoreen, A. L., et al., *RASCAL 3.0: Description of Models and Methods*, NUREG-1741, U.S. Nuclear Regulatory Commission, Washington, DC, 2001.

NRC77 *Calculation of Annual Doses to Man from Routine Releases of Reactor Effluent for the Purpose of Evaluating Compliance with 10 CFR Part 50, Appendix I*, Regulatory Guide 1.109, U.S. Nuclear Regulatory Commission, Washington, DC, 1977.

NRC85 *A Regulatory Analysis on Emergency Preparedness for Fuel Cycle and Other Radioactive Material Licensees*, NUREG-1140, U.S. Nuclear Regulatory Commission, Washington, DC, June 1985.

NRC86 *Assessment of the Public Health Impact from the Accidental Release of UF6 at the Sequoyah Falls Facility at Gore, Oklahoma*, Vols. 1 and 2, NUREG-1189, U.S. Nuclear Regulatory Commission, Washington, DC, March 1986.

NRC86a *Release of UF6 from a Ruptured Model 48Y Cylinder at Sequoyah Fuels Corporation Facility*, Supplement 1, NUREG-1198, U.S. Nuclear Regulatory Commission, Washington, DC, August 1986.

NRC95 Soffer, L., et al., *Accident Source Terms for Light-Water Nuclear Power Plants*, NUREG-1465, U.S. Nuclear Regulatory Commission, Washington, DC, 1995.

NRC96 *Response Technical Manual*, Vol. 1, rev. 4, RTM96, NUREG/BR-0150, U.S. Nuclear Regulatory Commission, Washington, DC, 1996.

PNNL03 *A Compendium of Transfer Factors for Agricultural and Animal Products*, PNNL-13421, Pacific Northwest National Laboratory, Richland, WA, 2003.

Th00 Thompson, J. M., and Thompson, E. A., *Savannah River Site Ingestion Pathway Methodology Manual for Airborne Radioactive Releases*, WSRC-TR-2000-00348, Rev. 0, Westinghouse Savannah River Company, Aiken, SC, September 2000.

Turbo FRMAC Fulton, J., et al.., Turbo FRMAC Assessment Software Package, Sandia National Laboratories, Albuquerque, NM, 2004 - current version.

WASH1400 *Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants*, NUREG-75/014 (WASH-1400), U.S. Nuclear Regulatory