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FEDERAL RADIOLOGICAL

MONITORING AND ASSESSMENT CENTER

FRMAC ASSESSMENT MANUAL

VOLUME 2

Overview And Methods

The Federal Manual for Assessing Environmental Data During a Radiological Emergency

May 2023

Prepared by

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FRMAC Assessment Manual

Volume 2

Overview and Methods

May 2023

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PREFACE

The Federal Radiological Monitoring and Assessment Center (FRMAC) Assessment Manual is the tool used to organize and guide activities of the FRMAC Assessment Division. The mission of the FRMAC Assessment Division in a radiological emergency is to interpret radiological data and predict worker and public doses. This information is used by Decision Makers to recommend protective actions 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.

The objectives of the FRMAC Assessment Manual are:

A. Document the assessment process.

The manual defines Assessment Division operations and provides descriptions of organization, functions, and objectives.

B. 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.

C. Provide technical basis for the Turbo FRMAC© software.

The Turbo FRMAC software automates the calculations in the Assessment Manual, allowing for rapid computation of important dose assessment data. Turbo FRMAC uses the default input values established by the FRMAC Assessment Working Group (AWG). Assessment Scientists can modify these input values to accommodate incident-specific conditions.

D. Function as an orientation and training guide for Assessment Division members.

The manual is used to train health physicists to use FRMAC assessment methods to evaluate environmental radiological conditions. It also describes the conduct of operations employed by FRMAC.

E. Provide Federal family consensus.

The manual is based on the guidance issued by the U.S. Nuclear Regulatory Commission (NRC), U.S. Environmental Protection Agency (EPA), and U.S. the Food and Drug Administration (FDA) and on consensus standards, such as the International Commission on Radiation Protection (ICRP) and the National Council on Radiation Protection (NCRP). It was developed by the FRMAC AWG and has had broad review from multiple Federal agencies (NNSA, NRC, EPA, FDA, U.S. Department of Agriculture [USDA], and the Centers for Disease Control and Prevention [CDC]), state agencies, and other participants.

This manual:

1) Is intended for use by trained FRMAC Assessment Scientists. It is the basis for training FRMAC Assessment Scientists in standard FRMAC technical methods, and

defines the standard technical methods used when responding to radiological incidents.

2) Represents the technical consensus of multiple federal agencies with expertise in and authority over aspects of radiological emergency response.

3) Defines methods to make many different radiological assessment calculations based on default assumptions agreed upon by the interagency FRMAC AWG as being most applicable to a wide variety of conditions. These default assumptions may or may not be appropriate for a specific incident.

4) Frequently uses the word "would" to define the result of the calculation, and it is important to be aware that this result is based on the established default assumptions. Should circumstances of the specific incident be different than the default assumptions, the predicted results may not reflect actual conditions. It is recommended that assessors obtain real-world data as soon as possible to validate the predictions made by the methods in this manual.

5) Is only intended to address the early and intermediate phases of a radiological incident. It does not address Late Phase issues, such as remediation.

6) Incorporates the EPA PAG Manual's Avoidable Dose concept.

   - Projected doses used to support protective action decisions are normally based upon the dose that can be avoided by taking protective actions (i.e., avoidable dose). The dose that is received before protective actions are taken (i.e., unavoidable dose) is normally not included in these dose projections.

   NOTE: The difference between the projected Total Dose (from the start of a release) and Avoidable Dose (starting when protective actions are possible) can be significant, depending on the radionuclides involved.

   - The Avoidable Dose concept is implemented as a default. Default Time Phases and Dose Pathways are based on when protective actions are reasonably expected to be implemented. Local Decision Makers have the authority to request changes to the FRMAC assumptions based on incident-specific conditions.

     NOTE: *The AWG has established the default start time for dose assessments at 12 hours after the release, based on the assumption that protective actions could be implemented at that time (e.g., in the case of a dirty bomb with no warning). This assumption may be modified based on incident-specific conditions at the request of Local Decision Makers.*

   - When there is sufficient warning to implement protective actions before the release occurs (e.g., some Nuclear Power Plant accident scenarios) , the entire dose (including that from the Plume) is considered avoidable and should be included in Early Phase dose assessments. In this case, the start of the Early Phase should be the time of the release.

7) Defaults to the 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.

- Multiple versions of ICRP 30+ and ICRP 60+ dose coefficients are available in the DCFPAK database. Turbo FRMAC defaults to DCFPAK 2.0 (2007 r2) for ICRP 30 and DCFPAK 3.0 (2015) for ICRP 60.

  NOTE: *ICRP 30 dose coefficients in DCFPAK are based on Federal Guidance Reports (FGR) 11 and 12 for inhalation and external pathways, respectively (EPA88, EPA93). Turbo FRMAC includes a 1992 EPA PAG Manual Emulation Mode for the Public Protection Derived Response Level calculation in which ICRP 30 dose coefficients are used. FGR 12 was published after the 1992 EPA PAG Manual, so external dose coefficients used by Turbo FRMAC in 1992 EPA PAG Manual Emulation Mode might differ slightly than those used to calculate values in the 1992 EPA PAG Manual.*

8) 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.

The manual is organized as follows:

Volume 1 describes the roles and responsibilities of the Assessment Division during a response.

Volume 2 contains the scientific bases and technical methods for assessment calculations. These calculations are broken up into sections:

Section 1 – Public Protection

Section 2 – Worker Protection

Section 3 – Ingestion Pathway

Section 4 – Supplemental Methods

Volume 3 provides analyses for pre-assessed scenarios. These default scenarios include:

1. Nuclear power plant
2. Nuclear fuel fabrication
3. Nuclear fuel accident
4. Radiological dispersal device
5. Nuclear detonation
6. Nuclear weapon accident
7. Radioisotope thermoelectric generator accident

Differences between FRMAC approach and other published guidance

The FRMAC 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 represents a unified federal consensus and is 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.

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ACKNOWLEDGMENTS

Development of this revision of the FRMAC Assessment Manual Volume 2 was a major undertaking to which many people contributed. Special recognition goes to the members of the FRMAC Assessment Working Group for their work on this revision in developing a health physics community consensus and identifying the appropriate radiological assessment methodologies.

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Acknowledgment is given to those who participated in development of previous versions 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. Headers in each section reflect the most recent revision date for the section (the "Effective Date"). Refer to Appendix H (Change History) for a list of changes made from the previous version.

Please check this table periodically to ensure that your printed copy of Volume 2 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.

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ACRONYMS AND ABBREVIATIONS

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

SNM	Special Nuclear Material
SRNL	Savannah River National Laboratory
SRD	Self Reading Dosimeter
ST	Stay Time
TBL	Turn-Back Limit
TED	Total Effective Dose
TF	Transfer Factor
USAF	US Air Force
USDA	US Department of Agriculture

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SECTION 1. PUBLIC PROTECTION METHODS

Effective Date

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Introduction to Public Protection Methods

This section defines radiological assessment methods to evaluate the radiological impacts to members of the public from exposure to radioactive material. Methods in this section have been developed to address hazards from exposure to the passage of a plume of radioactive material and the resulting ground deposition. Methods include developing Derived Response Levels (DRLs) and projecting doses by relating atmospheric dispersion modeling projections or field monitoring results to established Protective Action Guides (PAGs). (See Appendix C, Table 2-1 for PAG values.)

DRLs are levels of radioactivity in an environmental medium (i.e., the ground) that would be expected to produce a dose equal to the corresponding PAG (EPA17). DRLs are values which can be measured (e.g., $\mu Ci/m^2$ or mrem/h) with monitoring instrumentation.

An airborne release of radioactive material creates multiple pathways for radiation exposures. These methods include the dose contributions from the four primary pathways shown below.

- Plume Pathways (airborne material)
    - Inhalation of plume-borne material
    - External exposure from plume submersion
- Ground Pathways (deposited material)
    - Inhalation of resuspended material
    - External exposure from groundshine

Methods in this section may be performed for any combination of the four primary pathways.

Total Dose Assessments include the dose starting at the time of the release, while Avoidable Dose Assessments start at some time after the release (starting at an incident-specific time when protective actions are possible).

Under the Avoidable Dose concept, the incident-specific circumstances determine which of the four primary dose pathways should be considered. When there is uncertainty about the circumstances, all four pathways should be used for Early Phase Assessments until more information is available.

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

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

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

Therefore, because sufficient incident-specific information to account for wet deposition is often not available, the following methods are limited to dry deposition. Future revisions of this manual may include specific guidance on including the effects of washout and wet deposition. However, if data is available to enable determination of specific wet deposition effects, the Assessment Scientist can modify the default deposition velocity as appropriate to include wet deposition in assessment calculations.

Default Assumptions

FRMAC radiological assessment calculations utilize the default assumptions established by the FRMAC Assessment Working Group. Users are urged to use the default assumptions until site-specific values become available through consultations with the Advisory Team.

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

1) The dose projections from this section may include contributions from any combination of the four primary exposure pathways:
    - inhalation of radioactive material during plume passage;
    - external exposure (plume submersion) during plume passage;
    - inhalation of resuspended material deposited by the release; and,
    - external exposure (groundshine) from material deposited by the release.
2) The plume is assumed to be in contact with the ground, so that the receptor is in the plume. If plume dose pathways are included, the receptor is assumed to be exposed to the entire plume.
3) Because the temporal deposition of plume-borne radioactive material cannot be inferred from air sample data, any material deposited by plume passage is assumed to be immediately and completely deposited at the time of release.
4) Noble Gas Dose Projections – Radionuclides that are noble gases when initially released to the air:
    - are assumed to remain as gases during meteorological transport, even if they decay into a particulate daughter during transport.
    - are included in the external dose assessment from submersion in a plume.
    - do not contribute to inhalation dose because they are not assigned an inhalation dose coefficient.

- are **not** deposited on the ground and **are not** included in ground pathway assessment calculations.

NOTE: Noble gases that are daughters of ground-deposited radionuclides **are** assumed to remain on the ground and are included in ground pathway assessment calculations.

5) The effects of radioactive decay, weathering and resuspension are included in the calculations.

6) All deposition is assumed to be dry particulates. Wet deposition (increased localized deposition caused by rain or snow) is not included in these methods. (See Method 4.5 for discussion of deposition velocity.)

   NOTE: Certain radionuclides exist in multiple chemical/physical forms (e.g., particulate, vapor, gas). These radionuclides can be partitioned accordingly to more accurately calculate potential doses. See Appendix F, Supplement 4 for a discussion of partitioning and description of default assumptions.

7) Dose from ingestion is not included in Public Protection Methods. If ingestion is a significant dose pathway (i.e., >10% of the total dose), it should be addressed separately and included in protective action decisions. (See Section 3 – Ingestion Methods.)

8) The receptor is:

   - outside in the contaminated area continuously during the time phase under consideration without any protective measures (e.g., shielding or respiratory protection);

   - an adult; and,

   - inhaling 1-micron Activity Median Aerodynamic Diameter (AMAD) particles in the lung clearance type recommended by the ICRP.

     NOTE: This manual uses default Inhalation Dose Coefficients and Deposition Velocities based on the assumed particle size. Assessment Scientists are advised to modify the defaults based on actual particle size information if available.

     NOTE: Other lung clearance types may be more appropriate for certain radioactive materials with known physical forms. See Appendix C, Table 12 for more information.

     NOTE: Additionally, alternate particle sizes may be appropriate for some Radiological Dispersal Devices (RDDs). This information is sensitive and is not addressed in this manual. However, during a response, this information will be provided to individuals with need-to-know through the FRMAC.

9) Decay chains are truncated according to the following rules in order to save computation time without significantly affecting calculated dose (SNL17).

   a. Include the parent radionuclide and first daughter radionuclide, regardless of half-life

   b. Analyze first daughter radionuclide half-life

i. If first daughter radionuclide half-life is ≥ 5,000 years, truncate the chain (i.e., do not include the remaining radionuclides in the decay chain)

ii. If first daughter radionuclide half-life is < 5,000 years, include next radionuclide in chain

c. Analyze second and subsequent daughter half-lives according to Rule b until decay chain is truncated or entire chain has been included

The dose from the radionuclide at which the decay chain is truncated IS included in the dose projection.

10) Equilibrium rules are applied after truncation. Daughter radionuclides that meet the following rules are considered to be in equilibrium (secular, or transient when branching ratio ≠ 1) at deposition (t = 0) and are assigned the parent's half-life and decay constants for calculations:

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 years.

11) The Bateman Equations (Ba1910) are used to model the decay and in-growth of all radionuclides. See Appendix F, Supplement 1 for details.

12) FRMAC's Public Protection Methods generally assume that the organ of interest is the whole body (Total Effective Dose). However, other organs may be evaluated against PAGs by utilizing the organ-specific Dose Coefficients and PAGs. (See Method 1.1 Example 1, Section E1.8.)

Default Inputs

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

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

1) Data – This information may come from predictive analysis (atmospheric dispersion models) or field data (monitoring and/or samples):

- Composition of the plume and of the deposited radionuclide mixture (radionuclides and volumetric or areal activity, concentration, activity ratio, or mass ratio); and/or

- External dose (or exposure) rates.

2) Other Factors:

- Plume Deposition Velocity;

- Ground roughness;

- Weathering;
- Resuspension; and
- Decay of radionuclides during the time period under consideration.

3) Constants:

- Breathing rate (defaults: Activity-Averaged Breathing Rate of 0.92 m^3/h for inhalation of resuspended material and Light-Exercise Breathing Rate of 1.5 m^3/h for in-plume inhalation based on the ICRP 60+ lung model);
- Inhalation dose coefficient (defaults from ICRP 60+ dosimetry model);
- External dose coefficient (defaults from ICRP 60+ dosimetry model);
- Dose limits (e.g., PAGs – defaults from EPA/DHS guidance); and
- Exposure to Dose Conversion Factor (default of 1.0 mrem/mR).

4) Time Phase:

- Release Time (t_0) – The time the release begins. This time is usually assumed to correspond to the "Time of Deposition".
- Start Time (t_1) – The start of the Time Phase (integration period) under consideration.
- End Time (t_2) – The end of the Time Phase (integration period) under consideration.
- Evaluation Time (t_n) – The point in time, relative to the start of the release, for which the calculation, measurement, or prediction is valid.

The EPA and DHS have established certain default time phases (early, intermediate, etc.) with specified durations, but the time phase may be set to any period chosen by Decision Makers for a specific incident. Appendix C, Table 2-3 shows the default Time Phases, Evaluation Times, and Dose Pathways that are considered.

FRMAC uses a default Evaluation Time for DRL calculations of 12 hours after the start of the release, allowing atmospheric dispersion models to simulate 12 hours of downwind transport. This was chosen because 12 hours is generally sufficient for complete deposition of a single release to occur so that deposition contours can be plotted on data products.

In other scenarios (e.g., a protracted Power Plant accident) this may not be appropriate and other assumptions will be required. FRMAC may modify the Time Phases and Dose Pathways to accommodate incident-specific circumstances. The calculations presented in these methods are applicable to any time phase. To accommodate calculations for varying time phases, adjust the start (t_1) and end (t_2) of the integration period to the desired values.

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 1.1 INTEGRATED AIR AND DEPOSITION DERIVED RESPONSE LEVELS

Application

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

The $DRL_{\tilde{A}}$ represents the integrated air activity ($\tilde{A}$) (µCi•s/m^3), of radionuclide *i* at which the total dose from *all radionuclides* in a release from the pathways included in the assessment would equal the Protective Action Guide (PAG) over the time phase under consideration.

The DRL_{Dp} represents the areal activity (µCi/m^2), at a specific Evaluation Time (t_n), of radionuclide *i* at which the total dose from *all radionuclides* in a release from the pathways included in the assessment would equal the Protective Action Guide (PAG) over the time phase under consideration.

All DRLs developed in this Method are:

1) Derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA17) or the Department of Homeland Security (DHS) (DHS08). A projected or measured value greater than the DRL indicates the potential to exceed the PAG.

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

Discussion

The $DRL_{\tilde{A}}$:

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

The DRL_{Dp}:

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

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

NOTE: Because different elements and chemical/physical forms have different deposition velocities (V_d), the relative activity ratios of plume-borne radionuclides may be different than the activity ratios of the ground-deposited radionuclides. (See Method 4.5 for discussion.)

To assist field monitoring and laboratory measurements, FRMAC recommends that, when multiple radionuclides are present in a release, a single, easily-detected radionuclide is chosen to represent the hazard of the entire release. Monitoring and laboratory personnel can use the DRLs calculated for that radionuclide, as a part of the entire release, to eliminate the need to separately measure the concentration of every radionuclide in the release mixture.

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

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

Assumptions

There are no additional assumptions beyond the Default Assumptions above.

Inputs

There are no additional inputs beyond the Default Inputs above.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

Outputs

Final

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

$DRL_{\tilde{A}}$ = Integrated Air Derived Response Level, the integrated air activity ($\tilde{A}$) of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), μCi•s/m^3.

DRL_{Dp} = Deposition Derived Response Level, the areal activity, at time t_n, of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), μCi/m^2.

Intermediate

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

MTDP = Mixture Total Dose Parameter for all radionuclides (mrem)

TDP = Total Dose Parameter for each radionuclide (mrem)

Dp_ExDP = Deposition External Dose Parameter for each radionuclide (mrem)

Dp_InhDP = Deposition Inhalation Dose Parameter for each radionuclide (mrem)

Pl_ExDP = Plume External Dose Parameter for each radionuclide (mrem)

Pl_InhDP = Plume Inhalation Dose Parameter for each radionuclide (mrem)

Calculation

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

Prior to calculating a DRL, it is necessary for the assessor to determine which of the four primary pathways are applicable for the calculation. The DRLs are then calculated based on the dose from the mixture for the selected pathways.

1) Integrated Air Derived Response Level

Equation 1.1-1 shows the final form of the $DRL_{\tilde{A}}$ calculation:

$$DRL_{\tilde{A},i,TP} = \frac{PAG_{TP} * \tilde{A}_i}{MTDP_{TP}} \quad \text{(Eq. 1.1-1)}$$

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

where:

$DRL_{\tilde{A},\,i,\,TP}$ = Integrated Air Derived Response Level, the integrated air activity ($\tilde{A}$) of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), μCi•s/m^3;

> **NOTE:** When using an Integrated Air Sample result, there is no need to account for radioactive decay or weathering because the process of integration includes radioactive decay and weathering does not affect air samples.

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

$\tilde{A}_i$ = Integrated air activity of radionuclide *i* in a release, μCi•s/m^3; and

$MTDP_{TP}$ = Mixture Total Dose Parameter, the sum of the doses from *all radionuclides* in a release, over the time phase under consideration (*TP*), from the pathways included in the assessment, mrem.

2) Deposition Derived Response Level

Equation 1.1-2 shows the final form of the DRL_{Dp} calculation:

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

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

where:

$DRL_{Dp,\,i,\,tn,\,TP}$ = Deposition Derived Response Level, the areal activity, at time t_n, of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), μCi/m^2;

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

$Dp_{i,tn}$ = Deposition, the areal activity of radionuclide *i* at time t_n, µCi/m^2;

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

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

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

$MTDP_{TP}$ = Mixture Total Dose Parameter, the sum of the doses from *all radionuclides* in a release, over the time phase under consideration (*TP*), from the pathways included in the assessment, mrem.

1.1 Calculating the Total Dose Parameter for each Radionuclide in a Release

The critical factor in determining the DRLs is the Total Dose Parameter (TDP) for each radionuclide in a release. The Total Dose Parameter (TDP) represents the dose from the pathways included in the assessment and is obtained by summing the appropriate Dose Parameters from the following list:

- the Plume Inhalation Dose Parameter (Pl_InhDP);
- the Plume External Dose Parameter (Pl_ExDP);
- the Deposition Inhalation Dose Parameter (Dp_InhDP); and
- the Deposition External Dose Parameter (Dp_ExDP).

Calculating the Total Dose Parameter

The TDP is calculated using Equation 1.1-3.

$$TDP_{i,TP} = Pl\_InhDP_{i,TP} + Pl\_ExDP_{i,TP} + Dp\_InhDP_{i,TP} + Dp\_ExDP_{i,TP} \quad \text{(Eq. 1.1-3)}$$

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

where:

$TDP_{i,\,TP}$ = Total Dose Parameter, the sum of the doses from radionuclide *i*, over the time phase under consideration (*TP*), from the pathways included in the assessment, mrem;

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

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

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

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

The following sections show how to calculate the Dose Parameter for each of the four primary pathways that may be included as components of the TDP.

1.1.1 Calculating the Plume Inhalation Dose Parameter (Plume Inhalation Pathway)

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

$$Pl\_InhDP_{i,TP} = InhDC_i * \tilde{A}_i * BR_{LE} \qquad \text{(Eq. 1.1-4)}$$

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

where:

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

$InhDC_i$ = Inhalation Dose Coefficient, the committed dose coefficient for radionuclide *i*, mrem/µCi;

> **NOTE:** Inhalation Dose Coefficients for parent radionuclides include the dose contributions from daughter radionuclides that grow in after the parent is inhaled, but not from daughters that are inhaled.

Therefore, if daughter radionuclides are inhaled, they should be considered as a separate parent for the purpose of estimating dose.

$\tilde{A}_i$ = Integrated air activity of radionuclide *i* in a release, µCi•s/m^3; and

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

BR_{LE} = Light Exercise Breathing Rate, the volume of air breathed per unit time by an adult male during light exercise (ICRP, 1994, Table 6), 4.17E-04 m^3/s (1.5 m^3/h).

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

1.1.2 Calculating the Plume External Dose Parameter (Plume Submersion Pathway)

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

$$Pl\_ExDP_{i,TP} = Pl\_ExDC_i * \tilde{A}_i \qquad \text{(Eq. 1.1-5)}$$

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

where:

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

Pl_ExDC_i = Plume External Dose Coefficient, the external dose rate from submersion in radionuclide *i* in the plume, mrem•m^3/µCi•s; and

$\tilde{A}_i$ = Integrated air activity of radionuclide *i* in a release, µCi•s/m^3.

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

1.1.3 Calculating the Deposition Inhalation Dose Parameter (Resuspension Inhalation Pathway)

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

$$Dp\_InhDP_{i,TP} = InhDC_i * KP_{i,TP} * BR_{AA} \qquad \text{(Eq. 1.1-6)}$$

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

where:

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

$InhDC_i$ = Inhalation Dose Coefficient, the committed dose coefficient for radionuclide *i*, mrem/µCi;

> **NOTE:** Inhalation Dose Coefficients for parent radionuclides include the dose contributions from daughter radionuclides that grow in after the parent is inhaled, but not from daughters that are inhaled. Therefore, if daughter radionuclides are inhaled, they should be considered as a separate parent for the purpose of estimating dose.

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

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

BR_{AA} = Activity-Averaged Breathing Rate, the activity-weighted average volume of air breathed per unit time by an adult male (ICRP, 1994, Table B.16B), 2.56E-04 m^3/s (0.92 m^3/h).

1.1.4 Calculating the Deposition External Dose Parameter (Groundshine Pathway)

The Deposition External Dose Parameter (Dp_ExDP) is calculated by multiplying the External Dose Coefficient (Dp_ExDC) by a ground roughness factor (GRF) and the Weathering Parameter (WP) to calculate the effective dose from groundshine over the time period under consideration.

$$Dp\_ExDP_{i,TP} = Dp\_ExDC_i * GRF * WP_{i,TP} \qquad \text{(Eq. 1.1-7)}$$

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

where:

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

Dp_ExDC_i = Deposition External Dose Coefficient, the external dose rate from radionuclide *i* per unit activity deposited on the ground, mrem•m²/µCi•s;

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

$WP_{i,\,TP}$ = Weathering Parameter, the adjustment for radioactive decay and in-growth and the time-dependent weathering effects that change the amount of a radionuclide available to cause direct exposure or to be ingested over the time phase under consideration (*TP*), µCi•s/m².

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

1.2 Calculating the Mixture Total Dose Parameter

The Mixture Total Dose Parameter (MTDP) includes the dose contributions for all radionuclides in the mixture from each of the selected primary dose pathways, and is calculated by summing the TDPs for each radionuclide in the mixture.

$$MTDP_{TP} = \sum_i TDP_{i,TP} \qquad \text{(Eq. 1.1-8)}$$

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

where:

$MTDP_{TP}$ = Mixture Total Dose Parameter, the sum of the doses from *all radionuclides* in a release, over the time phase under consideration (*TP*), from the pathways included in the assessment, mrem;

$TDP_{i,\,TP}$ = Total Dose Parameter, the sum of the doses from radionuclide *i*, over the time phase under consideration (*TP*), from the pathways included in the assessment, mrem;

1.3 Comparing the MTDP to the PAG to Calculate DRLs

The calculated MTDP is used to determine the DRLs by comparing it to the PAG using the following equations.

1.3.1 Integrated Air Derived Response Level ($DRL_{\tilde{A}}$)

$$DRL_{\tilde{A},i,TP} = \frac{PAG_{TP} * \tilde{A}_i}{MTDP_{TP}} \qquad \text{(Eq. 1.1-1)}$$

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

where:

$DRL_{\tilde{A},\,i,\,TP}$ = Integrated Air Derived Response Level, the integrated air activity ($\tilde{A}$) of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), µCi•s/m^3;

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

$\tilde{A}_i$ = Integrated air activity of radionuclide *i* in a release, µCi•s/m^3; and

$MTDP_{TP}$ = Mixture Total Dose Parameter, the sum of the doses from *all radionuclides* in a release, over the time phase under consideration (*TP*), from the pathways included in the assessment, mrem.

The effects of radioactive decay during sample collection are inherently included in the calculation of the integrated air value. (See Method 4.6 for calculation details.) The integrated air activity represents the total amount of material in an airborne plume at the sampling location.

> **NOTE:** Evaluation Time (t_n) is not relevant to this type of DRL because Evaluation Time applies to the time after deposition that a measurement is made. The integrated air value is for material that has not yet been deposited – it is measured during plume passage.

1.3.2 Deposition Derived Response Level (DRL_{Dp})

$$DRL_{Dp,i,t_n TP} = \frac{PAG_{TP} * Dp_{i,t_n} * WF_{t_n}}{MTDP_{TP}} \qquad \text{(Eq. 1.1-2)}$$

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

where:

$DRL_{Dp,\,i,\,tn,\,TP}$ = Deposition Derived Response Level, the areal activity, at time t_n, of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (TP), µCi/m^2;

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

$Dp_{i,tn}$ = Deposition, the areal activity of radionuclide i at time t_n, µCi/m^2;

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

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

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

$MTDP_{TP}$ = Mixture Total Dose Parameter, the sum of the doses from *all radionuclides* in a release, over the time phase under consideration (TP), from the pathways included in the assessment, mrem.

EXAMPLE 1

Problem: Calculate the Total Effective Dose Deposition DRL for the Early Phase (Total Dose) Time Phase (0-96 hours) for the Following Mixture for an Evaluation Time (t_n) of 12 hours, including the dose from all four primary pathways.

Table 1.1-E1

Radionuclide	Integrated Air Activity (µCi•s/m^3)	Deposition (µCi/m^2)
Co-60	6.67E+02	2
Gd-148	3.33E+02	1
Sr-90	1.00E+03	3
Y-90 [a]	1.00E+03	3
[a] Y-90 included as a daughter at equilibrium.		

The default Early Phase (Total Dose) Time Phase includes all four Primary Dose Pathways. To determine the DRLs, the following intermediate terms are needed:

Dp_ExDP = Deposition External Dose Parameter for each radionuclide (mrem)

Dp_InhDP = Deposition Inhalation Dose Parameter for each radionuclide (mrem)

Pl_ExDP = Plume External Dose Parameter for each radionuclide (mrem)

Pl_InhDP = Plume Inhalation Dose Parameter for each radionuclide (mrem)

TDP = Total Dose Parameter for each radionuclide (mrem)

The TDP is then summed over each radionuclide to calculate the Mixture Total Dose Parameter (MTDP).

E1.1 Calculating Pl_InhDP (Equation 1.1-4)

This calculation requires the Inhalation Dose Coefficient (InhDC), and the Light Exercise Breathing Rate (BR_{LE}).

Example Pl_InhDP calculation for Co-60 and Pl_InhDP values for the radionuclide mixture for the Early Phase (Total Dose) time phase.

$$Pl\_InhDP_{^{60}Co} = 3.77\text{E+}01\,\frac{\text{mrem}}{\mu\text{Ci}} * 6.67\text{E+}02\,\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * 4.17\text{E-}04\,\frac{\text{m}^3}{\text{s}} = 1.05\text{E+}01\text{ mrem}$$

Table 1.1.E2

Radionuclide	InhDC [a] (mrem/µCi)	Integrated Air Activity (µCi•s/m³)	Breathing Rate (Light Exercise) [b] (m³/s)	Pl_InhDP (mrem)
Co-60	3.77E+01	6.67E+02	4.17E-04	**1.05E+01**
Gd-148	4.26E+04	3.33E+02	4.17E-04	**5.92E+03**
Sr-90	1.32E+02	1.00E+03	4.17E-04	**5.50E+01**
Y-90	5.14E+00	1.00E+03	4.17E-04	**2.14E+00**

[a] Value from DCFPAK 3.0 (ICRP 60+) for 1 micron particles. If particle size is known to be other than 1 micron, choose appropriate value.
[b] The light exercise breathing rate is used because it is assumed that the individual will be actively seeking to exit the plume.

E1.2 Calculating Pl_ExDP (Equation 1.1-5)

The External Dose Parameter (Pl_ExDP) is simply the External Dose Coefficient for submersion in a plume multiplied by the Integrated Air activity (Ã).

Example Pl_ExDP calculation for Co-60 and Pl_ExDP values for the radionuclide mixture for the Early Phase (Total Dose) time phase.

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

Table 1.1-E3

Radionuclide	Pl_ExDC [a] (mrem•m³/µCi•s)	Integrated Air Activity (µCi•s/m³)	Pl_ExDP (mrem)
Co-60	4.40E-04	6.67E+02	**2.93E-01**
Gd-148	0	3.33E+02	**0**
Sr-90	3.64E-07	1.00E+03	**3.64E-04**
Y-90	2.93E-06	1.00E+03	**2.93E-03**

[a] Values from DCFPAK 3.0 (ICRP 60+).

E1.3 Calculating Dp_InhDP (Equation 1.1-6)

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

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

Example KP calculation for Co-60 and KP values for the radionuclide mixture for the Early Phase (Total Dose) time phase.

$$KP_{^{60}Co} = 2\,\frac{\mu\text{Ci}}{\text{m}^2} * \left[\begin{array}{c} \dfrac{1.05\text{E-}05 * \left(e^{(-3.46\text{E+}05*(4.17\text{E-}09+8.1\text{E-}07))} - e^{(-0*(4.17\text{E-}09+8.1\text{E-}07))}\right)}{-(4.17\text{E-}09 + 8.1\text{E-}07)} \\ + \dfrac{7.0\text{E-}09 * \left(e^{(-3.46\text{E+}05*(4.17\text{E-}09+2.31\text{E-}08))} - e^{(-0*(4.17\text{E-}09+2.31\text{E-}08))}\right)}{-(4.17\text{E-}09 + 2.31\text{E-}08)} \\ + \dfrac{1.0\text{E}-09 * \left(e^{(-3.46\text{E+}05*(4.17\text{E-}09))} - e^{(-0*(4.17\text{E-}09))}\right)}{-(4.17\text{E-}09)} \end{array}\right] \frac{\text{s}}{\text{m}} = 6.03\,\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3}$$

Table 1.1-E4

Radionuclide	Deposition (μCi/m^2)	λ_i [a] (s^{-1})	t_1 (s)	t_2 (s)	KP_i – EP(TD) (μCi•s/m^3)
Co-60	2	4.17E-09	0	3.46E+05	6.03 [b]
Gd-148	1	2.94E-10	0	3.46E+05	3.02 [b]
Sr-90	3	7.63E-10	0	3.46E+05	9.05 [b]
Y-90	3	7.63E-10 [c]	0	3.46E+05	9.05 [d]

[a] Values from DCFPAK 3.0.
[b] Values approximated using equations in Appendix F, Supplement 2.
[c] Parent decay constant used for daughter at equilibrium.
[d] Value from Turbo FRMAC 2020©. Calculations for daughters are more complicated than can be readily discussed here. See Appendix F, Supplements 1 and 2 for more information.

E1.3.2 Calculating the Dp_InhDP

Example Dp_InhDP calculation for Co-60 and Dp_InhDP values for the radionuclide mixture for the Early Phase (Total Dose) time phase.

$$Dp\_InhDP_{^{60}Co} = 3.77\text{E+}01\,\frac{\text{mrem}}{\mu\text{Ci}} * 6.03\,\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * 2.56\text{E-}04\,\frac{\text{m}^3}{\text{s}} = 5.82\text{E-}02\ \text{mrem}$$

Table 1.1-E5

Radionuclide	InhDC [a] (mrem/µCi)	KP_i – EP(TD) (µCi•s/m^3)	Breathing Rate (Activity-averaged) [b] (m^3/s)	Dp_InhDP EP(TD) (mrem)
Co-60	3.77E+01	6.03	2.56E-04	**5.82E-02**
Gd-148	4.26E+04	3.02	2.56E-04	**3.29E+01**
Sr-90	1.32E+02	9.05	2.56E-04	**3.06E-01**
Y-90	5.14E+00	9.05 [c]	2.56E-04	**1.19E-02**

[a] Value from DCFPAK 3.0 (ICRP 60+) for 1 micron particles. If particle size is known to be other than 1 micron, choose appropriate value.
[b] Standard activity-averaged breathing rate.
[c] Value from Turbo FRMAC 2020©.

E1.4 Calculating Dp_ExDP (Equation 1.1-7)

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

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

Example WP calculation for Co-60 and WP values for the radionuclide mixture for the Early Phase (Total Dose) time phase.

$$WP_{^{60}Co} = 2\frac{\mu\text{Ci}}{\text{m}^2} * \left[\begin{array}{c} \dfrac{0.4 * \left(e^{(-3.46\text{E+}05*(4.17\text{E-}09+1.46\text{E-}08))} - e^{(-0*(4.17\text{E-}09+1.46\text{E-}08))}\right.}{-(4.17\text{E-}09 + 1.46\text{E-}08)} \\ + \dfrac{0.6 * \left(e^{(-3.46\text{E+}05*(4.17\text{E-}09+4.44\text{E-}10))} - e^{(-0*(4.17\text{E-}09+4.44\text{E-}10))}\right)}{-(4.17\text{E-}09 + 4.44\text{E-}10)} \end{array}\right] \text{s}$$

$$= 6.90\text{E+}05 \frac{\mu\text{Ci} \cdot \text{s}}{\text{m}^2}$$

Table 1.1-E6

Radionuclide	Deposition (μCi/m^2)	λ_i [a] (s^{-1})	t_1 (s)	t_2 (s)	WP_i – EP(TD) (μCi•s/m^2)
Co-60	2	4.17E-09	0	3.46E+05	6.90E+05 [b]
Gd-148	1	2.94E-10	0	3.46E+05	3.45E+05 [b]
Sr-90	3	7.63E-10	0	3.46E+05	1.04E+06 [b]
Y-90	3	7.63E-10 [c]	0	3.46E+05	1.04E+06 [d]

[a] Values from DCFPAK 3.0.
[b] Values approximated using equations in Appendix F, Supplement 2.
[c] Parent decay constant used for daughter at equilibrium.
[d] Value from Turbo FRMAC 2020©. Calculations for daughters are more complicated than can be readily discussed here. See Appendix F, Supplements 1 and 2 for more information.

E1.4.2 Calculating the Dp_ExDP

Example Dp_ExDP calculation for Co-60 and Dp_ExDP values for the radionuclide mixture for the Early Phase (Total Dose) time phase.

$$Dp\_ExDP_{^{60}Co} = 8.51\text{E-}06 \frac{\text{mrem} \cdot \text{m}^2}{\mu\text{Ci} \cdot \text{s}} * 0.82 * 6.90\text{E+}05 \frac{\mu\text{Ci} \cdot \text{s}}{\text{m}^2} = 4.81 \text{ mrem}$$

Table 1.1-E7

Radionuclide	Dp_ExDC [a] (mrem•m^2/s•μCi)	GRF (unitless)	WP_i – EP(TD) (μCi•s/m^2)	Dp_ExDP EP(TD) (mrem)
Co-60	8.51E-06	0.82	6.90E+05	**4.81**
Gd-148	0	0.82	3.45E+05	**0**
Sr-90	6.07E-09	0.82	1.04E+06	**5.15E-03**
Y-90	4.07E-07	0.82	1.04E+06 [b]	**3.47E-01**

[a] Values from DCFPAK 3.0 (ICRP 60+).
[b] Value from Turbo FRMAC 2020©.

E1.5 Calculating TDP (Eq 1.1-3)

Example TDP calculation for Co-60 and TDP values for the radionuclide mixture for the Early Phase (Total Dose) time phase.

$$\begin{aligned} \text{TDP}_{^{60}\text{Co}} &= 1.05\text{E+}01 \text{ mrem} \\ &+ 2.93\text{E-}01 \text{ mrem} \\ &+ 5.82\text{E-}02 \text{ mrem} \\ &+ 4.81 \text{ mrem} \\ &= 1.57\text{E+}01 \text{ mrem} \end{aligned}$$

Table 1.1-E8

Radionuclide	PI_InhDP (mrem)	PI_ExDP (mrem)	Dp_InhDP EP(TD) (mrem)	Dp_ExDP EP(TD) (mrem)	TDP EP(TD) (mrem)
Co-60	1.05E+01	2.93E-01	5.82E-02	4.81	**1.57E+01**
Gd-148	5.92E+03	0	3.29E+01	0	**5.95E+03**
Sr-90	5.50E+01	3.64E-04	3.06E-01	5.15E-03	**5.54E+01**
Y-90	2.14E+00	2.93E-03	1.19E-02	3.47E-01	**2.51**

E1.6 Calculating MTDP (Equation 1.1-8)

The Mixture Total Dose Parameter (MTDP) includes the dose contributions from the pathways included in the assessment for the entire radionuclide mixture, and is calculated by summing the TDPs for each radionuclide in the mixture.

Table 1.1-E9

Radionuclide	TDP EP(TD) (mrem)
Co-60	1.57E+01
Gd-148	5.95E+03
Sr-90	5.54E+01
Y-90	2.51
MTDP =	**6.02E+03**

E1.7 Calculating the Derived Response Levels

E1.7.1 Calculating DRLÃ (Equation 1.1-1)

Example DRLÃ calculation for Co-60 and DRLÃ values for the radionuclide mixture for the Early Phase (Total Dose) Time Phase with an Evaluation Time (t_n) of 12 hours.

PAG = 1000 mrem
MTDP = 6.02E+03 mrem

$$DRL_{\tilde{A}_{60Co}} = \frac{1000 \text{ mrem} * 6.67\text{E}{+}02 \frac{\mu\text{Ci} \cdot \text{s}}{\text{m}^3}}{6.02\text{E}{+}03 \text{ mrem}} = 1.10\text{E}{+}02 \frac{\mu\text{Ci} \cdot \text{s}}{\text{m}^3}$$

This means that a Co-60 Integrated Air Activity of 110 µCi•s/m^3 in the plume would indicate that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the Early Phase equal to the PAG of 1000 mrem when considering all four of the primary dose pathways.

Table 1.1-E10

Radionuclide	Integrated Air Activity (µCi•s/m³)	EP(TD) $DRL_{\tilde{A}}$ [a] (µCi•s/m³)
Co-60	6.67E+02	**1.11E+02**
Gd-148	3.33E+02	**5.53E+01**
Sr-90	1.0E+03	**1.66E+02**
Y-90	1.0E+03	**1.66E+02**
[a] Because this method uses a time integrated air activity, there is no need to account for decay during sample collection.		

E1.7.2 Calculating DRL_{Dp} (Equation 1.1-2)

Example DRL_{Dp} calculation for Co-60 and DRL_{Dp} values for the radionuclide mixture for the Early Phase (Total Dose) Time Phase with an Evaluation Time (t_n) of 12 hours.

PAG = 1000 mrem
MTDP = 6.02E+03 mrem

$$DRL_{Dp_{60Co}} = \frac{1000\text{ mrem} * \left(2\,\frac{\mu\text{Ci}}{\text{m}^2} * e^{-4.17\text{E-}09*(12*3600)}\right) * 0.9997}{6.02\text{E+03 mrem}} = 3.32\text{E-01}\,\frac{\mu\text{Ci}}{\text{m}^2}$$

This means that a Co-60 Areal Activity of 0.332 µCi/m^2 12 hours after deposition would indicate that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the Early Phase equal to the PAG of 1000 mrem when considering all four of the primary dose pathways.

Table 1.1-E11

Radionuclide	$Dp_{i,t0}$ (µCi/m²)	$WF_{12\,h}$ [a] (unitless)	EP(TD) DRL_{Dp} (µCi/m²)
Co-60	2	0.9997	**3.32E-01**
Gd-148	1	0.9997	**1.66E-01**
Sr-90	3	0.9997	**4.98E-01**
Y-90	3	0.9997	**4.98E-01**
[a] See Appendix F, Supplement 2 for details on calculating WF.			

E1.8 Calculating DRLs for an Individual Organ

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

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EXAMPLE 2

Problem: Calculate the Total Effective Dose Deposition DRL for the First-Year Time Phase (12-8772 hours) for the Following Mixture for an Evaluation Time (t_n) of 12 hours including only the two ground pathways from the list of primary pathways.

Table 1.1-E12

Radionuclide	Deposition (μCi/m^2)
Co-60	2
Gd-148	1
Sr-90	3
Y-90	3
[a] Y-90 included as a daughter at equilibrium.	

To determine the DRL_{Dp}, the following intermediate terms are needed:

Dp_ExDP = Deposition External Dose Parameter for each radionuclide (mrem)

Dp_InhDP = Deposition Inhalation Dose Parameter for each radionuclide (mrem)

TDP = Total Dose Parameter for each radionuclide (mrem)

The TDP for each radionuclide are then added to calculate the Mixture Total Dose Parameter (MTDP).

E2.1 Calculating Dp_InhDP (Equation 1.1-6)

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

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

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

$$KP_{^{60}Co} = 2\frac{\mu\text{Ci}}{\text{m}^2} * \left[\frac{1.05\text{E-}05 * (e^{(-3.16\text{E+}07*(4.17\text{E-}09+8.1\text{E-}07))} - e^{(-4.32\text{E+}04*(4.17\text{E-}09+8.1\text{E-}07))}}{-(4.17\text{E-}09 + 8.1\text{E-}07)} + \frac{7.0\text{E-}09 * \left(e^{(-3.16\text{E+}07*(4.17\text{E-}09+2.31\text{E-}08))} - e^{(-4.32\text{E+}04*(4.17\text{E-}09+2.31\text{E-}08))}\right)}{-(4.17\text{E-}09 + 2.31\text{E-}08)} + \frac{1.0\text{E-}09 * (e^{(-3.16\text{E+}07*(4.17\text{E-}09))} - e^{(-4.32\text{E+}04*(4.17\text{E-}09))}}{-(4.17\text{E-}09)} \right] \frac{\text{s}}{\text{m}}$$

$$= 2.41\text{E+}01 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3}$$

Table 1.1-E13

Radionuclide	Deposition (μCi/m^2)	λ_i [a] (s^{-1})	t_1 (s)	t_2 (s)	KP_i – First Year (μCi•s/m^3)
Co-60	2	4.17E-09	4.32E+04	3.16E+07	2.41E+01 [b]
Gd-148	1	2.94E-10	4.32E+04	3.16E+07	1.21E+01 [b]
Sr-90	3	7.63E-10	4.32E+04	3.16E+07	3.63E+01 [b]
Y-90	3	7.63E-10 [c]	4.32E+04	3.16E+07	3.63E+01 [d]

[a] Values from DCFPAK 3.0.
[b] Values approximated using equations in Appendix F, Supplement 2.
[c] Parent decay constant used for daughter at equilibrium.
[d] Value from Turbo FRMAC 2020©. Calculations for daughters are more complicated than can be readily discussed here. See Appendix F, Supplements 1 and 2 for more information.

E2.1.2 Calculating the Dp_InhDP

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

$$Dp\_InhDP_{^{60}Co} = 3.77\text{E+}01 \frac{\text{mrem}}{\mu\text{Ci}} * 2.41\text{E+}01 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * 2.56\text{E-}04 \frac{\text{m}^3}{\text{s}} = 2.32\text{E-}01 \text{ mrem}$$

Table 1.1-E14

Radionuclide	InhDC [a] (mrem/µCi)	KP_i – First Year (µCi•s/m^3)	Breathing Rate (Activity-averaged) [b] (m^3/s)	Dp_InhDP First Year (mrem)
Co-60	3.77E+01	2.41E+01	2.56E-04	**2.32E-01**
Gd-148	4.26E+04	1.21E+01	2.56E-04	**1.32E+02**
Sr-90	1.32E+02	3.63E+01	2.56E-04	**1.23**
Y-90	5.14E+00	3.63E+01 [c]	2.56E-04	**4.77E-02**

[a] Value from DCFPAK 3.0 (ICRP 60+) for 1 micron particles. If particle size is known to be other than 1 micron, choose appropriate value.
[b] Standard activity-averaged breathing rate.
[c] Value from Turbo FRMAC 2020©.

E2.2 Calculating Dp_ExDP (Equation 1.1-7)

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

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

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

$$WP_{^{60}Co} = 2\frac{\mu\text{Ci}}{\text{m}^2} * \left[\begin{array}{c} \dfrac{0.4 * \left(e^{(-3.16\text{E+07}*(4.17\text{E-09}+1.46\text{E-08}))} - e^{(-4.32\text{E+04}*(4.17\text{E-09}+1.46\text{E-08}))}\right)}{-(4.17\text{E-09} + 1.46\text{E-08})} \\ + \dfrac{0.6 * \left(e^{(-3.16\text{E+07}*(4.17\text{E-09}+4.44\text{E-10}))} - e^{(-4.32\text{E+04}*(4.17\text{E-09}+4.44\text{E-10}))}\right)}{-(4.17\text{E-09} + 4.44\text{E-10})} \end{array}\right] s$$

$$= 5.42\text{E+07}\frac{\mu\text{Ci} \cdot \text{s}}{\text{m}^2}$$

Table 1.1-E15

Radionuclide	Deposition (μCi/m^2)	λ_i [a] (s^{-1})	t_1 (s)	t_2 (s)	WP_i – First Year (μCi•s/m^2)
Co-60	2	4.17E-09	4.32E+04	3.16E+07	5.42E+07 [b]
Gd-148	1	2.94E-10	4.32E+04	3.16E+07	2.88E+07 [b]
Sr-90	3	7.63E-10	4.32E+04	3.16E+07	8.57E+07 [b]
Y-90	3	7.63E-10 [c]	4.32E+04	3.16E+07	8.57E+07 [d]

[a] Values from DCFPAK 3.0.
[b] Values approximated using equations in Appendix F, Supplement 2.
[c] Parent decay constant used for daughter at equilibrium.
[d] Value from Turbo FRMAC 2020©. Calculations for daughters are more complicated than can be readily discussed here. See Appendix F, Supplements 1 and 2 for more information.

E2.2.2 Calculating the Dp_ExDP

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

$$Dp\_ExDP_{^{60}Co} = 8.51\text{E}-06\,\frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}\cdot\text{s}} * 0.82 * 5.42\text{E+07}\,\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^2} = 3.78\text{E+02 mrem}$$

Table 1.1-E16

Radionuclide	Dp_ExDC [a] (mrem•m^2/s•μCi)	GRF (unitless)	WP_i First Year (μCi•s/m^2)	Dp_ExDP First Year (mrem)
Co-60	8.51E-06	0.82	5.42E+07	**3.78E+02**
Gd-148	0	0.82	2.88E+07	**0**
Sr-90	6.07E-09	0.82	8.57E+07	**4.26E-01**
Y-90	4.07E-07	0.82	8.57E+07 [b]	**2.86E+01**

[a] Values from DCFPAK 3.0 (ICRP 60+).
[b] Value from Turbo FRMAC 2020©.

E2.3 Calculating TDP (Eq. 1.1-3)

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

$$TDP_{^{60}Co} = 2.32\text{E-01 mrem} + 3.78\text{E+02 mrem} = 3.79\text{E+02 mrem}$$

Table 1.1-E17

Radionuclide	Dp_InhDP First Year (mrem)	Dp_ExDP First Year (mrem)	TDP First Year (mrem)
Co-60	2.32E-01	3.78E+02	**3.79E+02**
Gd-148	1.32E+02	0	**1.32E+02**
Sr-90	1.23	4.26E-01	**1.65**
Y-90	4.77E-02	2.86E+01	**2.86E+01**

E2.4 Calculating MTDP (Equation 1.1-8)

The Mixture Total Dose Parameter (MTDP) includes the dose contributions from the selected primary dose pathways for the radionuclide mixture, and is calculated by summing the TDP for all radionuclides in the mixture.

Table 1.1-E18

Radionuclide	TDP First Year (mrem)
Co-60	3.79E+02
Gd-148	1.32E+02
Sr-90	1.65
Y-90	2.86E+01
MTDP =	**5.41E+02**

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

Example DRL_{Dp} calculation for Co-60 and DRL_{Dp} values for the radionuclide mixture for the first-year time phase with an Evaluation Time (t_n) of 12 hours.

PAG = 2000 mrem
MTDP = 5.41E+02 mrem

$$DRL_{Dp_{60_{Co}}} = \frac{2000\text{ mrem} * \left(2\,\frac{\mu\text{Ci}}{\text{m}^2} * e^{-4.17\text{E-}09*(12*3600)}\right) * 0.9997}{5.41\text{E+}02\text{ mrem}} = 7.39\,\frac{\mu\text{Ci}}{\text{m}^2}$$

This means that a Co-60 Areal Activity of 7.39 µCi/m^2 12 hours after deposition would indicate that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the First Year equal to the PAG of 2000 mrem when considering only the two ground primary dose pathways.

Table 1.1-E19

Radionuclide	$Dp_{i,t0}$ (µCi/m^2)	WF_{tn} (unitless)	First Year DRL_{Dp} (µCi/m^2)
Co-60	2	0.9997	**7.39**
Gd-148	1	0.9997	**3.70**
Sr-90	3	0.9997	**11.1**
Y-90	3	0.9997	**11.1**
[a] See Appendix F, Supplement 2 for details on calculating WF.			

E2.6 Calculating DRLs for an Individual Organ

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

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

Application

This method has been developed to calculate Dose Rate DRLs and Exposure Rate DRLs for assessments of a radionuclide mixture.

The Dose Rate DRLs represent the external dose rate (mrem/h, measured at one meter above the ground) at a specific Evaluation Time (t_n), from *all radionuclides* in a release that would produce a dose equal to the Protective Action Guide (PAG) over the time phase under consideration.

The Exposure Rate DRLs represent the external exposure rate (mR/h, measured at one meter above the ground) at a specific Evaluation Time (t_n), from *all radionuclides* in a release that would produce a dose equal to the Protective Action Guide (PAG) over the time phase under consideration.

All DRLs derived in this Method are:

1) Derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA17), the Department of Homeland Security (DHS) (DHS08) or local Decision Makers. A projected or measured value greater than the DRL indicates the potential to exceed the PAG.

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

3) Calculated using the appropriate Mixture Total Dose Parameter value from Method 1.1.

Discussion

The DRL_{DR} and DRL_{XR}:

1) Represent the external dose (or exposure) rate at which the total dose from *all radionuclides* in a release from the pathways included in the assessment would equal the PAG over the time phase under consideration.

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

Assumptions

The following assumptions apply in addition to the Default Assumptions:

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

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

Inputs

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

Mixture Total Dose Parameter (MTDP) – Calculated using Method 1.1, Section 1.2.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

Outputs

Final

The final output of this method is the DRL_{DR} or DRL_{XR} for a release of radioactive material.

DRL_{DR} = Dose Rate Derived Response Level, the external dose rate one meter above the ground, at time t_n, at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), mrem/h.

DRL_{XR} = Exposure Rate Derived Response Level, the external exposure rate one meter above the ground, at time t_n, at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), mR/h.

Intermediate

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

Dp_MExDF = Deposition Mixture External Dose Factor for all radionuclides in the mixture of interest (mrem/h)

Method 1.2.1 Dose Rate Derived Response Level (DRL_{DR}) Calculation

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

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

Prior to calculating a DRL, it is necessary for the assessor to determine which of the four primary pathways are applicable for the calculation. The DRLs are then calculated based on the dose from the mixture for the selected pathways.

1.2.1.1 Calculating the Dose Rate DRL

Equation 1.2-1 shows the final form of the DRL_{DR} calculation.

$$DRL_{DR,t_n,TP} = PAG_{TP} * \frac{Dp\_MExDF_{t_n}}{MTDP_{TP}} \quad \text{(Eq. 1.2-1)}$$

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

where:

$DRL_{DR, tn, TP}$ = Dose Rate Derived Response Level, the external dose rate one meter above the ground, at time t_n, at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), mrem/h;

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

Dp_MExDF_{tn} = Deposition Mixture External Dose Factor, the external dose rate one meter above the ground at time t_n from a radionuclide mixture deposited on the ground, mrem/h; and

$MTDP_{TP}$ = Mixture Total Dose Parameter, the sum of the doses from *all radionuclides* in a release, over the time phase under consideration (*TP*), from the pathways included in the assessment, mrem. (See Method 1.1)

1.2.1.2 Calculating the Deposition Mixture External Dose Factor

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

$$Dp\_MExDF_{t_n} = WF_{t_n} * GRF * \sum_i (Dp_{i,t_n} * Dp\_ExDC_i) \qquad \text{(Eq. 1.2-2)}$$

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

where:

Dp_MExDF_{tn} = Deposition Mixture External Dose Factor, the external dose rate one meter above the ground at time t_n from a radionuclide mixture deposited on the ground, mrem/h;

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

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

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

$Dp_{i,tn}$ = Deposition, the areal activity of radionuclide *i* at time t_n, µCi/m^2; and

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

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

Dp_ExDC_i = Deposition External Dose Coefficient, the external dose rate from radionuclide *i* per unit activity deposited on the ground, mrem•m^2/µCi•h.

1.2.1.4 Comparing the Dp_MExDF to the PAG to Calculate DRLs

The Dp_MExDF for the mixture at a specific time can be used to determine the Dose Rate DRL by comparing it to the PAG and the appropriate Mixture Total Dose Parameter (MTDP from Method 1.1) value using the following equation.

$$DRL_{DR,t_n,TP} = PAG_{TP} * \frac{Dp\_MExDF_{t_n}}{MTDP_{TP}} \quad \text{(Eq. 1.2-1)}$$

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

where:

$DRL_{DR,\ tn,\ TP}$ = Dose Rate Derived Response Level, the external dose rate one meter above the ground, at time t_n, at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), mrem/h;

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

Dp_MExDF_{tn} = Deposition Mixture External Dose Factor, the external dose rate one meter above the ground at time t_n from a radionuclide mixture deposited on the ground, mrem/h; and

$MTDP_{TP}$ = Mixture Total Dose Parameter, the sum of the doses from *all radionuclides* in a release, over the time phase under consideration (*TP*), from the pathways included in the assessment, mrem. (See Method 1.1)

Method 1.2.2 Exposure Rate Derived Response Levels (DRL_{XR})

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

$$DRL_{XR,t_n,TP} = \frac{DRL_{DR,t_n,TP}}{XDCF} \quad \text{(Eq. 1.2-3)}$$

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

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EXAMPLE 1

Problem: Calculate the Total Effective Dose, Dose Rate DRL for the Early Phase (Total Dose) Time Phase (0-96 hours) for the Following Mixture for an Evaluation Time (t_n) of 12 hours including the dose from all four primary pathways.

Table 1.2-E1

Radionuclide	Deposition (μCi/m²)
Co-60	2
Gd-148	1
Sr-90	3
Y-90 [a]	3
[a] Y-90 included as a daughter at equilibrium.	

To determine the DRL_{DR}, the intermediate term for the Deposition Mixture External Dose Factor (Dp_MExDF) must first be calculated.

E1.1 Calculating Dp_MExDF (Equation 1.2-2)

This calculation multiplies the Deposition External Dose Coefficient (Dp_ExDC) and the Ground Roughness Factor (GRF) by the time-adjusted areal activity (Dp_i) for each radionuclide in the mixture and sums these products.

Table 1.2-E2

Radionuclide	$Dp_{i,0}$ (μCi/m²)	$WF_{12\ h}$ [a] (unitless)	Dp_ExDC [b] (mrem•m²) per (μCi•h)	GRF (unitless)	$Dp_{i,tn}$ x WF x Dp_ExDC x GRF (mrem/h)
Co-60	2	0.9997	3.06E-02	0.82	5.02E-02
Gd-148	1	0.9997	0	0.82	0
Sr-90	3	0.9997	2.19E-05	0.82	5.37E-05
Y-90	3	0.9997	1.47E-03	0.82	3.60E-03
				Dp_MExDF	5.39E-02

[a] See Appendix F, Supplement 2 for details on calculating WF.
[b] Values from DCFPAK 3.0 (ICRP 60+).

E1.2 Calculating DRL_{DR} (Equation 1.2-1)

DRL_{DR} calculation for the radionuclide mixture for the Early Phase (Total Dose) Time Phase with an Evaluation Time (t_n) of 12 hours.

Organ of Interest: Whole Body

PAG: 1000 mrem

MTDP: 6.02E+03 mrem (from Method 1.1, Example 1, Table 1.1-E9)

$$\mathrm{DRL_{DR}} = \frac{1000\ \mathrm{mrem} * 5.39\text{E-}02\ \frac{\mathrm{mrem}}{\mathrm{h}}}{6.02\text{E+}03\ \mathrm{mrem}} = 8.95\text{E-}03\,\frac{\mathrm{mrem}}{\mathrm{h}}$$

This means that a dose rate of 8.95E-03 mrem/h 12 hours after deposition indicates that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the Early Phase equal to the PAG of 1000 mrem when considering all four of the primary dose pathways.

E1.3 Calculating the 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 DRL_{DR} for a specific organ, the Deposition External Dose Coefficient (Dp_ExDC) must be changed to the organ of interest and then used to calculate a Dp_MExDF for that organ to be compared to an organ-specific dose limit.

EXAMPLE 2

Problem: Calculate the Total Effective Dose, Dose Rate DRL for the First-Year Time Phase (12-8772 hours) for the Following Mixture for an Evaluation Time (t_n) of 12 hours including only the two ground pathways from the list of primary pathways.

Table 1.2-E3

Radionuclide	Deposition (µCi/m^2)
Co-60	2
Gd-148	1
Sr-90	3
Y-90 [a]	3

[a] Y-90 included as a daughter at equilibrium.

To determine the DRL_{DR}, the intermediate term for the Deposition Mixture External Dose Factor (Dp_MExDF) must first be calculated.

E2.1 Calculating Dp_MExDF (Equation 1.2-3)

This calculation multiplies the Deposition External Dose Coefficient (Dp_ExDC) and the Ground Roughness Factor (GRF) by the time-adjusted areal activity (Dp_i) for each radionuclide in the mixture and sums these products.

Table 1.2-E4

Radionuclide	$Dp_{i,0}$ (µCi/m^2)	$WF_{12\ h}$ [a] (unitless)	Dp_ExDC [b] (mrem•m^2) per (µCi•h)	GRF (unitless)	$Dp_{i,tn}$ x WF x Dp_ExDC x GRF (mrem/h)
Co-60	2	0.9997	3.06E-02	0.82	5.02E-02
Gd-148	1	0.9997	0	0.82	0
Sr-90	3	0.9997	2.19E-05	0.82	5.37E-05
Y-90	3	0.9997	1.47E-03	0.82	3.60E-03
				Dp_MExDF	5.39E-02

[a] See Appendix F, Supplement 2 for details on calculating WF.
[b] Values from DCFPAK 3.0 (ICRP 60+).

E2.2 Calculating DRL_{DR} (Equation 1.2-2)

DRL_{DR} calculation for the radionuclide mixture for the first-year time phase with an Evaluation Time (t_n) of 12 hours.

Organ of Interest: Whole Body

PAG: 2000 mrem

MTDP: 5.41E+02 mrem (from Method 1.1, Example 2, Table 1.1-E18)

$$\mathrm{DRL_{DR}} = \frac{2000\ \mathrm{mrem} * 5.39\mathrm{E}\text{-}02\ \frac{\mathrm{mrem}}{\mathrm{h}}}{5.41\mathrm{E}02\ \mathrm{mrem}} = 1.99\mathrm{E}\text{-}01 \frac{\mathrm{mrem}}{\mathrm{h}}$$

This means that a dose rate of 0.199 mrem/h 12 hours after deposition indicates that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the First Year equal to the PAG of 2000 mrem when considering only the two ground primary dose pathways.

E2.3 Calculating the 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 DRL_{DR} for a specific organ, the Deposition External Dose Coefficient (Dp_ExDC) must be changed to the organ of interest and then used to calculate a Dp_MExDF for that organ to be compared to an organ-specific dose limit.

METHOD 1.3 ALPHA DERIVED RESPONSE LEVEL

Application

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

The $DRL_{\alpha,\tilde{A}}$:

1) Represents the integrated air alpha activity ($\mu Ci_{\alpha} \cdot s/m^3$), present in a release at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration.

2) Is calculated using the Integrated Air Derived Response Level calculated in Method 1.1, Section 1.3.1.

The $DRL_{\alpha,Dp,tn}$:

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

2) Is calculated using the Deposition Derived Response Level value calculated in Method 1.1, Section 1.3.2.

All DRLs developed in this Method are:

1) Derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA17), the Department of Homeland Security (DHS) (DHS08) or local Decision Makers. A projected or measured value greater than the DRL indicates the potential to exceed the PAG.

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

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

Discussion

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

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

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

Monitoring must account for the above factors when using the calculated Alpha DRL.

Assumptions

The following assumptions apply in addition to the Default Assumptions:

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

Inputs

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

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

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

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

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

Outputs

Final

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

$DRL_{\alpha,\tilde{A}}$ = Air Alpha Derived Response Level, the integrated air alpha activity of the mixture at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration *(TP)*, $\mu Ci_{\alpha} \bullet s/m^3$.

$DRL_{\alpha,Dp,tn}$ = Deposition Alpha Derived Response Level, the areal alpha activity of the mixture, at time t_n, of the mixture at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration *(TP)*, $\mu Ci_{\alpha}/m^2$.

Intermediate

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

None

Method 1.3.1 Air Alpha Derived Response Level ($DRL_{\alpha,\tilde{A}}$)

Calculation

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

$$DRL_{\alpha,\tilde{A},TP} = \sum_i (DRL_{\tilde{A},i,TP} * Y_{\alpha,i}) \qquad \text{(Eq. 1.3-1)}$$

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

where:

$DRL_{\alpha,\tilde{A},TP}$ = Air Alpha Derived Response Level, the integrated air alpha activity of the mixture at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), $\mu Ci_{\alpha} \cdot s/m^3$;

$DRL_{\tilde{A}, i, TP}$ = Integrated Air Derived Response Level, the integrated air activity ($\tilde{A}$) of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), $\mu Ci \cdot s/m^3$; and

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

Method 1.3.2 Deposition Alpha Derived Response Level ($DRL_{\alpha,Dp}$)

Calculation

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

$$DRL_{\alpha,Dp,t_n,TP} = \sum_i (DRL_{Dp,i,t_n,TP} * \ Y_{\alpha,i}) \qquad \text{(Eq. 1.3-2)}$$

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

where:

$DRL_{\alpha,Dp,tn,\, TP}$ = Deposition Alpha Derived Response Level, the areal alpha activity of the mixture, at time t_n, at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), $\mu Ci_{\alpha}/m^2$;

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

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

EXAMPLE 1

Problem: Calculate the Total Effective Dose Air Alpha DRL for the Early Phase (Total Dose) Time Phase (0-96 hours) for the Following Mixture for an Evaluation Time (t_n) of 12 hours including the dose from all four primary pathways.

Table 1.3-E1

Radionuclide	Integrated Air Activity (μCi•s/m³)	Deposition (μCi/m²)
Co-60	6.67E+02	2
Gd-148	3.33E+02	1
Sr-90	1.0E+03	3
Y-90	1.0E+03	3
[a] Y-90 included as a daughter at equilibrium.		

This calculation requires the Integrated Air Derived Response Level ($DRL_{\tilde{A}}$) for each radionuclide from the mixture for the early phase. Table 1.3-E2 shows the values calculated using Method 1.1.

Table 1.3-E2

Radionuclide	Integrated Air Activity (μCi•s/m³)	Alpha Yield	Early Phase (Total Dose) $DRL_{\tilde{A}}$ (μCi•s/m³)
Co-60	6.67E+02	0	1.11E+02
Gd-148	3.33E+02	1	5.53E+01
Sr-90	1.0E+03	0	1.66E+02
Y-90	1.0E+03	0	1.66E+02

Applying these values in equation 1.3-1 yields:

$$DRL_{\alpha,\tilde{A}} = \left(5.53\text{E}+01 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * 1 \frac{\mu\text{Ci}_\alpha}{\mu\text{Ci}}\right)$$

$$= 5.53\text{E+}01 \frac{\mu\text{Ci}_\alpha\cdot\text{s}}{\text{m}^3}$$

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

This means that a total Alpha Integrated Air Activity of 55.3 μCi•s/m^3 would indicate that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the Early Phase equal to the PAG of 1000 mrem when considering all four of the primary dose pathways.

EXAMPLE 2

Problem: Calculate the Total Effective Dose Deposition Alpha DRL for the First-Year Time Phase (12-8772 hours) for the Following Mixture for an Evaluation Time (t_n) of 12 hours including only the two ground pathways from the list of primary pathways.

Table 1.3-E3

Radionuclide	Deposition (µCi/m²)
Co-60	2
Gd-148	1
Sr-90	3
Y-90	3

[a] Y-90 included as a daughter at equilibrium.

This calculation requires the Deposition Derived Response Level (DRL_{Dp}) for each radionuclide from the mixture for the first year. Table 1.3-E4 shows the values calculated using Method 1.1.

Table 1.3-E4

Radionuclide	Deposition (µCi/m²)	Alpha Yield	First Year DRL_{Dp} (µCi/m²)
Co-60	2	0	7.39
Gd-148	1	1	3.70
Sr-90	3	0	1.11E+01
Y-90	3	0	1.11E+01

Applying these values in equation 1.3-3 yields:

$$DRL_{\alpha,Dp} = \left(3.70\,\frac{\mu\text{Ci}}{\text{m}^2} * 1\,\frac{\mu\text{Ci}_\alpha}{\mu\text{Ci}}\right)$$

$$= 3.70\,\frac{\mu\text{Ci}_\alpha}{\text{m}^3}$$

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

This means that a total Alpha Areal Activity of 3.70 µCi/m^2 12 hours after deposition would indicate that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the First Year equal to the PAG of 2000 mrem when considering only the two ground primary dose pathways.

METHOD 1.4 BETA DERIVED RESPONSE LEVEL

Application

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

The $DRL_{\beta,\tilde{A}}$:

1) Represents the integrated air beta activity ($\mu Ci_{\beta}\bullet s/m^3$), present in a release at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration.

2) Is calculated using the Air Activity Derived Response Level calculated in Method 1.1, Section 1.3.1.

The $DRL_{\beta,Dp,tn}$:

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

2) Is calculated using the Deposition Derived Response Level value calculated in Method 1.1, Section 1.3.2.

All DRLs developed in this Method are:

1) Derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA17), the Department of Homeland Security (DHS) (DHS08) or local Decision Makers. A projected or measured value greater than the DRL indicates the potential to exceed the PAG.

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

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

Discussion

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

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

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

Monitoring must account for the above factors when using the calculated Beta DRL.

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

Assumptions

The following assumptions apply in addition to the Default Assumptions:

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

Inputs

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

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

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

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

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

Outputs

Final

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

$DRL_{\beta,\tilde{A}}$ = Air Beta Derived Response Level, the integrated air beta activity of the mixture at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration *(TP)*, $\mu Ci_{\beta}\text{•}s/m^3$.

$DRL_{\beta,Dp,tn}$ = Deposition Beta Derived Response Level, the areal beta activity of the mixture, at time t_n, at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration *(TP)*, $\mu Ci_{\beta}/m^2$.

Intermediate

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

None

Method 1.4.1 Air Beta Derived Response Level ($DRL_{\beta,\tilde{A}}$)

Calculation

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

$$DRL_{\beta,\tilde{A},TP} = \sum_i (DRL_{\tilde{A},i,TP} * Y_{\beta,i}) \quad \text{(Eq. 1.4-1)}$$

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

where:

$DRL_{\beta,\tilde{A},TP}$ = Air Beta Derived Response Level, the integrated air beta activity of the mixture at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), μCi_β•s/m^3.

$DRL_{\tilde{A},i,TP}$ = Integrated Air Derived Response Level, the integrated air activity ($\tilde{A}$) of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), μCi•s/m^3; and

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

Method 1.4.2 Deposition Beta Derived Response Level ($DRL_{\beta,Dp}$)

Calculation

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

$$DRL_{\beta,Dp,t_n,TP} = \sum_i (DRL_{Dp,i,t_n,TP} * Y_{\beta,i}) \quad \text{(Eq. 1.4-2)}$$

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

where:

$DRL_{\beta,Dp,tn,TP}$ = Deposition Beta Derived Response Level, the areal beta activity of the mixture, at time t_n, at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), μCi_β/m^2;

$DRL_{Dp,i,tn,TP}$ = Deposition Derived Response Level, the areal activity, at time t_n, of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), μCi_{nt}/m^2; and

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

Example 1

Problem: Calculate the Total Effective Dose Air Beta DRL for the Early Phase (Total Dose) Time Phase (0-96 hours) for the Following Mixture for an Evaluation Time (t_n) of 12 hours including the dose from all four primary pathways.

Table 1.4-E1

Radionuclide	Integrated Air Activity (µCi•s/m³)	Deposition (µCi/m²)
Co-60	6.67E+02	2
Gd-148	3.33E+02	1
Sr-90	1.0E+03	3
Y-90	1.0E+03	3
[a] Y-90 included as a daughter at equilibrium.		

This calculation requires the Integrated Air Derived Response Level ($DRL_{\tilde{A}}$) for each radionuclide from the mixture for the early phase. Table 1.4-E2 shows the values calculated using Method 1.1.

Table 1.4-E2

Radionuclide	Integrated Air Activity (µCi•s/m³)	Beta Yield	Early Phase (Total Dose) $DRL_{\tilde{A}}$ (µCi•s/m³)
Co-60	6.67E+02	1	1.11E+02
Gd-148	3.33E+02	0	5.53E+01
Sr-90	1.0E+03	1	1.66E+02
Y-90	1.0E+03	1	1.66E+02

Applying these values in equation 1.4-1 yields:

$$DRL_{\beta,\tilde{A}} = \left(1.11\text{E+}02\,\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * 1\,\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}}\right) + \left(1.66\text{E+}02\,\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * 1\,\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}}\right) + \left(1.66\text{E+}02\,\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * 1\,\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}}\right)$$

$$= 4.43\text{E+}02\,\frac{\mu\text{Ci}_\beta\cdot\text{s}}{\text{m}^3}$$

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

This means that a total Beta Integrated Air Activity of 443 µCi•s/m³ would indicate that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the Early Phase equal to the PAG of 1000 mrem when considering all four of the primary dose pathways.

EXAMPLE 2

Problem: Calculate the Total Effective Dose Deposition Beta DRL for the First-Year Time Phase (12-8772 hours) for the Following Mixture for an Evaluation Time (t_n) of 12 hours including only the two ground pathways from the list of primary pathways.

Table 1.4-E3

Radionuclide	Deposition (µCi/m²)
Co-60	2
Gd-148	1
Sr-90	3
Y-90	3
[a] Y-90 included as a daughter at equilibrium.	

This calculation requires the Deposition Derived Response Level (DRL_{Dp}) for each radionuclide from the mixture for the first year. Table 1.4-E4 shows the values calculated using Method 1.1.

Table 1.4-E4

Radionuclide	Deposition (µCi/m²)	Beta Yield	First Year DRL_{Dp} (µCi•s/m³)
Co-60	2	1	7.39
Gd-148	1	0	3.70
Sr-90	3	1	1.11E+01
Y-90	3	1	1.11E+01

Applying these values in equation 1.4-3 yields:

$$DRL_{\beta,Dp} = \left(7.39\,\frac{\mu\text{Ci}}{\text{m}^2} * 1\,\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}}\right) + \left(1.11\text{E+01}\,\frac{\mu\text{Ci}}{\text{m}^2} * 1\,\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}}\right) + \left(1.11\text{E+01}\,\frac{\mu\text{Ci}}{\text{m}^2} * 1\,\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}}\right)$$

$$= 2.96\text{E+01}\,\frac{\mu\text{Ci}_\beta}{\text{m}^2}$$

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

This means that a total Beta Areal Activity of 29.6 µCi/m² 12 hours after deposition would indicate that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the First Year equal to the PAG of 2000 mrem when considering only the two ground primary dose pathways.

METHOD 1.5 PROJECTED PUBLIC DOSE

Application

This method has been developed to calculate the dose received by members of the public from exposure to a release of radioactive material. The dose can be calculated using any combination of the four primary dose pathways. Projected Public Doses may be calculated either from sample data showing the radionuclide mixture or a field dose rate measurement in comparison to the Dose Rate DRL.

The PPD:

1) Uses a measured integrated air activity and a measured ground deposition of a radionuclide, or a measured dose rate to calculate the dose that a receptor is projected to receive over a specified time phase due to the passage of a plume and the material deposited on the ground by the plume.
2) Is calculated from the:
   a. Plume Inhalation Dose Parameter (Pl_InhDP), the Plume External Dose Parameter (Pl_ExDP), the Deposition Inhalation Dose Parameter (Dp_InhDP), and the Deposition External Dose Parameter (Dp_ExDP) values calculated in Method 1.1, or
   b. Dose Rate Derived Response Level (DRL_{DR}) value calculated in Method 1.2.

PPDs are:

1) Compared to Protective Action Guides (PAGs) for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA17), the Department of Homeland Security (DHS) (DHS08) or local Decision Makers.
2) Used to create data products and define dose levels to help Decision Makers determine where protective actions (e.g., sheltering, evacuation, relocation) may be warranted.

Discussion

The Projected Public Dose (PPD) includes the dose contributions from the selected dose pathways, and is calculated by:

1) Summing appropriate pathway Dose Parameters for each radionuclide in the mixture.

or

2) Comparing a measured dose rate (mrem/h) to the calculated DRL_{DR} for a mixture. Because the DRL_{DR} is determined using a PAG, the ratio of the measured value to the appropriate DRL can be used to calculate a projected dose relative to the PAG.

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

Assumptions

There are no additional assumptions beyond the Default Assumptions above.

Inputs

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

1) Plume Inhalation Dose Parameter (Pl_InhDP), the Plume External Dose Parameter (Pl_ExDP), the Deposition Inhalation Dose Parameter (Dp_InhDP), and the Deposition External Dose Parameter (Dp_ExDP) for each radionuclide, calculated using Method 1.1.

or

2) Dose Rate DRLs (DRL_{DR}) for the mixture, calculated using Method 1.2.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

Outputs

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

Final

PPD_{TP} = Projected Public Dose, the sum of the doses of the selected dose pathways, over the time phase under consideration *(TP)*, from the radionuclide mixture, mrem

Intermediate

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

None

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

Calculation

Calculating the Projected Public Dose

The Projected Public Dose (PPD) includes the dose contributions from the plume-borne and ground-deposited radionuclide mixture, and is calculated by summing the appropriate pathway Dose Parameters for the selected dose pathways for each radionuclide in the mixture.

$$PPD_{TP} = \sum_i \begin{pmatrix} Pl\_InhDP_{i,TP} + Pl\_ExDP_{i,TP} \\ +Dp\_InhDP_{i,TP} + Dp\_ExDP_{i,TP} \end{pmatrix} \quad \text{(Eq. 1.5-1)}$$

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

where:

PPD_{TP} = Projected Public Dose, the sum of the doses of the selected dose pathways, over the time phase under consideration (TP), from the radionuclide mixture, mrem;

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

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

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

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

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

Calculation

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

Calculating the Projected Public Dose

$$\frac{ExDR_{t_n}}{DRL_{DR,t_n,TP}} = \frac{PPD_{TP}}{PAG_{TP}} \qquad \text{(Eq. 1.5-3a)}$$

Solving for PPD, (Eq. 1.5-3a) can be rewritten as:

$$PPD_{TP} = \frac{ExDR_{t_n} * PAG_{TP}}{DRL_{DR,t_n,TP}} \qquad \text{(Eq. 1.5-3b)}$$

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

where:

PPD_{TP} = Projected Public Dose, the sum of the doses of the selected dose pathways, over the time phase under consideration (TP), from the radionuclide mixture, mrem;

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

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

$DRL_{DR,\, tn,TP}$ = Dose Rate Derived Response Level, the external dose rate, at time t_n, at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), mrem/h.

EXAMPLE 1

Problem: Calculate the Projected Public Total Effective Dose for the Early Phase (Total Dose) Time Phase (0-96 hours) for the Following Mixture including the dose from all four primary pathways.

Table 1.5-E1

Radionuclide	Integrated Air Activity (μCi•s/m^3)	Deposition (μCi/m^2)
Co-60	6.67E+02	2
Gd-148	3.33E+02	1
Sr-90	1.0E+03	3
Y-90 [a]	1.0E+03	3

[a] Y-90 included as a daughter at equilibrium.

E1.1 Calculating PPD (Equation 1.5-1)

This calculation requires the Plume Inhalation Dose Parameter (Pl_InhDP), the Plume External Dose Parameter (Pl_ExDP), the Deposition Inhalation Dose Parameter (Dp_InhDP), and the Deposition External Dose Parameter (Dp_ExDP) for each radionuclide in the mixture. Table 1.5-E2 shows the values calculated in Method 1.1 (Table 1.1-E8) for the Early Phase.

Table 1.5-E2

Radionuclide	Pl_InhDP (mrem)	Pl_ExDP (mrem)	Dp_InhDP EP(TD) (mrem)	Dp_ExDP EP(TD) (mrem)
Co-60	1.05E+01	2.93E-01	5.82E-02	4.81E+00
Gd-148	5.92E+03	0.00E+00	3.29E+01	0.00E+00
Sr-90	5.50E+01	3.64E-04	3.06E-01	5.15E-03
Y-90	2.14E+00	2.93E-03	1.19E-02	3.47E-01

Summing the values from this table, Equation 1.5-1 results in a PPD of: 6.02E+03 mrem.

This means that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the Early Phase equal to 6.02E+03 mrem when considering all four of the primary dose pathways.

E1.2 Calculating a PPD for an Individual Organ

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

EXAMPLE 2

Problem: Calculate the Dose Rate Projected Public Dose for the First-Year Time Phase (12-8772 hours) for the Following Mixture for an Evaluation Time (t_n) of 12 hours including only the two ground pathways from the list of primary pathways. Assume the dose rate measurement was 5 mrem/h at 12 hours.

Table 1.5-E3

Radionuclide	Deposition ($\mu Ci/m^2$)
Co-60	2
Gd-148	1
Sr-90	3
Y-90 [a]	3

[a] Y-90 included as a daughter at equilibrium.

E2.1 Calculating PPD_{TP} (Equation 1.5-3b)

This calculation requires the Dose Rate DRL for the time (t_n) at which the measurement ($ExDR_{tn}$) was taken.

Organ of Interest: Whole Body

PAG: 2000 mrem

DRL_{DR} at 12 hours: 1.99E-01 mrem/h (from Method 1.2, Example 2, Section E2.2)

Applying these values to Equation 1.5-3b yields:

$$PPD_{TP} = \frac{5\,\frac{\text{mrem}}{\text{h}} * 2000\text{ mrem}}{1.99\text{E}-01\,\frac{\text{mrem}}{\text{h}}} = 5.02\text{E+04 mrem}$$

This means that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the First Year equal to 5.02E+04 mrem when considering only the two ground primary dose pathways.

E2.2 Calculating a PPD for an Individual Organ

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

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METHOD 1.6 PUBLIC SKIN DOSE

This method is reserved for future development.

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METHOD 1.7 ASSESSING NUCLEAR DETONATIONS

Application

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

The NF_DRL:

1) Represents the external dose rate (mrem/h, measured at 1 m above the ground) at a given time (t_n), at which the external dose from *all radionuclides* in a fallout deposition mixture may equal the appropriate Protective Action Guide (PAG) over the time phase under consideration.

2) Is derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA17) or the Department of Homeland Security (DHS) (DHS08). A projected or measured value greater than the NF_DRL indicates the potential to exceed the PAG.

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

4) Should only be used until the fallout mixture has been characterized. After radionuclide activities have been quantified, the other Methods in Section 1 should be used for Assessment.

Discussion

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

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

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

Assumptions

1) Prompt radiation (e.g., neutron, gamma) is NOT included in this method.

2) Doses and NF_DRLs are based on external gamma exposure only. Assume one rad external dose is equivalent to one rem.

3) During the time from 0.5 to 5,000 hours, the decay of fallout activity at a given location may be approximated by Equation 1.7-1 (Gl77):

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

where:

t = Time after detonation, h;

$ExDR_t$ = External dose rate at time t, mrem/h;

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

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

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

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

Inputs

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

Power Function Exponent (x) – Default of 1.2.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

Outputs

Final

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

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

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

Intermediate

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

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

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

Method 1.7.1 Nuclear Fallout Dose

Calculation

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

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

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

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

where:

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

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

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

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

Integrating this equation produces:

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

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

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

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

Method 1.7.2 Nuclear Fallout DRL

Calculation

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

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

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

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

where:

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

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

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

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

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

Integrating this equation produces:

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

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

Solving this equation for *ExDR*$_r$ yields:

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

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

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

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

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

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

where:

t_n = Evaluation Time, the point in time, relative to the start of the release, for which the calculation, measurement, or prediction is valid, h

Therefore the NF_DRL for time t_n in terms of the PAG is:

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

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

Or, for the default value of x = 1.2:

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

Method 1.7.3 Nuclear Fallout Stay Time:

Calculation

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

This is done by solving the dose equation (Equation 1.7-3) for the end of the time phase (t_2), the time interval from t_1 to t_2 is the "stay time" for that individual in the area that would produce a dose equal to an established Dose Limit.

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

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

Solving for t_2:

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

Taking the natural log of both sides:

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

Solving for t_2:

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

Therefore:

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

To obtain the stay time, subtract t_1 from t_2.

Method 1.7.4 Calculating the "power function" exponent (-x):

Calculation

The decay of fission products after a nuclear detonation can be approximated by the power function, t^{-x}. FRMAC uses a default value of 1.2 for the exponent (x) (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:

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

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

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

By the rule of the power function:

$$ExDR_a = ExDR_r * t_a^{-x}$$

and

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

Therefore:

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

and,

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

Taking the natural log of both sides:

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

Solving for -x:

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

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

Calculation

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

Calculating Dose using Equation 1.7-3,

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

when x=1, this is changed to:

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

Calculating NF_DRL using Equation 1.7-7a,

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

when x=1, this is changed to:

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

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

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

when x=1, this is changed to:

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

EXAMPLE 1

Problem: Calculate the NF_DRL for fallout for a time 48 hours after detonation assuming an Early Phase (96 hour) PAG of 100 rad (100 rem) and a start time (*t_1*) of 12 hours after detonation.

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

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

E1.1 Calculating "-x" using Equation 1.7-8e

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

E1.2 Calculating NF_DRL at t_n = 48 hours using Equation 1.7-7a

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

$$NF_{DRL_{48hours}} = 100\ \text{rem} * \left(\frac{-0.21}{108^{-0.21} - 12^{-0.21}}\right) * 48^{-1.21}$$

$$= 0.88\,\frac{\text{rem}}{\text{h}}$$

This means that a Dose Rate measurement of 880 mrem/h 48 hours after deposition would indicate that the entire fallout mixture has the potential to cause a Dose over the 12-108 hour time phase equal to the PAG of 100 rem.

EXAMPLE 2

Problem: Calculate the external dose received from fallout over the 96 hour period beginning 12 hours after detonation.

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

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

The external dose is calculated using equation 1.7-3:

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

x = 1.21 from Example 1,

ExDR_r is calculated using the modified form of Equation 1.7-1:

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

Then:

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

For the 96 hour period beginning <u>1 hour</u> after detonation, the dose would be:

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

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/h, 12 hours after detonation, and
2) 3.6 rem/h, 16 hours after detonation.

x = 1.21 from Example 1,

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

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

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

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

This means that the worker could remain at this location for 2.4 hours before receiving a 5 rem dose.

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SECTION 2. WORKER PROTECTION METHODS

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INTRODUCTION TO WORKER PROTECTION METHODS

These methods describe calculations for establishing the worker Turn-Back Limits (TBL), Stay Times (ST), and Derived Response Levels (DRLs) that are applied by the Health & Safety Division.

The EPA established guidance for workers performing emergency services (EPA17). Table 2-2 summarizes the EPA emergency worker dose guidance in terms of the projected Total Effective Dose (TED). When possible, TBLs, STs, and DRLs should be based on measured and/or projected work area conditions. Limits should be established and updated, as necessary, based on shift- and work area-specific monitoring data.

DRLs and TBLs are similar concepts in that both describe levels at which a Dose Limit (DL) may be exceeded. The distinction between them is described below:

- DRLs are values appropriate for a specific location at a specific time (which may be before the start of the work shift) which indicate whether workers in that location would potentially exceed their DL during their work shift. Workers are assumed to be at that location for their entire work shift. DRLs may be more appropriate for planning work locations and shifts. Atmospheric dispersion models can be used to identify areas where workers can work without exceeding the calculated DRLs.
- TBLs are values that indicate locations that workers should not enter to avoid potentially exceeding their DL during their work shift. Workers may be moving through multiple locations and should not enter areas exceeding their TBL. TBLs may be more appropriate for use by workers during work activities and are designed to be compared to self-reading dosimeters (SRD) and monitoring equipment readings.

NOTE: For the Methods in this section, the term "Time Phase" refers to the work shift under consideration.

Default Assumptions

FRMAC radiological assessment calculations utilize the Default Assumptions established by the FRMAC AWG. Users are urged to use the default assumptions until site-specific values become available through consultations with Health and Safety personnel.

The following Default Assumptions are used in the methods in this section:

1) The dose projections from this section may include contributions from any combination of the four primary exposure pathways:
    - inhalation of radioactive material during plume passage,
    - external exposure (plume submersion) during plume passage,
    - inhalation of resuspended material deposited by the release, and
    - external exposure (groundshine) from material deposited by the release.

2) The plume is assumed to be in contact with the ground, so that the receptor is in the plume. If plume dose pathways are included, the receptor is assumed to be exposed to the entire plume.
3) Because the temporal deposition of plume-borne radioactive material cannot be inferred from air sample data, any material deposited by plume passage is assumed to be immediately and completely deposited at the beginning of the passage of the plume.
4) Noble Gas Dose Projections:

   Radionuclides that are noble gases when initially released to the air:

   a. are assumed to remain as gases during meteorological transport, even if they decay into a particulate daughter during transport,

   b. are included in the external dose assessment from submersion in a plume,

   c. do not contribute to inhalation dose because they are not assigned an inhalation dose coefficient, and

   d. **are not** deposited on the ground and **are not** included in ground pathway assessment calculations.

   NOTE: Noble gases that are daughters of ground-deposited radionuclides **are** assumed to remain on the ground and are included in ground pathway assessment calculations.
5) The effects of radioactive decay, weathering and resuspension are included in the calculations.
6) All deposition is assumed to be dry particulates. Wet deposition (increased localized deposition caused by rain or snow) is not included in these methods. (See Method 4.5 for discussion of deposition velocity.)

   NOTE: Certain radionuclides exist in multiple chemical/physical forms (e.g., particulate, vapor, gas). These radionuclides can be partitioned accordingly to more accurately calculate potential doses. See Appendix F, Supplement 4 for a discussion of partitioning and description of Default Assumptions.
7) Dose from ingestion is not included in Worker Protection Methods. If ingestion is a significant dose pathway (i.e., >10% of the total dose), it should be addressed separately and included in protective action decisions. (See Section 3 – Ingestion Methods.)
8) The receptor is:

   a. outside in the contaminated area continuously during the time phase under consideration without any protective measures (e.g., shielding or respiratory protection);

      NOTE: Some Worker Protection calculations may include a Potassium Iodide Protection Factor (KIPF) and/or an Assigned Protection Factor (APF) for respirator use. See Appendix C, Table 6-3 for APFs for various respirators.

   b. an adult;

c. breathing at the Light Exercise Breathing Rate (Adult Male) of 1.5 m^3/h; and

d. inhaling 1-micron Activity Median Aerodynamic Diameter (AMAD) particles in the lung clearance type recommended by the ICRP.

NOTE: This manual uses default Inhalation Dose Coefficients and Deposition Velocities based on the assumed particle size. Assessment Scientists are advised to modify the defaults based on actual particle size information if available.

NOTE: Other lung clearance types may be more appropriate for certain radioactive materials with known physical forms. See Appendix C, Table 12 for more information.

NOTE: Additionally, alternate particle sizes may be appropriate for some RDDs. This information is sensitive and is not addressed in this manual. However, during a response, this information will be provided to individuals with need-to-know through the FRMAC.

9) Decay chains are truncated according to the following rules in order to save computation time without significantly affecting calculated dose (SNL17).

   a. Include the parent radionuclide and first daughter radionuclide, regardless of half-life

   b. Analyze first daughter radionuclide half-life

      i. If first daughter radionuclide half-life is ≥ 5,000 years, truncate the chain (i.e., do not include the remaining radionuclides in the decay chain)

      ii. If first daughter radionuclide half-life is < 5,000 years, include next radionuclide in chain

   c. Analyze second and subsequent daughter half-lives according to Rule b until decay chain is truncated or entire chain has been included

   The dose from the radionuclide after which the decay chain is truncated IS included in the dose projection.

10) Equilibrium rules are applied after truncation. Daughter radionuclides that meet the following rules are considered to be in equilibrium (secular, or transient when branching ratio ≠ 1) at deposition (t = 0) and are assigned the parent's half-life and decay constants for calculations:

   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 years.

11) The Bateman Equations (Ba1910) are used to model the decay and in-growth of all radionuclides. See Appendix F, Supplement 1 for details.

12) FRMAC's Worker Protection Methods generally assume that the organ of interest is the whole body (Total Effective Dose). However, other organs may be evaluated by utilizing the organ-specific Dose Coefficients and dose limits. (See Method 1.1 Example 1, Section E1.8.)

Default Inputs

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

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

1) Data – This information may come from predictive analysis (atmospheric dispersion models) or field data (monitoring and/or samples):

    - Composition of the plume and of the deposited radionuclide mixture (radionuclides and volumetric or areal activity, concentration, activity ratio, or mass ratio); and/or

    - External dose (or exposure) rates.

2) Other Factors:

    - Plume Deposition Velocity;

    - Ground roughness;

    - Weathering; and

    - Decay of radionuclides during the time period under consideration.

3) Constants:

    - Breathing rate (default: Light-Exercise Breathing Rate of 1.5 m^3/h based on the ICRP 60+ lung model);

    - Resuspension (default: 1.0E-05 m^{-1});

      NOTE: This assumes a 10x multiplier. See Table 6-4 in Appendix C for resuspension multipliers for different conditions.

    - Inhalation dose coefficient (defaults from ICRP 60+ dosimetry model);

    - External dose coefficient (defaults from ICRP 60+ dosimetry model);

    - Dose limits (defaults from EPA/DHS guidance); and

    - Exposure to Dose Conversion Factor (default of 1.0 mrem/mR).

4) Time Phase:

    NOTE: For Methods in this section, Time Phase refers to the work shift being evaluated.

- Release Time (t_0) – The time the release begins. This time is usually assumed to correspond to the "Time of Deposition".
- Start Time (t_1) – The start of the Time Phase under consideration.
- End Time (t_2) – The end of the Time Phase under consideration.
- Evaluation Time (t_n) – The point in time, relative to the start of the release, for which the calculation, measurement, or prediction is valid.

FRMAC uses a default Evaluation Time for DRL calculations of 12 hours after the start of the release, allowing atmospheric dispersion models to simulate 12 hours of downwind transport. This was chosen because 12 hours is generally sufficient for complete deposition of a single release to occur so that deposition contours can be plotted on data products.

NOTE: Many of the terms in the methods are dependent on variables (e.g., time phase, target organ, dose limit, 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 WORKER DOSES AND STAY TIMES

Application

This method is used to calculate worker dose estimates and Stay Times (ST) for workers entering a contaminated area, taking into account both inhalation and external hazards present in the work environment.

- The dose represents the Total Dose that a worker may have received, based on a dosimeter reading.
- The Stay Time represents the amount of time that a worker may stay in a given location and not exceed their established Dose Limit (DL) based on an external dose measurement made in the work location.

All quantities developed in this Method are:

- Derived from the emergency worker guidelines established by the Environmental Protection Agency (EPA) (EPA17) or other DLs established for worker protection.
- Calculated from the Dose Parameter values calculated in Method 1.1.

Discussion

This method provides a means to establish emergency worker doses 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) integrated dose (or exposure).

Assumptions

There are no additional assumptions beyond the Default Assumptions above.

Inputs

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

1) Worker DL for the proposed work shift.
2) Dose Parameters for each of the four primary dose pathways for each radionuclide in the mixture, based on the start and end times of the work shift (calculated using Method 1.1).
3) Measurements made in the work location (e.g., Dose Rates, worker Dosimeter readings).

4) Other Factors – Assigned Protection Factor (APF) for respirator use, Potassium Iodide Protection Factor (KIPF).

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

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

Outputs

Final

The final output of this method is the Worker Dose or Stay Time, for a given work shift.

Dose = Worker Dose, the Total Dose that a worker may have received based on a dosimeter reading, mrem.

ST = Worker Stay Time, how long the worker will be allowed to work in the contaminated area, h.

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 ($mrem_{inh+external}/mrem_{external}$)

Calculation

Method 2.1.1 Calculating the Worker Dose

To calculate a worker's dose at any point during the work shift, multiply the current reading on the worker's dosimeter by the ExTDCF for the work shift which is used to convert dosimeter readings measuring External Dose, to the Total Dose to which the worker has been exposed (See Method 2.1.3).

$$\text{Dose} = \text{SRD Readout} * ExTDCF_{TP} \qquad \text{(Eq. 2.1-1)}$$

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

where:

Dose = Worker (or receptor) dose, mrem;

SRD Readout = Current reading on Self-Reading Dosimeter, mrem; and

$ExTDCF_{TP}$ = External to Total Dose Conversion Factor, the ratio of the total dose (inhalation + external) to the external dose from a release of radioactive material over the time phase under consideration (*TP*), $mrem_{inh+external}/mrem_{external}$.

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

$$Dose = \text{SRD Readout} * XDCF_{A \text{ or } C} * ExTDCF_{TP} \quad \text{(Eq. 2.1-2)}$$

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

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.

Method 2.1.2 Calculating the Worker Stay Time

To calculate a worker's stay time at a given location, divide their DL for the work shift by the product of the external dose rate in the area and the ExTDCF for the work shift which is used to convert dosimeter readings measuring External Dose, to the Total Dose to which the worker has been exposed (See Method 2.1.3).

$$ST = \frac{DL_{TP}}{ExDR * ExTDCF_{TP}} \quad \text{(Eq. 2.1-3)}$$

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

where:

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

DL_{TP} = Dose that the worker is allowed to receive for the work shift, mrem;

$ExDR$ = External dose rate, mrem/h; and

$ExTDCF_{TP}$ = External to Total Dose Conversion Factor, the ratio of the total dose (inhalation + external) to the external dose from a release of radioactive material over the time phase under consideration (*TP*), $mrem_{inh+external}/mrem_{external}$.

Method 2.1.3 Calculating the External to Total Dose Conversion Factor (ExTDCF)

The External to Total Dose Conversion Factor ($ExTDCF_{TP}$) is used to convert a measurement from an SRD into a dose that includes the inhalation dose. The $ExTDCF_{TP}$ for the time phase of interest can be calculated by adding the contributions to total dose from external exposure and inhalation of radioactive material and dividing the total by the external contribution as shown in Equations 2.1-4(a-c).

Prior to calculating the ExTDCF, it is necessary for the assessor to determine which of the four primary pathways are applicable for the calculation. The ExTDCF is then calculated based on the dose from the mixture for the selected pathways.

NOTE: See Method 1.1, Section 1.1 for the derivation of the Dose Parameters applicable to the calculation being performed.

$$ExTDCF_{TP} = \frac{\sum_i\left(\frac{Pl\_InhDP_{i,TP}+Dp\_InhDP_{i,TP}}{KIPF*APF}\right)+\sum_i\left(Pl\_ExDP_{i,TP}+Dp\_ExDP_{i,TP}\right)}{\sum_i\left(Pl\_ExDP_{i,TP}+Dp\_ExDP_{i,TP}\right)}$$

(Eq. 2.1-4a)

which can be expanded to:

$$ExTDCF_{TP} = \frac{\sum_i\left(\frac{Pl\_InhDP_{i,TP}+Dp\_InhDP_{i,TP}}{KIPF*APF}\right)}{\sum_i\left(Pl\_ExDP_{i,TP}+Dp\_ExDP_{i,TP}\right)} + \frac{\sum_i\left(Pl\_ExDP_{i,TP}+Dp\_ExDP_{i,TP}\right)}{\sum_i\left(Pl\_ExDP_{i,TP}+Dp\_ExDP_{i,TP}\right)}$$

(Eq. 2.1-4b)

and then simplified to:

$$ExTDCF_{TP} = \frac{\sum_i\left(\frac{Pl\_InhDP_{i,TP}+Dp\_InhDP_{i,TP}}{KIPF*APF}\right)}{\sum_i\left(Pl\_ExDP_{i,TP}+Dp\_ExDP_{i,TP}\right)} + 1$$

(Eq. 2.1-4c)

$$\frac{\mathrm{mrem}_{\mathrm{inh+external}}}{\mathrm{mrem}_{\mathrm{external}}} = \frac{\left(\frac{\mathrm{mrem}_{\mathrm{inh}}}{\mathrm{unitless*unitless}}\right)}{\mathrm{mrem}_{\mathrm{external}}} + \frac{\mathrm{mrem}_{\mathrm{external}}}{\mathrm{mrem}_{\mathrm{external}}}$$

where:

$ExTDCF_{TP}$ = External to Total Dose Conversion Factor, the ratio of the total dose (inhalation + external) to the external dose from a release of radioactive material over the time phase under consideration (*TP*), $\mathrm{mrem}_{\mathrm{inh+external}}/\mathrm{mrem}_{\mathrm{external}}$;

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

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

> **NOTE:** For Worker Protection Calculations, *Dp_InhDP* should be calculated using the Adult Male Light Exercise Breathing Rate (BR_{LE}) of 4.17E-04 m^3/s (1.5 m^3/h) and a constant resuspension of 1.0E-05 m^{-1}.

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

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

KIPF = Potassium Iodide Protection Factor, the protection factor for thyroid dose from iodine radionuclides (Default of 1 when KI is not administered), unitless; and

APF = Assigned Protection Factor, the level of respiratory protection that a respirator is expected to provide (Default of 1 when no respirators are used), unitless.

> **NOTE:** Consult Health and Safety personnel for appropriate values for *APF* and/or *KIPF*. APFs for various respirators are available in Appendix C, Table 6-3.

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EXAMPLE 1

Problem: Calculate the worker dose for an 8-hour work shift during the plume with and without a full-face air-purifying respirator (APF=50) and an SRD readout of 0.6 mrem for the following mixture (measured at the start of the work shift).

Table 2.1-E1

Radionuclide	Deposition (μCi/m^2)
Co-60	2
Gd-148	1
Sr-90	3
Y-90 [a]	3
[a] Y-90 included as a daughter at equilibrium.	

E1.1 Calculating the ExTDCF (Equation 2.1-4c)

The worker dose calculation requires the ExTDCF. This term requires values for Pl_InhDP, Pl_ExDP, Dp_InhDP and Dp_ExDP. See Method 1.1 for development of these quantities.

Table 2.1-E2

Radionuclide	Dp_i (μCi/m^2)	Pl_InhDP[a] (mrem)	Pl_ExDP[a] (mrem)	Dp_InhDP[a] (mrem)	Dp_ExDP[a] (mrem)
Co-60	2	10.5	0.294	9.06E-03	0.402
Gd-148	1	5.91E+03	0	5.11	0
Sr-90	3	54.9	3.64E-04	4.75E-02	4.30E-04
Y-90	3	2.15	2.93E-03	1.85E-03	2.88E-02
	∑	**5.98E+03**	**0.297**	**5.17**	**0.431**

[a] Values from Turbo FRMAC 2020© – Breathing rate for "Light Exercise" and constant resuspension of 1.0E-05 m^{-1}.

Applying these values in Equation 2.1-4c yields,

With a respirator:

$$ExTDCF_{TP} = \frac{\left(\frac{5.98\text{E}{+}03+5.17}{1*50}\right)}{(0.297+0.431)} + 1 = 1.65\text{E}{+}02\ \frac{\text{mrem}_{\text{inh+external}}}{\text{mrem}_{\text{external}}}$$

Without a respirator:

$$ExTDCF_{TP} = \frac{\left(\frac{5.98\text{E+03}+5.17}{1*1}\right)}{(0.297+0.431)} + 1 = 8.22\text{E+03}\ \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}$$

E1.2 Calculating the Worker Dose (Equation 2.1-1)

The ExTDCF is multiplied by the SRD readout to calculate the worker dose:

With a respirator:

$$\text{Dose} = 0.6\ \text{mrem} * 1.65\text{E+02}\ \frac{\text{mrem}_{\text{inh+external}}}{\text{mrem}_{\text{external}}} = 99\ \text{mrem}_{\text{inh+external}}$$

This means that when a worker's dosimeter indicates an external dose of **0.6** mrem, the worker has potentially received 99 mrem of total (inhalation + external) dose.

Without a respirator:

$$\text{Dose} = 0.6\ \text{mrem} * 8.22\text{E+03}\ \frac{\text{mrem}_{\text{inh+external}}}{\text{mrem}_{\text{external}}} = 4.92\text{E+03}\ \text{mrem}_{\text{inh+external}}$$

This means that when a worker's dosimeter indicates an external dose of **0.6** mrem, the worker has potentially received 4.93E+03 mrem of total (inhalation + external) dose.

EXAMPLE 2

Problem: Calculate the Stay Time for a work shift during the plume <u>with and without</u> a full-face air-purifying respirator (APF=50), a measured external dose rate of 3 mrem/h, and a worker Dose Limit of 5000 mrem for the following mixture (measured at the start of the work shift).

Table 2.1-E1

Radionuclide	Deposition (μCi/m^2)
Co-60	2
Gd-148	1
Sr-90	3
Y-90 [a]	3

[a] Y-90 included as a daughter at equilibrium.

E2.1 Calculating the Stay Time (Equation 2.1-3)

This calculation requires the ExTDCF. This was determined to be 1.65E+02 $\text{mrem}_{\text{inh+external}}/\text{mrem}_{\text{external}}$ with a respirator and 8.22E+03 $\text{mrem}_{\text{inh+external}}/\text{mrem}_{\text{external}}$ without a respirator in Example 1.

With a respirator:

$$ST = \frac{5000\ \text{mrem}_{\text{inh+external}}}{3\frac{\text{mrem}_{\text{external}}}{\text{h}} * 1.65\text{E}{+}02 \frac{\text{mrem}_{\text{inh+external}}}{\text{mrem}_{\text{external}}}} = 10.1\ \text{h}$$

Workers may stay in the contaminated area for approximately 10 hours before they potentially exceed their 5000 mrem Dose Limit.

Without a respirator:

$$ST = \frac{5000\ \text{mrem}_{\text{inh+external}}}{3\frac{\text{mrem}_{\text{external}}}{\text{h}} * 8.22\text{E}{+}03\ \frac{\text{mrem}_{\text{inh+external}}}{\text{mrem}_{\text{external}}}} = 0.203\ \text{h} \approx 12\ \text{min}$$

Workers may stay in the contaminated area for approximately 12 minutes before they potentially exceed their 5000 mrem Dose Limit.

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METHOD 2.2 INTEGRATED TURN-BACK LIMITS

Application

This method is used to calculate integrated Turn-Back Limits (TBL) for workers entering a contaminated area, taking into account both inhalation and external hazards present in the work environment.

- The Integrated Dose/Exposure TBL represents the external dose (or exposure) that would produce a total dose (inhalation and external) over a work shift equal to the appropriate Dose Limit (DL).

- The Dose/Exposure Rate, Alpha, and Beta TBLs are values that should not be exceeded to ensure the worker does not exceed their DL for the work shift.

All quantities developed in this Method are:

- Derived from the emergency worker guidelines established by the Environmental Protection Agency (EPA) (EPA17) or other DL established for worker protection.

- Calculated from the Dose Parameter values calculated in Method 1.1.

Discussion

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

NOTE: For work activities conducted during plume passage, FRMAC does not recommend using Alpha or Beta TBLs because field instrumentation designed to measure these quantities cannot differentiate between ground and air activity.

Alpha and Beta TBLs in this method are expressed in units of $\mu Ci/m^2$.

- It is not appropriate for the FRMAC Assessment Division to calculate instrument-specific Alpha or Beta TBLs in units of counts per minute (cpm) per a given probe area (e.g., 550 $cpm_\alpha/100\ cm^2$) for a given radionuclide mixture because it is difficult to foresee what instruments will be used by monitoring personnel.
- Rather, the value calculated by this method is an intermediate value and must be adjusted for conditions in the field (e.g., instrument efficiency, active probe area, surface conditions, and environmental conditions).
- Therefore, the monitoring & sampling or health & safety personnel are responsible for converting the units presented in this method (e.g., $\mu Ci_\alpha/m^2$) to the units generated in the field (e.g., $cpm_\alpha/100\ cm^2$).

Assumptions

There are no additional assumptions beyond the Default Assumptions above.

Inputs

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

1) Worker DL for the proposed work shift.
2) Dose Parameters for each of the four primary dose pathways for each radionuclide in the mixture, based on the start and end times of the work shift (calculated using Method 1.1).
3) Measurements made in the work location (e.g., Dose Rates, worker Dosimeter readings).
4) Other Factors – Assigned Protection Factor (APF) for respirator use, Potassium Iodide Protection Factor (KIPF).

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

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the Default Inputs until site-specific values become available through consultations with the Advisory Team.

Outputs

Final

The final output of this method is the turn-back limit for a given work shift.

TBL_D = Worker Turn-Back Limit for External Dose, the external dose, as recorded by the SRD, received from a radionuclide mixture over the time phase under consideration that indicates that a worker may have reached their DL, $mrem_{external}$.

TBL_X = Worker Turn-Back Limit for External Exposure, the external exposure, as recorded by the SRD, received from a radionuclide mixture over the time phase under consideration that indicates that a worker may have reached their DL, $mR_{external}$.

TBL_{DR} = Worker Dose Rate Turn-Back Limit, the external dose rate one meter above the ground that should not be exceeded to ensure the worker does not exceed their DL for the work shift, mrem/h.

TBL_{XR} = Worker Exposure Rate Turn-Back Limit, the external exposure rate one meter above the ground that should not be exceeded to ensure the worker does not exceed their DL for the work shift, mR/h;

TBL_{α} = Worker Turn-Back Limit for Alpha Contamination, the alpha contamination level that should not be exceeded to ensure the worker does not exceed their DL for the work shift, $\mu Ci_{\alpha}/m^2$.

TBL_{β} = Worker Turn-Back Limit for Beta Contamination, the beta contamination level that should not be exceeded to ensure the worker does not exceed their DL for the work shift, $\mu Ci_{\beta}/m^2$.

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 ($mrem_{inh+external}/mrem_{external}$)

$MTDP_{Worker}$ = Worker Mixture Total Dose Parameter (mrem)

Calculation

Calculating TBLs requires use of either the External to Total Dose Conversion Factor (ExTDCF) or the Worker Mixture Total Dose Parameter. The ExTDCF is calculated as shown in Method 2.1.3.

Method 2.2.1 Calculating the Worker Mixture Total Dose Parameter ($MTDP_{Worker}$)

The Worker Mixture Total Dose Parameter ($MTDP_{Worker}$) is the MTDP adjusted for the use of Potassium Iodide (KIPF) and/or respirators (APF). It is calculated using Equation 2.2-1. Pathway Dose Parameters are calculated as in Method 1.1.

Prior to calculating the $MTDP_{Worker}$, it is necessary for the assessor to determine which of the four primary pathways are applicable for the calculation. The $MTDP_{Worker}$ is then calculated based on the dose from the mixture for the selected pathways.

NOTE: See Method 1.1, Section 1.1 for the derivation of the Dose Parameters applicable to the calculation being performed.

$$MTDP_{Worker,TP} = \sum_i \left(\frac{Pl\_InhDP_{i,TP} + Dp\_InhDP_{i,TP}}{KIPF * APF}\right) + \sum_i \left(Pl\_ExDP_{i,TP} + Dp\_ExDP_{i,TP}\right) \quad \text{(Eq. 2.2-1)}$$

$$\text{mrem} = \left(\frac{\text{mrem} + \text{mrem}}{\text{unitless} * \text{unitless}}\right) + (\text{mrem} + \text{mrem})$$

where:

$MTDP_{Worker,\ TP}$ = Worker Mixture Total Dose Parameter, the sum of the doses from *all radionuclides* in a release, over the time phase under consideration, from the pathways included in the assessment, in which the inhalation dose parameters may be adjusted for the use of Potassium Iodide and/or Respiratory Protection, mrem;

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

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

> **NOTE:** For Worker Protection Calculations, *Dp_InhDP* should be calculated using the Adult Male Light Exercise Breathing Rate (BR_{LE}) of 4.17E-04 m^3/s (1.5 m^3/h) and a constant resuspension of 1.0E-05 m^{-1}.

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

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

KIPF = Potassium Iodide Protection Factor, the protection factor for thyroid dose from iodine radionuclides (Default of 1 when KI is not administered), unitless; and

APF = Assigned Protection Factor, the level of respiratory protection that a respirator is expected to provide (Default of 1 when no respirators are used), unitless.

> **NOTE:** Consult Health and Safety personnel for appropriate values for *APF* and/or *KIPF*. APFs for various respirators are available in Appendix C, Table 6-3.

Method 2.2.2 Calculating the Worker Turn-Back Limits

1) External Dose/Exposure Turn-Back Limits

The calculation of the Turn-Back Limit for External Dose (TBL_D) is based on the Dose Limit chosen by the decision makers for the incident and the ratio of total (inhalation + external) dose to external dose. This calculation requires the ExTDCF calculated in Method 2.1.3.

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.

$$TBL\_D_{TP} = \frac{DL_{TP}}{ExTDCF_{TP}} \qquad \text{(Eq. 2.2-2)}$$

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

where:

TBL_D_{TP} = Turn-Back Limit for External Dose, the external dose, as recorded by the SRD, received from a radionuclide mixture over the time phase under consideration (*TP*) that indicates that a worker may have reached their DL, $\text{mrem}_{\text{external}}$;

DL_{TP} = Dose that the worker is allowed to receive for the work shift, mrem; and

$ExTDCF_{TP}$ = External to Total Dose Conversion Factor, the ratio of the total dose (inhalation + external) to the external dose from a release of radioactive material over the time phase under consideration (*TP*), $\text{mrem}_{\text{inh+external}}/\text{mrem}_{\text{external}}$.

When the worker's SRD reaches the calculated external dose, this indicates that the worker has potentially received the DL (external plus inhalation dose) from the radionuclides deposited on the ground.

If workers are using dosimeters that read out in units of exposure (mR), divide the TBL_D by the Exposure to Dose Conversion Factor ($XDCF_{A\ or\ C}$) to determine the Turn-Back Limit for External Exposure (TBL_X) in $\text{mR}_{\text{external}}$.

$$TBL\_X_{TP} = \frac{TBL\_D_{TP}}{XDCF_{A \text{ or } C}} \qquad \text{(Eq. 2.2-3)}$$

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

where:

TBL_X_{TP} = Turn-Back Limit for External Exposure, the external exposure, as recorded by the SRD, received from a radionuclide mixture over the time phase under consideration (*TP*) that indicates that a worker may have reached their DL, $\text{mR}_{\text{external}}$;

TBL_D_{TP} = Turn-Back Limit for External Dose, the external dose, as recorded by the SRD, received from a radionuclide mixture over the time phase under consideration (TP) that indicates that a worker may have reached their DL, $mrem_{external}$;

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

$XDCF_C$ = Exposure to Dose Conversion Factor (chronic), the constant used to convert external exposure (mR) to deep tissue (1 cm) dose (mrem), 1.0 mrem/mR.

These limits should be used as the Dose (or Exposure) Limit in the calculation of stay time shown in Method 2.1.

2) Dose Rate Turn-Back Limit

The ExTDCF can also be used to calculate the Dose Rate TBL (TBL_{DR}) for the workers. Equation 2.2-4 shows the TBL_{DR} calculation. This method should NOT be used during plume passage because of the inability of field instrumentation to differentiate between ground and air activity. This calculation requires the ExTDCF calculated in Method 2.1.1.

$$TBL_{DR,TP} = \frac{DL_{TP}}{ExTDCF_{TP} * (t_2 - t_1)} \quad \text{(Eq. 2.2-4)}$$

$$\frac{\text{mrem}}{\text{h}} = \frac{\text{mrem}_{\text{inh+external}}}{\text{mrem}_{\text{inh+external}} / \text{mrem}_{\text{external}} * (\text{h} - \text{h})}$$

where:

TBL_{DR} = Dose Rate Turn-Back Limit, the external dose rate one meter above the ground that should not be exceeded to ensure the worker does not exceed their DL for the work shift, mrem/h;

DL_{TP} = Dose that the worker is allowed to receive for the work shift, mrem;

$ExTDCF_{TP}$ = External to Total Dose Conversion Factor, the ratio of the total dose (inhalation + external) to the external dose from a release of radioactive material over the time phase under consideration (TP), $mrem_{inh+external}/mrem_{external}$;

t_2 = End Time, the end of the time phase under consideration (TP), h; and

t_1 = Start Time, the start of the time phase under consideration (TP), h.

If workers are using instruments that read out in units of exposure rate (mR/h), divide the TBL_{DR} by the Exposure to Dose Conversion Factor ($XDCF_{A\ or\ C}$) to determine the Exposure Rate Turn-Back Limit (TBL_{XR}).

$$TBL_{XR,TP} = \frac{TBL_{DR,TP}}{XDCF_{A \text{ or } C}} \quad \text{(Eq. 2.2-5)}$$

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

where:

TBL

TBL_{XR} = Exposure Rate Turn-Back Limit, the external exposure rate one meter above the ground that should not be exceeded to ensure the worker does not exceed their DL for the work shift, mR/h;

TBL_{DR} = Dose Rate Turn-Back Limit, the external dose rate one meter above the ground that should not be exceeded to ensure the worker does not exceed their DL for the work shift, mrem/h;

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

$XDCF_C$ = Exposure to Dose Conversion Factor (chronic), the constant used to convert external exposure (mR) to deep tissue (1 cm) dose (mrem), 1.0.

3) Alpha Turn-Back Limit

This method has been developed to calculate a Turn-Back Limit for comparison to alpha contamination readings. This method should NOT be used during plume passage because of the inability of field instrumentation to differentiate between ground and air activity.

The calculation of the Alpha Turn-Back Limit (TBL_α) considers the total dose over the work shift from internal and external exposure. Equation 2.2-6 shows the TBL_α calculation. This calculation requires the $MTDP_{Worker}$ calculated in Method 2.2.1.

$$TBL_{\alpha,TP} = \frac{DL_{TP} * \sum_i \left(Y_{\alpha,i} * WP_{i,TP}\right)}{MTDP_{Worker,TP} * (t_2 - t_1)} \quad \text{(Eq. 2.2-6)}$$

$$\frac{\mu\text{Ci}_\alpha}{\text{m}^2} = \frac{\text{mrem} * \sum\left(\frac{\mu\text{Ci}_\alpha}{\mu\text{Ci}} * \frac{\mu\text{Ci}\cdot\text{h}}{\text{m}^2}\right)}{\text{mrem} * (\text{h} - \text{h})}$$

where:

$TBL_{\alpha,TP}$ = Alpha Turn-Back Limit, the alpha contamination level that should not be exceeded to ensure the worker does not exceed their DL for the work shift, $\mu Ci_\alpha/m^2$;

DL_{TP} = Dose that the worker is allowed to receive for the work shift, mrem;

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

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

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

$MTDP_{Worker,\,TP}$ = Worker Mixture Total Dose Parameter, the sum of the doses from *all radionuclides* in a release, over the time phase under consideration, from the pathways included in the assessment, in which the inhalation dose parameters may be adjusted for the use of Potassium Iodide and/or Respiratory Protection, mrem;

t_2 = End Time, the end of the time phase under consideration (TP), h; and

t_1 = Start Time, the start of the time phase under consideration (TP), h.

4) Beta Turn-Back Limit

This method has been developed to calculate a Turn-Back Limit for comparison to beta contamination readings. This method should NOT be used during plume passage because of the inability of field instrumentation to differentiate between ground and air activity.

The calculation of the Beta Turn-Back Limit (TBL_β) considers the total dose over the work shift from internal and external exposure. Equation 2.2-7 shows the TBL_β calculation. This calculation requires the $MTDP_{Worker}$ calculated in Method 2.2.1.

$$TBL_{\beta,TP} = \frac{DL_{TP} * \sum_i \left(Y_{\beta,i} * WP_{i,TP}\right)}{MTDP_{Worker,TP} * (t_2 - t_1)} \quad \text{(Eq. 2.2-7)}$$

$$\frac{\mu Ci_\beta}{m^2} = \frac{mrem * \sum\left(\frac{\mu Ci_\beta}{\mu Ci} * \frac{\mu Ci \cdot h}{m^2}\right)}{mrem * (h - h)}$$

where:

$TBL_{\beta,TP}$ = Beta Turn-Back Limit, the beta contamination level that should not be exceeded to ensure the worker does not exceed their DL for the work shift, $\mu Ci_\beta/m^2$;

DL_{TP} = Dose that the worker is allowed to receive for the work shift, mrem;

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

$WP_{i,\,TP}$ = Weathering Parameter, the adjustment of radioactive decay and in-growth and the time-dependent weathering effects that change the amount of a radionuclide available to cause direct exposure or to be ingested over the time phase under consideration (*TP*), μCi•h/m^2;

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

$MTDP_{Worker,\,TP}$ = Worker Mixture Total Dose Parameter, the sum of the doses from *all radionuclides* in a release, over the time phase under consideration, from the pathways included in the assessment, in which the inhalation dose parameters may be adjusted for the use of Potassium Iodide and/or Respiratory Protection, mrem;

t_2 = End Time, the end of the time phase under consideration (TP), h; and

t_1 = Start Time, the start of the time phase under consideration (TP), h.

EXAMPLE 1

Problem: Calculate the worker Turn-Back Limits for an 8-hour work shift starting 12 h after the plume has passed with and without a full-face air-purifying respirator (APF=50) with a worker Dose Limit of 5000 mrem for the following mixture (measured at the start of the work shift).

Table 2.2-E1

Radionuclide	Deposition (µCi/m²)
Co-60	2
Gd-148	1
Sr-90	3
Y-90 [a]	3

[a] Y-90 included as a daughter at equilibrium.

E1.1 Calculating the ExTDCF (Equation 2.1-c)

The External Dose/Exposure Turn-Back Limits require the ExTDCF. This term requires values for Dp_InhDP and Dp_ExDP. See Method 1.1 for development of these quantities.

Table 2.2-E2

Radionuclide	Dp_i (µCi/m²)	WP[a] (µCi•h/m²)	Dp_InhDP[a] (mrem)	Dp_ExDP[a] (mrem)
Co-60	2	16	9.06E-03	0.402
Gd-148	1	8	5.11	0
Sr-90	3	24	4.75E-02	4.30E-04
Y-90	3	24	1.85E-03	2.88E-02
		∑	**5.17**	**0.431**

[a] Values from Turbo FRMAC 2020© – Breathing rate for “Light Exercise” and constant resuspension of 1.0E-05 m⁻¹.

With a respirator:

$$ExTDCF_{TP} = \frac{\frac{5.17}{1*50}}{0.431} + 1 = 1.24\ \frac{mrem_{inh+external}}{mrem_{external}}$$

Without a respirator:

$$ExTDCF_{TP} = \frac{\frac{5.17}{1*1}}{0.431} + 1 = 13.0\ \frac{mrem_{inh+external}}{mrem_{external}}$$

E1.2 Calculating the TBL_D (Equation 2.2-2)

The Turn-Back Limits for External Dose and Exposure for this radionuclide mixture with a DL of 5000 mrem would be:

With a respirator:

$$TBL\_D_{TP} = \frac{5000\ \text{mrem}_{inh+external}}{1.24\ \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}} = 4030\ \text{mrem}_{external}$$

This means that when a worker's dosimeter indicates an external dose of **4030** mrem, the worker has potentially received 5000 mrem of total (inhalation + external) dose and should exit the work area.

Without a respirator:

$$TBL\_D_{TP} = \frac{5000\ \text{mrem}_{inh+external}}{13.0\ \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}} = 385\ \text{mrem}_{external}$$

This means that when a worker's dosimeter indicates an external dose of **385** mrem, the worker has potentially received 5000 mrem of total (inhalation + external) dose and should exit the work area.

E1.3 Calculating the TBL_{DR} (Equation 2.2-4)

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

With a respirator:

$$TBL_{DR,TP} = \frac{5000\ \text{mrem}_{inh+external}}{1.24\ \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}} * (20\text{h} - 12\text{h})} = 504\ \frac{\text{mrem}_{external}}{\text{h}}$$

This means that when a worker's instrument indicates that the dose rate in the area exceeds 500 mrem/h, the worker should move to a less contaminated area to ensure they do not exceed their DL for the work shift.

Without a respirator:

$$TBL_{DR,TP} = \frac{5000\ \text{mrem}_{inh+external}}{13\ \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}} * (20\text{h} - 12\text{h})} = 48.1\ \frac{\text{mrem}_{external}}{\text{h}}$$

This means that when a worker's instrument indicates that the dose rate in the area exceeds 48.1 mrem/h, the worker should move to a less contaminated area to ensure they do not exceed their DL for the work shift.

E1.4 Calculating the $MTDP_{Worker}$ (Equation 2.2-1)

The Alpha and Beta Turn-Back Limits require the $MTDP_{Worker}$. This term requires values for Dp_InhDP and Dp_ExDP, included in Table 2.2-E2. See Method 1.1 for development of these quantities.

With a respirator:

$$MTDP_{Worker,TP} = \left(\frac{0+5.17\text{ mrem}}{1*50}\right) + (0 + 0.431\text{ mrem}) = 0.534\text{ mrem}$$

Without a respirator:

$$MTDP_{Worker,TP} = \left(\frac{0+5.17\text{ mrem}}{1*1}\right) + (0 + 0.431\text{ mrem}) = 5.60\text{ mrem}$$

E1.5 Calculating the TBL_α and TBL_β (Equation 2.2-6, 2.2-7)

This calculation requires values for WP and $MTDP_{Worker}$. See Supplement 2 for development of WP. These parameters are provided in Table 2.2-E2.

Calculating the Turn-Back Limits with a respirator:

$$TBL_{\alpha,TP} = \frac{5000\text{ mrem}*\left(1\frac{\mu\text{Ci}_\alpha}{\mu\text{Ci}}*8\frac{\mu\text{Ci}\cdot\text{h}}{\text{m}^2}\right)}{0.534\text{ mrem}*(20\text{h}-12\text{h})} = 9.36\text{E+03 }\frac{\mu\text{Ci}_\alpha}{\text{m}^2}$$

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

$$TBL_{\beta,TP} = \frac{5000\text{ mrem}*\left[\left(1\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}}*16\frac{\mu\text{Ci}\cdot\text{h}}{\text{m}^2}\right)+\left(1\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}}*24\frac{\mu\text{Ci}\cdot\text{h}}{\text{m}^2}\right)+\left(1\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}}*24\frac{\mu\text{Ci}\cdot\text{h}}{\text{m}^2}\right)\right]}{0.534\text{ mrem}*(20\text{h}-12\text{h})}$$

$$= 7.49\text{E} + 04\frac{\mu\text{Ci}_\beta}{\text{m}^2}$$

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

This means that when a worker's instrument indicates that contamination in the area exceeds 9.36E+03 $\mu Ci_\alpha/m^2$ or 7.49E+04 $\mu Ci_\beta/m^2$, the worker should move to a less contaminated area to ensure they do not exceed their DL for the work shift.

Calculating the Turn-Back Limits without a respirator:

$$TBL_{\alpha,TP} = \frac{5000\ \text{mrem} * \left(1\frac{\mu\text{Ci}_\alpha}{\mu\text{Ci}} * 8\frac{\mu\text{Ci}\cdot\text{h}}{\text{m}^2}\right)}{5.60\ \text{mrem} * (20\text{h} - 12\text{h})} = 8.93\text{E}{+}02\ \frac{\mu\text{Ci}_\alpha}{\text{m}^2}$$

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

$$TBL_{\beta,TP} = \frac{5000\ \text{mrem} * \left[\left(1\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}} * 16\frac{\mu\text{Ci}\cdot\text{h}}{\text{m}^2}\right) + \left(1\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}} * 24\frac{\mu\text{Ci}\cdot\text{h}}{\text{m}^2}\right) + \left(1\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}} * 24\frac{\mu\text{Ci}\cdot\text{h}}{\text{m}^2}\right)\right]}{5.60\ \text{mrem} * (20\text{h} - 12\text{h})}$$

$$= 7.14\text{E}{+}03\,\frac{\mu\text{Ci}_\beta}{\text{m}^2}$$

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

This means that when a worker's instrument indicates that contamination in the area exceeds 8.93E+02 $\mu Ci_{\alpha}/m^2$ or 7.14E+03 $\mu Ci_{\beta}/m^2$, the worker should move to a less contaminated area to ensure they do not exceed their DL for the work shift.

METHOD 2.3 WORKER PROTECTION DERIVED RESPONSE LEVELS

Application

This method has been developed to calculate DRLs for Worker Protection. This method modifies equations found in Methods 1.1-1.4 of this Manual to be applicable to workers in radioactive contamination areas and considers both the inhalation and external hazards.

All DRLs developed in this Method are:

1) Based on Dose Limits (DL) established for the workers and the work shift. A projected or measured value greater than the DRL indicates the potential to exceed the DL for the work shift.

2) Used to create data products and define radionuclide activity levels and dose and/or exposure rates to determine where workers may work without exceeding the DL for their work shift.

Discussion

These methods are variations of the Public Protection DRL calculations presented in Methods 1.1-1.4.

Alpha and Beta DRLs in this method are expressed in units of $\mu Ci \bullet s/m^3$ or $\mu Ci/m^2$.

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

Assumptions

There are no additional assumptions beyond the Default Assumptions above.

Inputs

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

1) Worker DL for the proposed work shift.

2) Mixture Total Dose Parameter for Workers as defined in Method 2.2

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

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the Default Inputs until site-specific values become available through consultations with the Advisory Team.

Outputs

Final

The final output of this method is the Worker Protection Derived Response Level (DRL) for a release of radioactive material.

$DRL_{\tilde{A}}$ = Integrated Air Derived Response Level, the integrated air activity of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the DL over the time phase under consideration, $\mu Ci \bullet s/m^3$.

DRL_{Dp} = Deposition Derived Response Level, the areal activity, at time t_n, of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the DL over the time phase under consideration, $\mu Ci/m^2$.

DRL_{DR} = Dose Rate Derived Response Level, the external dose rate one meter above the ground, at time t_n, at which the total dose from *all radionuclides* in a release would equal the DL over the time phase under consideration, mrem/h.

DRL_{XR} = Exposure Rate Derived Response Level, the external exposure rate one meter above the ground, at time t_n, at which the total dose from *all radionuclides* in a release would equal the DL over the time phase under consideration, mR/h.

$DRL_{\alpha,\tilde{A}}$ = Integrated Air Alpha Derived Response Level, the integrated air alpha activity of the mixture at which the total dose from *all radionuclides* in a release would equal the DL over the time phase under consideration, $\mu Ci_{\alpha} \bullet s/m^3$.

$DRL_{\alpha,Dp}$ = Deposition Alpha Derived Response Level, the areal alpha activity of the mixture, at time t_n, of the mixture at which the total dose from *all radionuclides* in a release would equal the DL over the time phase under consideration, $\mu Ci_{\alpha}/m^2$.

$DRL_{\beta,\tilde{A}}$ = Integrated Air Beta Derived Response Level, the integrated air beta activity of the mixture at which the total dose from *all radionuclides* in a release would equal the DL over the time phase under consideration, $\mu Ci_{\beta} \bullet s/m^3$.

$DRL_{\beta,Dp}$ = Deposition Beta Derived Response Level, the areal beta activity of the mixture, at time t_n, of the mixture at which the total dose from *all radionuclides* in a release would equal the DL over the time phase under consideration, $\mu Ci_{\beta}/m^2$.

Intermediate

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

None.

Calculation

Worker Protection DRLs are calculated the same as Public Protection DRLs, but using the Worker Protection Default Inputs.

Method 2.3.1 Calculating Nuclide Specific DRLs

1) Integrated Air Derived Response Level

$$DRL_{\tilde{A},i,TP} = \frac{DL_{TP} * \tilde{A}_i}{MTDP_{Worker,TP}} \quad \text{(Eq. 2.3-1)}$$

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

where:

$DRL_{\tilde{A},i,TP}$ = Integrated Air Derived Response Level, the integrated air activity ($\tilde{A}$) of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the DL over the time phase under consideration (*TP*), μCi•s/m^3;

DL_{TP} = Dose that the worker is allowed to receive for the work shift, mrem;

$\tilde{A}_i$ = Integrated air activity of radionuclide *i* in a release, μCi•s/m^3; and

$MTDP_{Worker,TP}$ = Worker Mixture Total Dose Parameter, the sum of the doses from *all radionuclides* in a release, over the time phase under consideration, from the pathways included in the assessment, in which the inhalation dose parameters may be adjusted for the use of Potassium Iodide and/or Respiratory Protection, mrem.

2) Deposition Derived Response Level

$$DRL_{Dp,i,t_n,TP} = \frac{DL_{TP} * Dp_{i,t_n} * WF_{t_n}}{MTDP_{Worker,TP}} \quad \text{(Eq. 2.3-2)}$$

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

where:

$DRL_{Dp,i,,tn,TP}$ = Deposition Derived Response Level, the areal activity, at time t_n, of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the DL over the time phase under consideration, μCi/m^2;

DL_{TP} = Dose that the worker is allowed to receive for the work shift, mrem;

$Dp_{i,tn}$ = Deposition, the areal activity of radionuclide *i* at time t_n, µCi/m^2;

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

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

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

$MTDP_{Worker,\ TP}$ = Worker Mixture Total Dose Parameter, the sum of the doses from *all radionuclides* in a release, over the time phase under consideration, from the pathways included in the assessment, in which the inhalation dose parameters may be adjusted for the use of Potassium Iodide and/or Respiratory Protection, mrem.

Method 2.3.2 Calculating Dose Rate DRLs

$$DRL_{DR,t_n,TP} = DL_{TP} * \frac{DP\_MExDF_{t_n}}{MTDP_{Worker,TP}} \quad \text{(Eq. 2.3-3)}$$

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

where:

$DRL_{DR,tn,TP}$ = Dose Rate Derived Response Level, the external dose rate one meter above the ground, at time t_n, at which the total dose from *all radionuclides* in a release would equal the DL for the time phase, mrem/h;

DL_{TP} = Dose that the worker is allowed to receive for the work shift, mrem;

Dp_MExDF_{tn} = Deposition Mixture External Dose Factor, the external dose rate one meter above the ground at time t_n from a radionuclide mixture deposited on the ground, mrem/h; and

> **NOTE:** See Section 1.2.1.2 for details on calculating Dp_MExDF.

$MTDP_{Worker,\ TP}$ = Worker Mixture Total Dose Parameter, the sum of the doses from *all radionuclides* in a release, over the time phase under consideration, from the pathways included in the assessment, in which the inhalation dose parameters may be adjusted for the use of Potassium Iodide and/or Respiratory Protection, mrem.

NOTE: Exposure Rate Derived Response Levels (DRL_{XR}) are calculated as in Method 1.2.2.

Method 2.3.3 Calculating Alpha DRLs

1) Integrated Air Alpha Derived Response Level

$$DRL_{\alpha,\tilde{A},TP} = \sum_i \left(DRL_{\tilde{A},i,TP} * Y_{\alpha,i} \right) \quad \text{(Eq. 2.3-4)}$$

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

where:

$DRL_{\alpha,\tilde{A},TP}$ = Integrated Air Alpha Derived Response Level, the integrated air alpha activity of the mixture at which the total dose from *all radionuclides* in a release would equal the DL over the time phase under consideration, $\mu Ci_{\alpha} \bullet s/m^3$;

$DRL_{\tilde{A},i,TP}$ = Integrated Air Derived Response Level, the integrated air activity ($\tilde{A}$) of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the DL over the work shift under consideration, $\mu Ci_{nt} \bullet s/m^3$; and

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

2) Deposition Alpha Derived Response Level

$$DRL_{\alpha,Dp,t_n,TP} = \sum_i \left(DRL_{Dp,i,t_n,TP} * Y_{\alpha,i} \right) \quad \text{(Eq. 2.3-5)}$$

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

where:

$DRL_{\alpha,Dp,tn,TP}$ = Deposition Alpha Derived Response Level, the areal alpha activity of the mixture, at time t_n, at which the total dose from *all radionuclides* in a release would equal the DL over the time phase under consideration, $\mu Ci_{\alpha}/m^2$;

$DRL_{Dp,i,tn,TP}$ = Deposition Derived Response Level, the areal activity, at time t_n, of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the DL over 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, $\mu Ci_{\alpha}/\mu Ci_{nt}$.

Method 2.3.4 Calculating Beta DRLs

1) Integrated Air Beta Derived Response Level

$$DRL_{\beta,\tilde{A},TP} = \sum_i \left(DRL_{\tilde{A},i,TP} * Y_{\beta,i} \right) \quad \text{(Eq. 2.3-6)}$$

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

where:

$DRL_{\beta,\tilde{A},TP}$ = Integrated Air Beta Derived Response Level, the integrated air beta activity of the mixture at which the total dose from *all radionuclides* in a release would equal the DL over the time phase under consideration, $\mu Ci_{\beta} \cdot s/m^3$;

$DRL_{\tilde{A},i,TP}$ = Integrated Air Derived Response Level, the integrated air activity ($\tilde{A}$) of radionuclide i at which the total dose from *all radionuclides* in a release would equal the DL over the time phase under consideration , $\mu Ci_{nt} \cdot s/m^3$; and

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

2) Deposition Beta Derived Response Level

$$DRL_{\beta,Dp,t_n,TP} = \sum_i \left(DRL_{Dp,i,t_n,TP} * Y_{\beta,i} \right) \quad \text{(Eq. 2.3-7)}$$

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

where:

$DRL_{\beta,Dp,tn,TP}$ = Deposition Beta Derived Response Level, the areal beta activity of the mixture, at time t_n, at which the total dose from *all radionuclides* in a release would equal the DL over the time phase under consideration, $\mu Ci_{\beta}/m^2$;

$DRL_{Dp,i,tn,TP}$ = Deposition Derived Response Level, the areal activity, at time t_n, of radionuclide i at which the total dose from *all radionuclides* in a release would equal the DL over 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, $\mu Ci_{\beta}/\mu Ci_{nt}$.

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Example 1

Problem: Calculate the worker Derived Response Levels for an 8-hour work shift starting 12 h after the plume has passed with a full-face air-purifying respirator (APF=50) and a worker Dose Limit of 5000 mrem for an Evaluation Time (t_n) of 12 hours and the following mixture (measured at the start of the work shift).

Table 2.3-E1

Radionuclide	Integrated Air Activity (μCi•s/m³)	Deposition (μCi/m²)
Co-60	6.67E+02	2
Gd-148	3.33E+02	1
Sr-90	1.00E+03	3
Y-90 [a]	1.00E+03	3

[a] Y-90 included as a daughter at equilibrium.

E1.1 Calculating the $MTDP_{Worker}$ (Equation 2.2-1)

The DRLs for workers require the $MTDP_{Worker}$. This term requires values for Dp_InhDP and Dp_ExDP. See Method 1.1 for development of these quantities.

Table 2.3-E2

Radionuclide	Dp_i (μCi/m²)	Dp_InhDP[a] (mrem)	Dp_ExDP[a] (mrem)
Co-60	2	9.06E-03	0.402
Gd-148	1	5.11	0
Sr-90	3	4.75E-02	4.30E-04
Y-90	3	1.85E-03	2.88E-02
	∑	**5.17**	**0.431**

[a] Values from Turbo FRMAC 2020© – Breathing rate for "Light Exercise" and constant resuspension of 1.0E-05 m^{-1}.

$$MTDP_{Worker,TP} = \left(\frac{0+5.17\text{ mrem}}{1*50}\right) + (0 + 0.431\text{ mrem}) = 0.534\text{ mrem}$$

E1.2 Calculating the Derived Response Levels

E.1.2.1 Calculating $DRL_{\tilde{A}}$ (Equation 2.3-1)

Example $DRL_{\tilde{A}}$ calculation for Co-60 and $DRL_{\tilde{A}}$ values for the radionuclide mixture for an 8-hour work shift starting 12 h after the plume has passed.

DL = 5000 mrem
$MTDP_{Worker}$ = 0.534 mrem

$$DRL_{\tilde{A}_{^{60}Co}} = \frac{5000 \text{ mrem} * 6.67\text{E+02} \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3}}{0.534 \text{ mrem}} = 6.25\text{E+06} \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3}$$

This means that a Co-60 Integrated Air Activity of 6.25E+06 µCi•s/m^3 in the plume would indicate that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the 8-hour work shift starting 12 hours after plume passage to equal the DL of 5000 mrem when considering only the two ground pathways.

Table 2.3-E3

Radionuclide	Integrated Air Activity (µCi•s/m³)	$DRL_{\tilde{A}}$ [a] (µCi•s/m³)
Co-60	6.67E+02	**6.25E+06**
Gd-148	3.33E+02	**3.12E+06**
Sr-90	1.00E+03	**9.36E+06**
Y-90 [a]	1.00E+03	**9.36E+06**

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

E1.2.2 Calculating DRL_{Dp} (Equation 2.3-2)

Example DRL_{Dp} calculation for Co-60 and DRL_{Dp} values for the radionuclide mixture for an 8-hour work shift starting 12 h after the plume has passed and an Evaluation Time (t_n) of 12 hours.

DL = 5000 mrem
$MTDP_{Worker}$ = 0.534 mrem

$$DRL_{Dp_{^{60}Co}} = \frac{5000 \text{ mrem} * \left(2 \frac{\mu\text{Ci}}{\text{m}^2} * e^{-4.17\text{E-}09*(12*3600)}\right) * 0.9997}{0.534 \text{ mrem}} = 1.87\text{E+04} \frac{\mu\text{Ci}}{\text{m}^2}$$

This means that a Co-60 Areal Activity of 1.87E+04 µCi/m^2 12 hours after deposition would indicate that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the 8-hour work shift to equal the DL of 5000 mrem when considering only the two ground pathways.

Table 2.3-E4

Radionuclide	$Dp_{i,t0}$ (µCi/m²)	$WF_{12\ h}$ [a] (unitless)	DRL_{Dp} (µCi/m²)
Co-60	2	0.9997	**1.87E+04**
Gd-148	1	0.9997	**9.36E+03**
Sr-90	3	0.9997	**2.81E+04**
Y-90	3	0.9997	**2.81E+04**

[a] See Appendix F, Supplement 2 for details on calculating WF.

E1.2.3 Calculating DRL_{DR} (Equation 2.3-3)

Calculating the Deposition Mixture External Dose Factor (Dp_MExDF) (Equation 1.2-2)

To calculate the DRL_{DR} at 12 hours after deposition, we must decay the deposited mixture to the Evaluation Time. Then we use those activities to calculate the Dp_MExDF at the Evaluation Time using Equation 1.2-2.

Table 2.3-E5

Radionuclide	$Dp_{i,0}$ (µCi/m²)	$WF_{12\ h}$ [a] (unitless)	Dp_ExDC [b] (mrem•m²) per (µCi•h)	GRF (unitless)	$Dp_{i,tn}$ x WF x Dp_ExDC x GRF (mrem/h)
Co-60	2	0.9997	3.06E-02	0.82	5.02E-02
Gd-148	1	0.9997	0	0.82	0
Sr-90	3	0.9997	2.19E-05	0.82	5.37E-05
Y-90	3	0.9997	1.47E-03	0.82	3.60E-03
				Dp_MExDF	5.39E-02

[a] See Appendix F, Supplement 2 for details on calculating WF.
[b] Values from DCFPAK 3.0 (ICRP 60+).

Comparing the Dp_MExDF to the DL to Calculate the DRL (Equation 2.3-3)

Example DRL_{DR} calculation for the radionuclide mixture for an 8-hour work shift and an Evaluation Time (t_n) of 12 hours.

DL = 5000 mrem
$MTDP_{Worker}$ = 0.534 mrem

$$DRL_{DR} = \frac{5000\ \text{mrem} * 5.39\text{E-}02\ \frac{\text{mrem}}{\text{h}}}{0.534\ \text{mrem}} = 5.05\text{E+}02\ \frac{\text{mrem}}{\text{h}}$$

This means that a dose rate of 505 mrem/h 12 hours after deposition indicates that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the 8-

hour work shift to equal the DL of 5000 mrem when considering only the two ground pathways.

E1.2.4 Calculating $DRL_{\alpha,\tilde{A}}$ (Equation 2.3-4)

This calculation requires the Integrated Air Derived Response Level ($DRL_{\tilde{A}}$) for each radionuclide in the mixture. Table 2.3-E6 shows the values calculated using Equation 2.3-1.

Table 2.3-E6

Radionuclide	Integrated Air Activity (μCi•s/m^3)	Alpha Yield	$DRL_{\tilde{A}}$ (μCi•s/m^3)
Co-60	6.67E+02	0	6.25E+06
Gd-148	3.33E+02	1	3.12E+06
Sr-90	1.0E+03	0	9.36E+06
Y-90	1.0E+03	0	9.36E+06

Applying these values in Equation 2.3-4 yields:

$$DRL_{\alpha,\tilde{A}} = \left(3.12\text{E+06}\,\frac{\mu\text{Ci}_{\text{nt}} \cdot \text{s}}{\text{m}^3} * 1\,\frac{\mu\text{Ci}_{\alpha}}{\mu\text{Ci}_{\text{nt}}}\right)$$

$$= 3.12\text{E+06}\,\frac{\mu\text{Ci}_{\alpha} \cdot \text{s}}{\text{m}^3}$$

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

This means that a total Alpha Integrated Air Activity of 3.12E+06 μCi_{nt}•s/m^3 would indicate that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the 8-hour work shift to equal the DL of 5000 mrem when considering only the two ground pathways.

E1.2.5 Calculating $DRL_{\alpha,Dp}$ (Equation 2.3-5)

This calculation requires the Deposition Derived Response Level (DRL_{Dp}) for each radionuclide in the mixture. Table 2.3-E7 shows the values calculated using Equation 2.3-2.

Table 2.3-E7

Radionuclide	Deposition ($\mu Ci/m^2$)	Alpha Yield	DRL_{Dp} ($\mu Ci/m^2$)
Co-60	2	0	1.87E+04
Gd-148	1	1	9.36E+03
Sr-90	3	0	2.81E+04
Y-90	3	0	2.81E+04

Applying these values in Equation 2.3-5 yields:

$$DRL_{\alpha,Dp} = \left(9.36\text{E+03}\,\frac{\mu\text{Ci}_{\text{nt}}}{\text{m}^2} * 1\,\frac{\mu\text{Ci}_{\alpha}}{\mu\text{Ci}_{\text{nt}}}\right)$$

$$= 9.36\text{E+03}\,\frac{\mu\text{Ci}_{\alpha}}{\text{m}^3}$$

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

This means that a total Alpha Areal Activity of 9.36E+03 $\mu Ci_{nt}/m^2$ 12 hours after deposition would indicate that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the 8-hour work shift to equal the DL of 5000 mrem when considering only the two ground pathways.

E1.2.6 Calculating $DRL_{\beta,\tilde{A}}$ (Equation 2.3-6)

This calculation requires the Integrated Air Derived Response Level ($DRL_{\tilde{A}}$) for each radionuclide in the mixture. Table 2.3-E8 shows the values calculated using Equation 2.3-1.

Table 2.3-E8

Radionuclide	Integrated Air Activity ($\mu Ci{\bullet}s/m^3$)	Beta Yield	$DRL_{\tilde{A}}$ ($\mu Ci{\bullet}s/m^3$)
Co-60	6.67E+02	1	6.25E+06
Gd-148	3.33E+02	0	3.12E+06
Sr-90	1.0E+03	1	9.36E+06
Y-90	1.0E+03	1	9.36E+06

Applying these values in Equation 2.3-6 yields:

$$DRL_{\beta,\tilde{A}} = \left(6.25\text{E+06}\,\frac{\mu\text{Ci}_{nt}\cdot\text{s}}{\text{m}^3} * 1\,\frac{\mu\text{Ci}_{\beta}}{\mu\text{Ci}_{nt}}\right) + \left(9.36\text{E+03}\,\frac{\mu\text{Ci}_{nt}\cdot\text{s}}{\text{m}^3} * 1\,\frac{\mu\text{Ci}_{\beta}}{\mu\text{Ci}_{nt}}\right)$$
$$+ \left(9.36\text{E+03}\,\frac{\mu\text{Ci}_{nt}\cdot\text{s}}{\text{m}^3} * 1\,\frac{\mu\text{Ci}_{\beta}}{\mu\text{Ci}_{nt}}\right)$$

$$= 2.50\text{E+07}\,\frac{\mu\text{Ci}_{\beta}\cdot\text{s}}{\text{m}^3}$$

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

This means that a total Beta Integrated Air Activity of 2.50E+07 µCi•s/m^3 would indicate that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the 8-hour work shift to equal the DL of 5000 mrem when considering only the two ground pathways.

E1.2.7 Calculating $DRL_{\beta,Dp}$ (Equation 2.3-7)

This calculation requires the Deposition Derived Response Level (DRL_{Dp}) for each radionuclide in the mixture. Table 2.3-E9 shows the values calculated using Equation 2.3-2.

Table 2.3-E9

Radionuclide	Deposition (µCi/m^2)	Beta Yield	DRL_{Dp} (µCi•s/m^3)
Co-60	2	1	1.87E+04
Gd-148	1	0	9.36E+03
Sr-90	3	1	2.81E+04
Y-90	3	1	2.81E+04

Applying these values in Equation 2.3-7 yields:

$$DRL_{\beta,Dp} = \left(1.87\text{E+04}\,\frac{\mu\text{Ci}_{nt}}{\text{m}^2} * 1\,\frac{\mu\text{Ci}_{\beta}}{\mu\text{Ci}_{nt}}\right) + \left(2.81\text{E+04}\,\frac{\mu\text{Ci}_{nt}}{\text{m}^2} * 1\,\frac{\mu\text{Ci}_{\beta}}{\mu\text{Ci}_{nt}}\right) + \left(2.81\text{E+04}\,\frac{\mu\text{Ci}_{nt}}{\text{m}^2} * 1\,\frac{\mu\text{Ci}_{\beta}}{\mu\text{Ci}_{nt}}\right)$$

$$= 7.49\text{E+04}\,\frac{\mu\text{Ci}_{\beta}}{\text{m}^2}$$

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

This means that a total Beta Areal Activity of 7.49E+04 µCi/m^2 12 hours after deposition would indicate that the entire mixture has the potential to cause a Total Effective Dose (Internal + External) over the 8-hour work shift to equal the DL of 5000 mrem when considering only the two ground pathways.

E1.3 Calculating DRLs for an Individual Organ

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

NOTE: KIPF should only be applied thyroid dose from iodine radionuclides.

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METHOD 2.4 WORKER PROTECTION - SKIN DOSE

This method is reserved for future development.

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SECTION 3. INGESTION PATHWAY METHODS

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INTRODUCTION TO INGESTION PATHWAY METHODS

These methods are used to assess measured or projected radionuclide concentrations for comparison to the FDA guidelines for radioactive contamination in food. These methods **do not** apply to non-edible agricultural products. Assessment of non-edible products should be performed using incident-specific information and guidance from the A-Team, and State, Local, or Tribal response organizations and decision makers.

These methods can be used to assess food products at all stages of maturity, addressing physical processes of radioactive decay and weathering as appropriate for the specific conditions of the incident.

Age Groups

ICRP guidance provides age-group-specific ingestion dose coefficients. FDA98 considered six age groups, (e.g., 3 month, 1 year, 5 year, 10 year, 15 year, and adult) for Intervention Level calculations. FDA98 used the term "Infant" which the FDA considered to include the 3-month and 1-year-old age groups. However, FDA currently recommends that the 3-month old age group be excluded from analysis of non-FDA-listed radionuclides. Assessors should indicate the controlling age group when presenting results to the Advisory Team.

NOTE: The Intervention Levels for some FDA-listed radionuclides (FDA98) are based on the 3-month-old. FRMAC will continue to use these values until directed otherwise.

Intervention Levels

Intervention Levels are based on Protective Action Guides (PAGs) of 0.5 rem Committed Effective Dose (E) or 5 rem to any specific organ (H_T), whichever is more limiting when evaluated for the most sensitive age group and organ. This manual discusses two types of Intervention Levels:

- The FDA (FDA98) has established guidance levels called Derived Intervention Levels (DILs) for contamination in food for a list of 24 radionuclides and three groups of radionuclides.

- FRMAC has developed a method to calculate analogous "FRMAC Intervention Levels" (FILs) for all other radionuclides.

FDA Ingestion PAGs are shown in Appendix C, Table 2-1, and DILs and FILs for selected radionuclides (including the full FDA list) are presented in Appendix C, Table 8-1 and Table 8-2.

Ingestion Derived Response Levels (DRLs)

These methods include calculations of Ingestion DRLs for several different food types. Ingestion DRLs are radionuclide concentrations in the environment that may result in concentrations in human-ingested food products that would equal the Intervention Level. Default calculations include Crops, Milk and Meat.

FRMAC uses a default Evaluation Time for DRL calculations of 12 hours after the start of the release, allowing atmospheric dispersion models to simulate 12 hours of downwind transport. This was chosen because 12 hours is generally sufficient for complete deposition of a single release to occur so that deposition contours can be plotted on data products.

Ingestion Dose

The Intervention Level and DRL Methods only consider the dose impacts from individual radionuclides. The Ingestion Dose Method can be used to calculate the dose from ingesting food contaminated with one or more radionuclides. When evaluating the impacts from contaminated food, both organ Dose Equivalents and Effective Dose should be considered.

NOTE: Ingestion Dose Coefficients for parent radionuclides include the dose contributions from daughter radionuclides that grow in after the parent is consumed, but not from daughters that are consumed. Therefore, if daughter radionuclides are consumed, they should be considered as a separate parent for the purpose of estimating dose.

Transfer Factors

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, animal feed, or water (PNNL20).

NOTE: Animal feed, for the purposes of these methods, includes forage, fodder, or other material designated as food for the animal of interest.

The equations presented in these methods use the following assumptions about Transfer Factors:

1) Transfer Factors assume that the impacted product will remain in the contaminated area long enough for it to reach equilibrium with the radioactive material deposited over the affected area. Therefore, these methods may overestimate uptake for crops or animals that are immediately ready for harvest after contamination.

2) Transfer Factors used in these methods for terrestrial plants are based on dry weight.

3) Transfer Factors used in these methods for animal products and aquatic plants are based on wet weight.

Default Assumptions

FRMAC radiological assessment calculations utilize the default assumptions established by the FRMAC Assessment Working Group. Users are urged to use the default assumptions until site-specific values become available through consultations with the Advisory Team.

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

1) Default calculations use the International Commission on Radiological Protection (ICRP) 60+ dosimetry model.
2) The default Ingestion PAGs are the more limiting of:
    - 500 mrem to the whole body or
    - 5000 mrem to an individual organ.
3) Annual intake for each group and subgroup of foods varies by age group (FDA98). If specific intake rates are known, use those instead of defaults.
4) 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. (Inadvertent Soil Ingestion is discussed in Method 3.7.)
5) Calculations are based on samples of foods as prepared for consumption and assume a consumption period of the contaminated food of 1 year.
6) DRLs apply to individual radionuclides; there is no sum-of-fraction rule (except for the FDA-listed ^{103}Ru and ^{106}Ru).
7) DRLs are based on the most restrictive Intervention Level for each radionuclide based on age group and target organ. See Method 3.1 for Intervention Level calculation assumptions.
8) DRLs for FDA grouped radionuclides (e.g., ^{134}Cs + ^{137}Cs) are adjusted for decay using the decay constant for the longest-lived group member.
9) DRLs are calculated in terms of "wet weight." To compare with analytical results, it may be necessary to convert to "dry weight," see Method 4.2.
10) Milk and Meat DRLs assume only one contaminated intake pathway is present (i.e., if feed/soil is contaminated, drinking water is clean) and assume that 100% of the contaminated pathway (feed or water) is contaminated.
11) Impacted crops will remain growing in the contaminated soil long enough to reach equilibrium.
12) Impacted animals will consume the contaminated material (forage, fodder, or water) long enough for the animal product intended for human consumption to reach equilibrium
13) Minimum root depth is used when reference values are presented as a range
14) The term "feed" refers both to forage (pasture grazing) and fodder (stored food).

Default Inputs

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

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

1) Crop Yields of 2.0 kg_{wet}/m^2 for crops and 0.7 kg_{wet}/m^2 for forage
2) Half-life for material weathering off plants in the field of 15 days
3) Mixing Depths of 1.0E-03 m before plowing and 0.15 m after plowing
4) Soil Density of 1600 kg_{soil}/m^3
5) Time to Market of 1 day for fresh produce, 2 days for milk and 20 days for meat
6) Animal intake rates of:
    - Cow – 50 kg_{wet}/d for feed, 60 l/d for water (50 l/d for beef cattle), 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) Forage root depth of 0.6 m
8) Crop Retention Factors for iodine radionuclides of 1.0
9) Crop Retention Factors for non-iodine radionuclides of 0.2 for crops and 0.5 for forage

METHOD 3.1 INGESTION INTERVENTION LEVELS

Application

This method discusses the FDA's Derived Intervention Levels (DILs) and describes how to calculate FRMAC Intervention Levels (FILs) for radioactive material deposited on areas of food production.

The Intervention Levels (IL):

1) Represent the concentration ($\mu Ci/kg_{wet}$) of radioactive material in food that, in the absence of any intervention, could lead to an individual receiving a dose equal to the appropriate Protective Action Guide (PAG) if consumed over 1 year.

2) Are derived from the PAG for radiological emergency planning established by the Food and Drug Administration (FDA) (FDA98). A projected or measured value greater than the Intervention Level indicates the potential to exceed the PAG.

3) Apply to the activity concentration in the food "as prepared for consumption" which is generally "wet." Special considerations are necessary for foods which are eaten in a dried form (e.g., dried fruit, jerky). More information is provided the Methods describing the specific DRL type associated with that food.

4) Apply during the first year after an incident and are based on the most sensitive population (age group) and target organ to provide a large margin of safety to the public. If there is concern that food will continue to be significantly contaminated beyond the first year, the long-term circumstances need to be evaluated to determine whether the DILs should be continued or if other guidance may be more applicable. (FDA98).

5) Are 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

This method discusses two types of Ingestion Intervention Levels:

- FDA's published Derived Intervention Levels (DILs) and
- Calculated FRMAC Intervention Levels (FILs).

DILs were recommended by the FDA in 1998 as the radionuclide activity concentration in food at which point protective actions should be considered. The FDA established DILs for a list of 24 radionuclides and three groups of radionuclides. The nuclides with FDA-provided DILs are shown in Table 3.1-1 below and in Appendix C, Table 8-1 and Table 8-2. Food with activity concentrations below the DIL is permitted to move in commerce without restriction. However, local decision makers, in consultation with the Advisory Team, have the flexibility to apply alternate Intervention Levels in special circumstances.

FRMAC has developed the FIL method to calculate values analogous to the FDA DILs for all radionuclides not considered by the FDA. FRMAC does not have the authority to calculate FILs for radionuclides for which the FDA has provided recommended values unless alternate values are requested by the Advisory Team or local decision makers. FIL values for selected radionuclides are shown in Appendix C, Table 8-1 and Table 8-2.

Assumptions

The following assumptions apply in addition to the Default Assumptions:

1) FILs are not calculated for radionuclides for which the FDA has supplied a DIL (FDA Radionuclides) without specific instructions from the Advisory Team or local decision makers.
2) FILs apply to individual radionuclides.
3) FILs are based on average annual dietary intake (kg_{wet}/year) of all dietary components (e.g., produce, grains, meat, etc.), including tap water used for drinking.
4) 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 the 1-year-old where it is assumed to be 1.0.
5) FILs are applicable to foods "as prepared for consumption" which is generally "wet". To compare with analytical results, it may be necessary to convert to "dry weight," see Method 4.2.

Inputs

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

1) Data – Composition of the deposited radionuclide mixture (radionuclides and concentration). This information may come from predictive analysis (atmospheric dispersion models) or field data (monitoring and/or samples).
2) Other Factors – Decay of radionuclides during the time period under consideration.
3) Constants – Fraction of diet contaminated, daily food intake rate, ingestion dose coefficient, dose limits (e.g., FDA PAGs).

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

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

Outputs

Final

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

FIL_i = FRMAC Intervention Level, the concentration of radionuclide *i* in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG, $\mu Ci/kg_{wet}$.

Intermediate

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

None

Method 3.1.1 FDA DILs

Table 3.1-1 provides the DILs for the FDA-listed radionuclides. These values must be used when evaluating the radionuclides (and groups of radionuclides) in the table unless an alternate value is requested by the Advisory Team or decision makers. Follow the calculation steps in Method 3.1.2 for alternate values or for any radionuclides not listed here.

Table 3.1-1 FDA-Listed Ingestion DILs (FDA98)

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	5.9E-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 3.1.2 FRMAC Intervention Levels (FILs)

Calculation

FIL 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.

Equation 3.1-1 shows the FIL calculation for an individual radionuclide.

$$FIL_{organ,age,i} = \frac{PAG_{organ}}{FDC_{age,i} * DFIR_{age} * \frac{1-e^{-\lambda_i t_c}}{\lambda_i} * IngDC_{organ,age,i}}$$

(Eq. 3.1-1)

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

where:

$FIL_{organ,age,i}$ = FRMAC Intervention Level, the concentration of radionuclide *i* in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG, $\mu Ci/kg_{wet}$;

PAG_{organ} = Protective Action Guide, as specified by the FDA or other Decision Makers, for the target organ, mrem;

$FDC_{age,i}$ = Fraction of Diet Contaminated, unitless;

NOTE: See Appendix C, Table 11 for default *FDC* values. If there is convincing local information that the actual *FDC* is considerably different, local authorities may decide to use a different *FDC*.

$DFIR_{age}$ = Daily Food Intake Rate, the daily intake rate (as prepared for consumption, i.e., wet mass) for a specific age group (see Appendix C, Table 10), kg_{wet}/d;

λ_i = Decay constant for radionuclide i, d^{-1};

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; and

$IngDC_{organ,age,i}$ = 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 FIL for one age group and one organ. To determine the most restrictive value for a given radionuclide:

- Calculate the FIL for the whole body and for the organ with the highest IngDC for each age group.
- Apply the FIL for the age group and organ with the most conservative (lowest) activity concentration level ($\mu Ci/kg_{wet}$).

EXAMPLE 1

Problem: Calculate the FRMAC Intervention Level for ^{136}Cs.

^{136}Cs is not an FDA-listed radionuclide; therefore, the FIL must be calculated according to Method 3.1.2. Determining a final FIL requires calculating the FIL for each age group for each organ and choosing the most conservative value.

$$FIL_{organ,age,i} = \frac{PAG_{organ}}{FDC_{age,i} * DFIR_{age} * \frac{1-e^{-\lambda_i t_c}}{\lambda_i} * IngDC_{organ,age,i}}$$

(Eq. 3.1-1)

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

Table 3.1-E1 shows the values, calculated using Equation 3.1-1, for each age group for the Whole Body and for the organ with the highest IngDC.

Table 3.1-E1

Age Group	Organ	PAG (mrem)	FDC	DFIR (kg_{wet}/d)	$\frac{1-e^{-\lambda_i t_c}}{\lambda_i}$ (d)	IngDC [a] (mrem/µCi)	FIL (µCi/kg_{wet})
1 year	Whole Body	500	0.3	1.38	19.0	35.6	1.79
	LLI [b]	5000				58.1	11.0
5 year	Whole Body	500	0.3	1.81	19.0	22.6	2.15
	LLI	5000				34.2	14.2
10 year	Whole Body	500	0.3	2.14	19.0	16.2	2.53
	LLI	5000				22	18.7
15 year	Whole Body	500	0.3	2.38	19.0	12.7	2.91
	Pancreas	5000				14.6	25.3
Adult	Whole Body	500	0.3	2.59	19.0	11.4	2.97
	LLI	5000				13.7	24.8
						Most Restrictive FIL	**1.79**

[a] Value from DCFPAK 3.0 (ICRP 60+).
[b] Lower Large Intestine

The reported FIL should be 1.79 µCi/kg_{wet} for ^{136}Cs based on the (most restrictive) 1-year-old/Whole Body value.

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METHOD 3.2 CROP DERIVED RESPONSE LEVELS

Application

This method has been developed to calculate Ingestion Derived Response Levels for radioactive material deposited on cropland.

The Crop Derived Response Level (Crop_DRL):

1) Is calculated using the Intervention Levels – either published FDA Derived Intervention Level (DIL) or calculated FRMAC Intervention Level (FIL) – from Method 3.1

2) Represents the areal activity (μCi/m^2), of radionuclide *i* that may cause the crop growing in that area to equal the Intervention Level for that radionuclide when the crop is distributed in commerce.

3) Is indirectly derived (through the Intervention Level) from the PAG for radiological emergency planning established by the Food and Drug Administration (FDA) (FDA98). A projected or measured value greater than the Crop_DRL indicates the potential to exceed the PAG.

4) Is applied during the first year after an incident and based on the most sensitive population (age group) and target organ to provide a large margin of safety to the public (FDA98).

5) 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).

Discussion

The Crop_DRL predicts the amount of radioactivity deposited on an area (μCi/m^2) that may cause the crop grown in that area to equal the Intervention Level. This method is used for crops which have reached maturity while growing in a contaminated field regardless of whether the crop was growing above ground at the time of contamination.

This method accounts for the following processes that change the level of radioactive material present on and/or in a crop:

1. Reduction in radioactivity level due to radioactive decay until the crop is collected,

2. Reduction in radioactivity level due to material weathering off the crop until the crop is collected,

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 addresses 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, non-leafy vegetable, fruit, or grain). (See PNNL20 for details on TFs). Use of TFs includes the assumption that the impacted crop will remain growing in the contaminated soil long enough to reach equilibrium. Therefore, this method may overestimate root uptake for crops that are immediately ready for harvest after contamination, resulting in a more conservative DRL.

Crop sampling efforts should concentrate on the area where the contamination is equal to or greater than the Crop_DRL to determine if the Intervention Level has been exceeded in those areas. Protective actions should be considered in areas where the Intervention Level is exceeded. FDA guidance permits food with radioactivity concentrations below the Intervention Level to move in commerce without restriction. However, the FDA and local decision makers have flexibility in whether to apply restrictions in special circumstances.

Assumptions

The following default assumptions are used in this method:

1) Crop DRLs predict contamination in the edible portion of the plant (e.g., apples on the tree). If available, TFs that predict the contamination level of specific plant parts may be considered.
2) Assume a Time to Market of 1 day for fresh produce.
3) Are calculated in terms of "wet weight." To compare with analytical results, it may be necessary to convert to "dry weight," see Method 4.2.
4) Use Crop Retention Factors for crops of:
   - 1.0 for iodine radionuclides and
   - 0.2 for all other radionuclides.
5) DRLs for FDA grouped radionuclides (e.g., $^{134}Cs + ^{137}Cs$) are adjusted for decay using the decay constant for the longest-lived group member.

Inputs

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

1) Data – Composition of the deposited radionuclide mixture (radionuclides). This information may come from predictive analysis (atmospheric dispersion models) or field data (monitoring and/or samples).
2) Constants – Crop Retention Factor, Crop Yield, Transfer Factors for different food types and for each radionuclide.
3) Other Factors – Decay and weathering of radionuclides during the time period under consideration, soil mixing depth, mature root depth, timing inputs.
4) Appropriate Intervention Level for each radionuclide – From Method 3.1.
5) Evaluation Time (t_n) – The point in time, relative to the start of the release, for which the calculation, measurement, or prediction is valid.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

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

Outputs

Final

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

$Crop\_DRL_{i,tn}$ = Ingestion Derived Response Level for Crop, the areal activity, at time t_n, of radionuclide *i* that may cause the crop growing in that area to equal the applicable Intervention Level at the time it is distributed in commerce, $\mu Ci/m^2$.

Intermediate

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

None

Calculation

Equation 3.2-1 shows the $Crop\_DRL_{i,tn}$ calculation.

$$Crop\_DRL_{i,t_n} = \frac{IL_{organ,age,i} * e^{-\lambda_i t_n} * WF_{t_n}}{\left(\frac{CRF_{crop} * e^{-\lambda_w t_h}}{Y_{crop}} + \frac{TF_{crop,i} * MCF_{D-W,crop}}{\rho_{soil} * d_{e,crop}}\right) * e^{-\lambda_i (t_h + t_m)}}$$

(Eq. 3.2-1)

$$\frac{\mu Ci}{m^2} = \frac{\frac{\mu Ci}{kg_{wet}} * unitless * unitless}{\left(\frac{unitless * unitless}{\frac{kg_{wet}}{m^2}} + \frac{\left(\frac{\mu Ci}{kg_{dry}} \Big/ \frac{\mu Ci}{kg_{soil}}\right) * \frac{kg_{dry}}{kg_{wet}}}{\frac{kg_{soil}}{m^3} * m}\right) * unitless}$$

where:

$Crop\_DRL_{i,tn}$ = Ingestion Derived Response Level for Crop, the areal activity, at time t_n, of radionuclide i that may cause the crop growing in that area to equal the applicable Intervention Level at the time it is distributed in commerce, $\mu Ci/m^2$.

$IL_{organ,age,i}$ = Intervention Level, the concentration of radionuclide i in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG, $\mu Ci/kg_{wet}$;

NOTE: Intervention Levels may be either a published FDA Derived Intervention Level (DIL) or calculated FRMAC Intervention Level (FIL) from Method 3.1.

λ_i = Decay constant for radionuclide i, d^{-1};

t_n = Evaluation Time, the point in time, relative to the start of the release, for which the calculation, measurement, or prediction is valid, d;

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

CRF_{crop} = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop (See Appendix C, Table 11), unitless;

NOTE: For crops not growing above the surface at the time of deposition, the CRF=0.

λ_w = Decay constant for weathering radioactive material off plants (See Appendix C, Table 11), d^{-1};

t_h = Time to Harvest, the time from deposition until the crop is collected, d;

Y_{crop} = Crop Yield, the mass of crop grown per area of land (See Appendix C, Table 11), kg_{wet}/m^2;

$TF_{crop,i}$ = Transfer Factor for a food crop, the fraction of radionuclide *i* deposited on the growing medium that is transferred to the plant prior to collection (See Appendix C, Table 8-1), $\mu Ci/kg_{dry}$ per $\mu Ci/kg_{soil}$;

$MCF_{D\text{-}W,crop}$ = Mass Conversion Factor (dry to wet), the ratio of dry mass to wet mass for a crop (See Appendix C, Table 9-1), kg_{dry}/kg_{wet};

ρ_{soil} = Soil density (See Appendix C, Table 11), kg_{soil}/m^3;

$d_{e,crop}$ = Effective Soil Depth, the maximum of the mixing depth (d_m) and the mature root depth (d_r) for the crop (See Appendix C, Table 11), m; and

NOTE: Default mixing depth is 1.0E-3 m prior to plowing and 0.15 m after plowing. Mature root depth is dependent on the type of crop.

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d.

EXAMPLE 1

Problem: Calculate the Crop DRL for a lettuce crop that has already been planted and will be harvested 90 days after deposition from an area with ^{60}Co ground contamination, measured at an evaluation time of 7 days after deposition.

The most conservative Intervention Level for Co-60 is 3.55E-02 µCi/kg_{wet} (1-year-old, whole body).

Equation 3.2-1 can be used to calculate the DRL.

$$Crop\_DRL_{i,t_n} = \frac{IL_{organ,age,i} * e^{-\lambda_i t_n} * WF_{t_n}}{\left(\frac{CRF_{crop} * e^{-\lambda_i t_h}}{Y_{crop}} + \frac{TF_{crop,i} * MCF_{D-W,crop}}{\rho_{soil} * d_{e,crop}}\right) * e^{-\lambda_i (t_h + t_m)}}$$

(Eq. 3.2-1)

Assuming:

$\lambda_{Co\text{-}60}$ = 3.6E-04 d^{-1},

t_n = 7 d,

WF_{tn} = 0.996,

$CRF_{lettuce}$ = 0.2,

λ_w = 4.62E-02 d^{-1},

t_h = 90 d,

$Y_{lettuce}$ = 2.0 kg_{wet}/m^2,

$TF_{lettuce,Co}$ = 0.17 µCi/kg_{dry} per µCi/kg_{soil},

$MCF_{D\text{-}W,lettuce}$ = 0.2 kg_{dry}/kg_{wet} (leafy vegetable),

ρ_{soil} = 1600 kg_{soil}/m^3,

$d_{e,lettuce}$ = 0.30 m (leafy vegetable), and

t_m = 1 d.

$$Crop\_DRL_{^{60}Co,7d} = \frac{3.55\text{E-}02\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * e^{-3.6\text{E-}04\text{d}^{-1}*7\text{d}} * 0.996}{\left(\frac{0.2*e^{-4.62\text{E}-02\text{d}^{-1}*90\text{d}}}{2.0\frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \frac{0.17\left(\frac{\mu\text{Ci}}{\text{kg}_{\text{dry}}}\Big/\frac{\mu\text{Ci}}{\text{kg}_{\text{soil}}}\right)*0.2\frac{\text{kg}_{\text{dry}}}{\text{kg}_{\text{soil}}}}{1600\frac{\text{kg}_{\text{soil}}}{\text{m}^3}*0.30\text{m}}\right) * e^{-3.6\text{E-}04\ \text{d}^{-1}*(90+1)\text{d}}}$$

$$= 22.3\,\frac{\mu\text{Ci}}{\text{m}^2}$$

This means that a Co-60 Areal Activity of 22.3 μCi/m^2 on the ground 7 days after deposition has the potential to cause a dose equal to the PAG of 500 mrem to the 1-year-old whole body when the crop is harvested 90 days after deposition.

METHOD 3.3 MILK DERIVED RESPONSE LEVEL

Application

This method has been developed to calculate Ingestion Derived Response Levels for radioactive material deposited on animal feed (forage or fodder) or water for the milk pathway.

The Milk Derived Response Level (Milk_DRL):

1) Is calculated using the Intervention Levels – either published Food and Drug Administration (FDA) Derived Intervention Level (DIL) or calculated FRMAC Intervention Level (FIL) – from Method 3.1

2) Represents:
   a. $Milk\_DRL_{area,A,i}$: The areal activity, at time t_n, of radionuclide *i* present in a grazing area that may cause the grazing animal's milk to equal the applicable Intervention Level for that radionuclide at the time it is distributed in commerce;
   b. $Milk\_DRL_{mass,A,i}$: The mass concentration of radionuclide *i* present in animal fodder that may cause the animal's milk to equal the applicable Intervention Level for that radionuclide at the time it is distributed in commerce; or
   c. $Milk\_DRL_{water,A,i}$: The water concentration of radionuclide *i* present in animal drinking water that may cause the animal's milk to equal the applicable Intervention Level for that radionuclide at the time it is distributed in commerce.

3) Is indirectly derived (through the Intervention Level) from the PAG for radiological emergency planning established by the FDA (FDA98). A projected or measured concentration value greater than the Milk_DRL indicates the potential to exceed the PAG.

4) Is applied during the first year after an incident and based on the most sensitive population (age group) and target organ to provide a large margin of safety to the public (FDA98).

5) 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).

Discussion

The Milk_DRL predicts the amount of radioactivity deposited either on an animal's grazing area ($\mu Ci/m^2$) or in an animal's feed (forage or fodder, $\mu Ci/kg_{wet}$) or water ($\mu Ci/l$) that may cause the animal's milk to equal the Intervention Level at the time it is distributed in commerce. Sampling efforts should concentrate on the area where the contamination is equal to or greater than the Milk_DRL to determine if the Intervention Level has been exceeded in those areas.

Protective actions (e.g., use of uncontaminated stored feed (fodder)) should be considered in areas where the Intervention Level is exceeded. Milk embargo protective actions should be considered after milk samples indicate that the Intervention Level has actually been exceeded. FDA guidance permits food with radioactivity concentrations below the Intervention Level to move in commerce without restriction. However, the FDA and local decision makers have flexibility in whether to apply restrictions in special circumstances.

Each section of this method accounts for some or all the following processes that change the level of radioactive material present in an animal's milk:

	DRL Type		
Process	Area	Mass	Water
1. Reduction in radioactivity level due to biological processes in the animal's forage	X		
2. Increase in radioactivity level due to root uptake to the animal's forage from contaminated soil	X		
3. Increase in radioactivity level due to re-deposition of resuspended material on the animal's forage	X		
4. Reduction in radioactivity level due to material weathering off the animal's forage until the animal begins grazing	X		
5. Increase in radioactivity level due to the animal consuming contaminated feed/water	X	X	X
6. Reduction in radioactivity level due to radioactive decay until the milk is collected	X	X	X
7. Reduction in radioactivity level due to transport time to market	X	X	X

This method addresses processes 1, 2, 3, and 5 using element-dependent Transfer Factors (TFs).

Two different TFs are included in the calculations in this Method:

1. Transfer from the soil to growing forage in the contaminated grazing area (Process 1-3)

2. Transfer from the contaminated feed/water to the animal's milk (Process 5)

Use of TFs includes the assumption that the impacted animal will remain grazing or drinking in the contaminated area long enough for its milk to reach equilibrium with the radioactive material deposited over the grazing area or on its fodder or water supply. Therefore, this method may overestimate uptake for animals that are immediately ready for harvest after contamination, resulting in a more conservative DRL.

Assumptions

There are no additional assumptions beyond the Default Assumptions above.

Inputs

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

1) Data – Composition of the deposited radionuclide mixture (radionuclides). This information may come from predictive analysis (atmospheric dispersion models) or field data (monitoring and/or samples).
2) Constants – Crop Retention Factor, Crop Yield, Animal Daily Intake Rates (Feed, Water, Soil), Transfer Factor for each type of Milk for each radionuclide, Transfer Factor for forage for each radionuclide.
3) Other Factors – Decay of radionuclides during the time period under consideration, fraction of animals' diet contaminated, soil mixing depth, mature root depth, timing inputs.
4) Appropriate Intervention Level for each radionuclide – From Method 3.1.
5) Evaluation Time (t_n) – The point in time, relative to the start of the release, for which the calculation, measurement, or prediction is valid.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

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

Outputs

Final

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

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

a. $Milk\_DRL_{area}$: The areal activity, at time t_n, of radionuclide *i* deposited over a grazing area that may result in the grazing animal's milk equaling the Intervention Level for that radionuclide at the time it is distributed in commerce; ($\mu Ci/m^2$)
b. $Milk\_DRL_{mass}$: The mass concentration, at time t_n, of radionuclide *i* in animal fodder that may result in the animal's milk equaling the Intervention Level for that radionuclide at the time it is distributed in commerce; ($\mu Ci/kg_{wet}$) or
c. $Milk\_DRL_{water}$: The water concentration, at time t_n, of radionuclide *i* in an animal's drinking water that may result in the animal's milk equaling the Intervention Level for that radionuclide at the time it is distributed in commerce, ($\mu Ci/l_{water}$).

Intermediate

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

None

Method 3.3.1 Milk DRL based on areal activity (µCi/m²) on forage

This method calculates the areal activity level (µCi/m²) of a radionuclide deposited over a grazing area that may result in a grazing animal's milk equaling the Intervention Level for the radionuclide at the time it is distributed in commerce.

Calculation

Equation 3.3-1 shows this $Milk\_DRL_{area}$ calculation.

$$Milk\_DRL_{area,A,i,t_n} = \frac{IL_{organ,age,i} * e^{-\lambda_i t_n} * WF_{t_n}}{\left[\left(\frac{CRF_{forage} * e^{-\lambda_w t_g}}{Y_{forage}} + \frac{TF_{forage,i} * MCF_{D-W,forage}}{\rho_{soil} * d_{e,forage}}\right) * AFDIR_{A,forage} + \frac{WF_{t_g} * ASDIR_A}{\rho_{soil} * d_m}\right] * FDC_{forage} * \frac{TF_{Milk,A,i}}{\rho_{milk}} * e^{-\lambda_i (t_h + t_m)}}$$

(Eq. 3.3-1)

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

where:

$Milk\_DRL_{area,A,i,tn}$= Milk Derived Response Level – Area, the areal activity, at time t_n, of radionuclide i present in a grazing area that may cause the grazing animal's (A) milk to equal the applicable Intervention Level at the time it is distributed in commerce, µCi/m^2;

$IL_{organ,age,i}$ = Intervention Level, the concentration of radionuclide i in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG, µCi/kg$_{wet}$;

NOTE: Intervention Levels may be either a published FDA Derived Intervention Level (DIL) or calculated FRMAC Intervention Level (FIL) from Method 3.1.

λ_i = Decay constant for radionuclide i, d^{-1};

t_n = Evaluation Time, the point in time, relative to the start of the release, for which the calculation, measurement, or prediction is valid, d;

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

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

CRF_{forage} = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the forage (See Appendix C, Table 11), unitless;

NOTE: For crops not growing above the surface at the time of deposition, the CRF=0.

λ_w = Decay constant for weathering radioactive material off plants (See Appendix C, Table 11), d^{-1};

t_g = Time to Grazing, the time from deposition until the animal begins eating the contaminated forage, d;

Y_{forage} = Crop Yield, the mass of forage grown per area of pastureland (See Appendix C, Table 11), kg$_{wet}$/m^2;

$TF_{forage,i}$ = Transfer Factor for forage, the fraction of radionuclide i deposited on the growing medium that is transferred to the forage (See Appendix C, Table 8-1), µCi/kg$_{dry}$ per µCi/kg$_{soil}$;

$MCF_{D\text{-}W,forage}$ = Mass Conversion Factor (dry to wet), the ratio of dry mass to wet mass for forage (See Appendix C, Table 9-1), kg$_{dry}$/kg$_{wet}$;

ρ_{soil} = Soil density (See Appendix C, Table 11), kg$_{soil}$/m^3;

$d_{e,forage}$ = Effective Soil Depth, the maximum of the mixing depth (d_m) and the mature root depth (d_r) for the forage (See Appendix C, Table 11), m;

NOTE: Default mixing depth is 1.0E-3 m prior to plowing and 0.15 m after plowing.

$AFDIR_{A,forage}$ = Animal Feed Daily Intake Rate (forage), the daily rate at which an animal (*A*) consumes forage (See Appendix C, Table 11), kg_{wet}/d;

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

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

d_m = Mixing Depth (See Appendix C, Table 11), m;

$ASDIR_A$ = Animal Soil Daily Intake Rate, the daily rate at which an animal (*A*) consumes soil (See Appendix C, Table 11), kg_{soil}/d;

FDC_{forage} = Fraction of Diet Contaminated (forage), the fraction of the animal's forage that is contaminated (See Appendix C, Table 11), unitless;

$TF_{Milk,A,i}$ = Transfer Factor for Milk, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the milk produced by the animal (See Appendix C, Table 8-2), µCi/l_{milk} per µCi/d;

ρ_{milk} = Milk density (See Appendix C, Table 11), kg_{wet}/l_{milk};

t_h = Time to Harvest, the time from deposition until the animal product is collected, d; and

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d.

Method 3.3.2 Milk DRL based on radionuclide concentration (µCi/kg_{wet}) in fodder mass

This method calculates the mass concentration level (µCi/kg_{wet}) of a radionuclide in animal fodder that may result in the animal's milk equaling the Intervention Level for the radionuclide at the time it is distributed in commerce.

The Time to Grazing (when the animal starts eating the contaminated fodder) is not needed in this calculation because:

1. Transfer factors assume instantaneous equilibrium between the animal product and the fodder.
2. Weathering is not included; therefore, the only removal function is radioactive decay.
3. Time to Harvest accounts for all radioactive decay from deposition to the time the animal product is collected for introduction into commerce.

NOTE: Because any form of "weathering" that could be applied to this calculation could vary by such a large amount (dependent on the method of storage of the fodder source), and because not including weathering is the conservative approach, no consideration of physical removal of contamination from the fodder mass is addressed in this method.

NOTE: Soil ingestion is not included in this method because any soil (and any radioactive material) included in the fodder being analyzed may inherently be included in the mass and activity values determined by the measurement process.

Calculation

Equation 3.3-2 shows this $Milk\_DRL_{mass}$ calculation.

$$Milk\_DRL_{mass,A,i,t_n} = \frac{IL_{organ,age,i} * e^{-\lambda_i t_n}}{AFDIR_{A,fodder} * FDC_{fodder} * \frac{TF_{Milk,A,i}}{\rho_{milk}} * e^{-\lambda_i (t_h + t_m)}} \quad \text{(Eq. 3.3-2)}$$

$$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} = \frac{\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \text{unitless}}{\frac{\text{kg}_{\text{wet}}}{\text{d}} * \text{unitless} * \frac{\left(\frac{\mu\text{Ci}}{\text{l}_{\text{milk}}} / \frac{\mu\text{Ci}}{\text{d}}\right)}{\frac{\text{kg}_{\text{wet}}}{\text{l}_{\text{milk}}}} * \text{unitless}}$$

where:

$Milk\_DRL_{mass,A,i,tn}$ = Milk Derived Response Level – Mass, the mass concentration of radionuclide *i* in animal fodder, at time t_n, that may result in the grazing animal's (*A*) milk equaling the Intervention Level for that radionuclide at the time it is distributed in commerce, μCi/kg$_{\text{wet}}$;

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

NOTE: Intervention Levels may be either a published FDA Derived Intervention Level (DIL) or calculated FRMAC Intervention Level (FIL) from Method 3.1.

λ_i = Decay constant for radionuclide i, d^{-1};

t_n = Evaluation Time, the point in time, relative to the start of the release, for which the calculation, measurement, or prediction is valid, d;

$AFDIR_{A,fodder}$ = Animal Feed Daily Intake Rate (fodder), the daily rate at which an animal (A) consumes fodder (See Appendix C, Table 11), kg_{wet}/d;

FDC_{fodder} = Fraction of Diet Contaminated (fodder), the fraction of the animal's fodder that is contaminated (See Appendix C, Table 11), unitless;

$TF_{Milk,A,i}$ = Transfer Factor for Milk, the fraction of radionuclide i consumed by an animal (A) that is transferred to the milk produced by the animal (See Appendix C, Table 8-2, µCi/l_{milk} per µCi/d;

ρ_{milk} = Milk density (See Appendix C, Table 11), kg_{wet}/l_{milk};

t_h = Time to Harvest, the time from deposition until the animal product is collected, d; and,

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d.

Method 3.3.3 Milk DRL 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 may result in the animal's milk equaling the Intervention Level for the radionuclide at the time it is distributed in commerce.

The time when the animal starts drinking the contaminated water is not needed in this calculation because:

1. Transfer factors assume instantaneous equilibrium between the animal product and the water.
2. Weathering is not included; therefore, the only removal function is radioactive decay.
3. Time to Harvest accounts for all effects of radioactive decay from deposition to the time the animal product is collected for introduction into commerce.

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.

NOTE: Soil ingestion is not included in this method because any soil (and any radioactive material) included in the water being analyzed may inherently be included in the mass and activity values determined by the measurement process.

Calculation

Equation 3.3-3 shows this $Milk\_DRL_{water}$ calculation.

$$Milk\_DRL_{water,A,i,t_n} = \frac{IL_{organ,age,i} * e^{-\lambda_i t_n}}{AFDIR_A * FDC_{water} * \frac{TF_{Milk,A,i}}{\rho_{milk}} * e^{-\lambda_i (t_h + t_m)}} \quad \text{(Eq. 3.3-3)}$$

$$\frac{\mu\text{Ci}}{\text{l}_{\text{water}}} = \frac{\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \text{unitless}}{\frac{\text{l}_{\text{water}}}{\text{d}} * \text{unitless} * \frac{\left(\frac{\mu\text{Ci}}{\text{l}_{\text{milk}}} / \frac{\mu\text{Ci}}{\text{d}}\right)}{\frac{\text{kg}_{\text{wet}}}{\text{l}_{\text{milk}}}} * \text{unitless}}$$

where:

$Milk\_DRL_{water,A,i,tn}$ = Milk Derived Response Level – Water, the water concentration of radionuclide *i* in an animal's drinking water, at time t_n, that may result in the grazing animal's (*A*) milk equaling the Intervention Level for that radionuclide at the time it is distributed in commerce, µCi/l_{water};

$IL_{organ,age,i}$ = Intervention Level, the concentration of radionuclide *i* in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG, µCi/kg_{wet};

NOTE: Intervention Levels may be either a published FDA Derived Intervention Level (DIL) or calculated FRMAC Intervention Level (FIL) from Method 3.1.

λ_i = Decay constant for radionuclide *i*, d^{-1};

t_n = Evaluation Time, the point in time, relative to the start of the release, for which the calculation, measurement, or prediction is valid, d;

$AWDIR_A$ = Animal Water Daily Intake Rate, the daily rate at which an animal (*A*) consumes water (See Appendix C, Table 11), l_{water}/d;

FDC_{water} = Fraction of Diet Contaminated (water), the fraction of the animal's water that is contaminated (See Appendix C, Table 11), unitless;

$TF_{Milk,A,i}$ = Transfer Factor for Milk, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the milk produced by the animal (See Appendix C, Table 8-2), µCi/l_{milk} per µCi/d;

ρ_{milk} = Milk density (See Appendix C, Table 11), kg_{wet}/l_{milk};

t_h = Time to Harvest, the time from deposition until the animal product is collected, d; and,

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d.

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EXAMPLE 1

Problem: Calculate the Milk DRL for Area measured 7 days after deposition for a milk cow that will graze in an area contaminated with Co-60 beginning 14 days after deposition and whose milk will be harvested 30 days after deposition.

The most conservative Intervention Level for Co-60 is 3.55E-02 µCi/kg_{wet} (1-year-old, whole body).

Equation 3.3-1 can be used to calculate the DRL.

$$Milk\_DRL_{area,A,i,t_n} = \frac{IL_{organ,age,i} * e^{-\lambda_i t_n} * WF_{t_n}}{\left[\left(\frac{CRF_{forage} * e^{-\lambda_w t_g}}{Y_{forage}} + \frac{TF_{forage,i} * MCF_{D-W,forage}}{\rho_{soil} * d_{e,forage}}\right) * AFDIR_{A,forage} + \frac{WF_{t_g} * ASDIR_A}{\rho_{soil} * d_m}\right] * FDC_{forage} * \frac{TF_{Milk,A,i}}{\rho_{milk}} * e^{-\lambda_i (t_h + t_m)}}$$

Assuming:

$\lambda_{Co\text{-}60}$ = 3.60E-04 d^{-1},
t_n = 7 d,

WF_{7d} = 0.996,

CRF_{forage} = 0.5,
λ_w = 4.62E-02 d^{-1},

t_g = 14 d,

Y_{forage} = 0.7 kg_{wet}/m^2,
$TF_{forage,Co}$ = 4.5E-02 µCi/kg_{dry} per µCi/kg_{soil},

$MCF_{D\text{-}W,\,forage}$ = 0.22 kg_{dry}/kg_{wet},

ρ_{soil} = 1600 kg_{soil}/m^3,
$d_{e,forage}$ = 0.6 m,

$AFDIR_{cow,forage}$ = 50 kg_{wet}/d,
WF_{14d} = 0.993,
$ASDIR_{cow}$ = 0.5 kg_{soil}/d,
d_m = 1.0E-03 m,
FDC_{forage} = 1.0,
$TF_{Milk,cow,Co}$ = 1.1E-04 µCi/l_{milk} per µCi/d,
ρ_{milk} = 1.04 kg_{wet}/l_{milk},
t_h = 30 d, and

t_m = 2 d.

The *Milk_DRL_{area}* for Co-60 for cow milk equals:

$$Milk\_DRL_{area,cow,{}^{60}Co,7d} = \frac{3.55\text{E-}02\frac{\mu Ci}{kg_{wet}} * e^{-3.6\text{E-}04 d^{-1} * 7d} * 0.996}{\left[\left(\frac{0.5 * e^{-4.62\text{E-}02 d^{-1} * 14d}}{0.7\frac{kg_{wet}}{m^2}} + \frac{4.5\text{E-}02\left(\frac{\mu Ci/kg_{dry}}{\mu Ci/kg_{soil}}\right) * 0.22\frac{kg_{dry}}{kg_{wet}}}{1600\frac{kg_{soil}}{m^3} * 0.6m}\right) * 50\frac{kg_{wet}}{d} + \frac{0.993 * 0.5\frac{kg_{soil}}{d}}{1600\frac{kg_{soil}}{m^3} * 1.0\text{E-}03m}\right] * 1.0 * \frac{1.1\text{E-}04\left(\frac{\mu Ci}{l_{milk}}/\frac{\mu Ci}{d}\right)}{1.04\frac{kg_{wet}}{l_{milk}}} * e^{-3.6\text{E-}04 d^{-1} * (30d + 2d)}}$$

$$= 17.7\ \frac{\mu Ci}{m^2}$$

Therefore, cows which started grazing 14 days after deposition, in areas with Co-60 contamination on the ground greater than 17.7 $\mu Ci/m^2$ 7 days after deposition, have the potential to produce milk that may equal the Intervention Level when that milk enters commerce 32 days after deposition. Milk that equals the Intervention Level could produce a dose that equals the PAG when consumed by a 1 year old.

EXAMPLE 2

Problem: Calculate the Milk DRL for Mass measured 7 days after deposition for a milk cow that will eat fodder contaminated with Co-60 and whose milk will be harvested 30 days after deposition.

The most conservative Intervention Level for Co-60 is 3.55E-02 µCi/kg_{wet} (1-year-old, whole body).

Equation 3.3-2 can be used to calculate the DRL.

$$Milk\_DRL_{mass,A,i,t_n} = \frac{IL_{organ,age,i} * e^{-\lambda_i t_n}}{AFDIR_{A,fodder} * FDC_{fodder} * \frac{TF_{Milk,A,i}}{\rho_{Milk}} * e^{-\lambda_i (t_h + t_m)}}$$

Assuming:

$\lambda_{Co\text{-}60}$ = 3.60E-04 d^{-1},
t_n = 7 d,

$AFDIR_{cow,fodder}$ = 50 kg_{wet}/d,
FDC_{fodder} = 1.0,
$TF_{Milk,cow,Co}$ = 1.1E-04 µCi/l_{milk} per µCi/d,
ρ_{milk} = 1.04 kg_{wet}/l_{milk},
t_h = 30 d, and
t_m = 2 d.

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

$$Milk\_DRL_{mass,cow,{}^{60}Co,7d} = \frac{3.55\text{E-}02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * e^{-3.6\text{E-}04\text{d}^{-1} * 7\text{d}}}{50 \frac{\text{kg}_{\text{wet}}}{\text{d}} * 1 * \frac{1.1\text{E-}04 \frac{\mu\text{Ci}/1_{\text{milk}}}{\mu\text{Ci}/\text{d}}}{1.04 \frac{\text{kg}_{\text{wet}}}{1_{\text{milk}}}} * e^{-3.6\text{E-}04\text{d}^{-1} * (30\text{d} + 2\text{d})}}$$

$$= 6.77 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

Therefore, cows that eat fodder with Co-60 contamination greater than 6.77 µCi/kg_{wet} 7 days after deposition, have the potential to produce milk that may equal the Intervention Level when that milk enters commerce 32 days after deposition. Milk that equals the Intervention Level could produce a dose that equals the PAG when consumed by a 1-year-old.

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EXAMPLE 3

Problem: Calculate the Milk DRL for Water measured 7 days after deposition for a milk cow that will drink water contaminated with Co-60 and whose milk will be harvested 30 days after deposition.

The most conservative Intervention Level for Co-60 is 3.55E-02 µCi/kg_{wet} (1-year-old, whole body).

Equation 3.3-3 can be used to calculate the DRL.

$$Milk\_DRL_{water,A,i,t_n} = \frac{IL_{organ,age,i} * e^{-\lambda_i t_n}}{AFDIR_A * FDC_{water} * \frac{TF_{Milk,A,i}}{\rho_{Milk}} * e^{-\lambda_i (t_h + t_m)}}$$

Assuming:

$\lambda_{Co\text{-}60}$ = 3.60E-04 d^{-1},
t_n = 7 d,

$AWDIR_{cow,milk}$ = 60 l_{water}/d,
FDC_{water} = 1.0,
$TF_{Milk,cow,Co}$ = 1.1E-04 µCi/l_{milk} per µCi/d,
ρ_{milk} = 1.04 kg_{wet}/l_{milk},
t_h = 30 d, and

t_m = 2 d.

The *Milk_DRL*$_{water}$ for Co-60 for cow milk equals:

$$Milk\_DRL_{water,cow,{}^{60}Co,7d} = \frac{3.55\text{E-}02 \frac{\mu\text{Ci}}{\text{kg}_\text{wet}} * e^{-3.6\text{E-}04\text{d}^{-1} * 7\text{d}}}{60 \frac{1_\text{water}}{\text{d}} * 1 * \frac{1.1\text{E-}04 \frac{\mu\text{Ci}/l_\text{milk}}{\mu\text{Ci}/\text{d}}}{1.04 \frac{\text{kg}_\text{wet}}{l_\text{milk}}} * e^{-3.6\text{E-}04\text{d}^{-1} * (30\text{d}+2\text{d})}}$$

$$= 5.64 \frac{\mu\text{Ci}}{l_\text{milk}}$$

Therefore, cows that drink water with Co-60 contamination greater than 5.64 µCi/l 7 days after deposition, have the potential to produce milk that may equal the Intervention Level when that milk enters commerce 32 days after deposition. Milk that equals the Intervention Level could produce a dose that equals the PAG when consumed by a 1-year-old.

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METHOD 3.4 MEAT DERIVED RESPONSE LEVEL

Application

This method has been developed to calculate Ingestion Derived Response Levels for radioactive material deposited on animal feed (forage or fodder) or water for the meat pathway.

The Meat Derived Response Level (Meat_DRL):

1) Is calculated using the Intervention Levels – either published Food and Drug Administration (FDA) Derived Intervention Level (DIL) or calculated FRMAC Intervention Level (FIL) – from Method 3.1

2) Represents:
   a. $Meat\_DRL_{area,A,i}$: The areal activity, at time t_n, of radionuclide *i* present in a grazing area that may cause the grazing animal's meat to equal the applicable Intervention Level for that radionuclide at the time it is distributed in commerce;
   b. $Meat\_DRL_{mass,A,i}$: The mass concentration of radionuclide *i* present in animal fodder that may cause the animal's meat to equal the applicable Intervention Level for that radionuclide at the time it is distributed in commerce; or
   c. $Meat\_DRL_{water,A,i}$: The water concentration , of radionuclide *i* present in an animal's drinking water that may cause the animal's meat to equal the applicable Intervention Level for that radionuclide at the time it is distributed in commerce.

3) Is indirectly derived (through the Intervention Level) from the PAG for radiological emergency planning established by the FDA (FDA98). A projected or measured concentration value greater than the Meat_DRL indicates the potential to exceed the PAG.

4) Is applied during the first year after an incident and based on the most sensitive population (age group) and target organ to provide a large margin of safety to the public (FDA98).

5) 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).

Discussion

The Meat_DRL predicts the amount of radioactivity deposited either on an animal's grazing area ($\mu Ci/m^2$) or in an animal's feed (forage or fodder) or water ($\mu Ci/kg_{wet}$ or $\mu Ci/l$) that may cause the animal's meat to equal the Intervention Level at the time it is distributed in commerce. Sampling efforts should concentrate on the area where the contamination is equal to or greater than the Meat_DRL to determine if the Intervention Level has been exceeded in those areas.

Protective actions (e.g., use of uncontaminated stored feed (fodder)) should be considered in areas where the Intervention Level is exceeded. Meat embargo protective actions should be considered after meat samples indicate that the Intervention Level has actually been exceeded. FDA guidance permits food with radioactivity concentrations below the Intervention Level to move in commerce without restriction. However, the FDA and local decision makers have flexibility in whether to apply restrictions in special circumstances.

Each section of this method accounts for some or all the following processes that change the level of radioactive material present in an animal's meat:

	DRL Type		
Process	Area	Mass	Water
1. Reduction in radioactivity level due to biological processes in the animal's forage	X		
2. Increase in radioactivity level due to root uptake to the animal's forage from contaminated soil	X		
3. Increase in radioactivity level due to re-deposition of resuspended material on the animal's forage	X		
4. Reduction in radioactivity level due to material weathering off the animal's forage until the animal begins grazing	X		
5. Increase in radioactivity level due to the animal consuming contaminated feed/water	X	X	X
6. Reduction in radioactivity level due to radioactive decay until the meat is harvested	X	X	X
7. Reduction in radioactivity level due to transport time to market	X	X	X

This method addresses processes 1, 2, 3, and 5 using element-dependent Transfer Factors (TFs).

Two different TFs are included in the calculations in this Method:

1. Transfer from the soil to growing forage in the contaminated grazing area (Process 1-3)

2. Transfer from the contaminated feed/water to the animal's meat (Process 5)

Use of TFs includes the assumption that the impacted animal will remain grazing or drinking in the contaminated area long enough for its meat to reach equilibrium with the radioactive material deposited over the grazing area or on its fodder or water supply. Therefore, this method may overestimate uptake for animals that are immediately ready for harvest after contamination, resulting in a more conservative DRL.

Assumptions

There are no additional assumptions beyond the Default Assumptions above.

Inputs

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

1) Data – Composition of the deposited radionuclide mixture (radionuclides). This information may come from predictive analysis (atmospheric dispersion models) or field data (monitoring and/or samples).

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

3) Other Factors – Decay of radionuclides during the time period under consideration, fraction of animals' diet contaminated, soil mixing depth, mature root depth, timing inputs.

4) Appropriate Intervention Level for each radionuclide – From Method 3.1.

5) Evaluation Time (t_n) – The point in time, relative to the start of the release, for which the calculation, measurement, or prediction is valid.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

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

Outputs

Final

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

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

a. $Meat\_DRL_{area}$: The areal activity, at time t_n, of radionuclide *i* deposited over a grazing area that may result in the grazing animal's meat equaling the Intervention Level for that radionuclide at the time it is distributed in commerce ($\mu Ci/m^2$);
b. $Meat\_DRL_{mass}$: The mass concentration, at time t_n, of radionuclide *i* in animal fodder that may result in the animal's meat equaling the Intervention Level for that radionuclide at the time it is distributed in commerce; ($\mu Ci/kg_{wet}$) or
c. $Meat\_DRL_{water}$: The water concentration, at time t_n, of radionuclide *i* in an animal's drinking water that may result in the animal's meat equaling the Intervention Level for that radionuclide at the time it is distributed in commerce; ($\mu Ci/l_{water}$).

Intermediate

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

None

Method 3.4.1 Meat DRL based on areal activity (µCi/m²) on forage

This method calculates the areal activity level (µCi/m²) of a radionuclide deposited over a grazing area that may result in a grazing animal's meat equaling the Intervention Level for the radionuclide at the time it is distributed in commerce.

Calculation

Equation 3.4-1 shows this $Meat\_DRL_{area}$ calculation.

$$Meat\_DRL_{area,A,i,t_n} = \frac{IL_{organ,age,i} * e^{-\lambda_i t_n} * WF_{t_n}}{\left[\left(\frac{CRF_{forage} * e^{-\lambda_w t_g}}{Y_{forage}} + \frac{TF_{forage,i} * MCF_{D-W,forage}}{\rho_{soil} * d_{e,forage}}\right) * AFDIR_{A,forage} + \frac{WF_{t_g} * ASDIR_A}{\rho_{soil} * d_m}\right] * FDC_{forage} * TF_{Meat,A,i} * e^{-\lambda_i (t_h + t_m)}}$$

(Eq. 3.4-1)

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

where:

$Meat\_DRL_{area,A,i,tn}$= Meat Derived Response Level – Area, the areal activity, at time t_n, of radionuclide i present in a grazing area that may cause the grazing animal's (A) meat to equal the applicable Intervention Level at the time it is distributed in commerce, µCi/m²;

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

NOTE: Intervention Levels may be either a published FDA Derived Intervention Level (DIL) or calculated FRMAC Intervention Level (FIL) from Method 3.1.

λ_i = Decay constant for radionuclide *i*, d^{-1};

t_n = Evaluation Time, the point in time, relative to the start of the release, for which the calculation, measurement, or prediction is valid, d;

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

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

CRF_{forage} = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the forage (See Appendix C, Table 11), unitless;

NOTE: For crops not growing above the surface at the time of deposition, the CRF=0.

λ_w = Decay constant for weathering radioactive material off plants (See Appendix C, Table 11), d^{-1};

t_g = Time to Grazing, the time from deposition until the animal begins eating the contaminated forage, d;

Y_{forage} = Crop Yield, the mass of forage grown per area of pastureland (See Appendix C, Table 11), kg_{wet}/m^2;

$TF_{forage,i}$ = Transfer Factor for forage, the fraction of radionuclide *i* deposited on the growing medium that is transferred to the forage (See Appendix C, Table 8-1), $\mu Ci/kg_{dry}$ per $\mu Ci/kg_{soil}$;

$MCF_{D\text{-}W,forage}$ = Mass Conversion Factor (dry to wet), the ratio of dry mass to wet mass for forage (See Appendix C, Table 9-1), kg_{dry}/kg_{wet};

ρ_{soil} = Soil density (See Appendix C, Table 11), kg_{soil}/m^3;

$d_{e,forage}$ = Effective Soil Depth, the maximum of the mixing depth (d_m) and the mature root depth (d_r) for the forage (See Appendix C, Table 11), m;

NOTE: Default mixing depth is 1.0E-3 m prior to plowing and 0.15 m after plowing.

$AFDIR_{A,forage}$ = Animal Feed Daily Intake Rate (forage), the daily rate at which an animal (A) consumes forage (See Appendix C, Table 11), kg_{wet}/d;

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

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

d_m = Mixing Depth (See Appendix C, Table 11), m;

$ASDIR_A$ = Animal Soil Daily Intake Rate, the daily rate at which an animal (A) consumes soil (See Appendix C, Table 11), kg_{soil}/d;

FDC_{forage} = Fraction of Diet Contaminated (forage), the fraction of the animal's forage that is contaminated (See Appendix C, Table 11), unitless;

$TF_{Meat,A,i}$ = Transfer Factor for Meat, the fraction of radionuclide i consumed by an animal (A) that is transferred to the meat produced by the animal (See Appendix C, Table 8-2), µCi/kg_{meat} per µCi/d;

t_h = Time to Harvest, the time from deposition until the animal product is collected, d; and

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d.

Method 3.4.2 Meat DRL based on radionuclide concentration (µCi/kg_{wet}) in fodder mass

This method calculates the mass concentration level (µCi/kg_{wet}) of a radionuclide in animal fodder that may result in the animal's meat equaling the Intervention Level for the radionuclide at the time it is distributed in commerce.

The Time to Grazing (when the animal starts eating the contaminated fodder) is not needed in this calculation because:

1. Transfer factors assume instantaneous equilibrium between the animal product and the fodder.
2. Weathering is not included; therefore, the only removal function is radioactive decay.
3. Time to Harvest accounts for all radioactive decay from deposition to the time the animal product is collected for introduction into commerce.

NOTE: Because any form of "weathering" that could be applied to this calculation could vary by such a large amount (dependent on the method of storage of the fodder source), and because not including weathering is the conservative approach, no consideration of physical removal of contamination from the fodder mass is addressed in this method.

NOTE: Soil ingestion is not included in this method because any soil (and any radioactive material) included in the fodder being analyzed may inherently be included in the mass and activity values determined by the measurement process.

Calculation

Equation 3.4-2 shows this $Meat\_DRL_{mass}$ calculation.

$$Meat\_DRL_{mass,A,i,t_n} = \frac{IL_{organ,age,i} * e^{-\lambda_i t_n}}{AFDIR_{A,fodder} * FDC_{fodder} * TF_{Meat,A,i} * e^{-\lambda_i(t_h+t_m)}}$$

(Eq. 3.4-2)

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

where:

$Meat\_DRL_{mass,A,i,tn}$ = Meat Derived Response Level – Mass, the mass concentration of radionuclide i in animal fodder, at time t_n, that may result in the grazing animal's (A) meat equaling the Intervention Level for that radionuclide at the time it is distributed in commerce, µCi/kg_{wet};

$IL_{organ,age,i}$ = Intervention Level, the concentration of radionuclide i in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG, µCi/kg_{wet};

NOTE: Intervention Levels may be either a published FDA Derived Intervention Level (DIL) or calculated FRMAC Intervention Level (FIL) from Method 3.1.

λ_i = Decay constant for radionuclide i, d^{-1};

t_n = Evaluation Time, the point in time, relative to the start of the release, for which the calculation, measurement, or prediction is valid, d;

$AFDIR_{A,fodder}$ = Animal Feed Daily Intake Rate (fodder), the daily rate at which an animal (A) consumes fodder (See Appendix C, Table 11), kg_{wet}/d;

FDC_{fodder} = Fraction of Diet Contaminated (fodder), the fraction of the animal's fodder that is contaminated (See Appendix C, Table 11), unitless;

$TF_{Meat,A,i}$ = Transfer Factor for Meat, the fraction of radionuclide i consumed by an animal (A) that is transferred to the meat produced by the animal (See Appendix C, Table 8-2), µCi/kg_{wet} per µCi/d;

t_h = Time to Harvest, the time from deposition until the animal product is collected, d; and,

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d.

Method 3.4.3 Meat DRL 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 may result in the animal's meat equaling the Intervention Level for the radionuclide at the time it is distributed in commerce.

The time when the animal starts drinking the contaminated water is not needed in this calculation because:

1. Transfer factors assume instantaneous equilibrium between the animal product and the water.
2. Weathering is not included; therefore, the only removal function is radioactive decay.
3. Time to Harvest accounts for all effects of radioactive decay from deposition to the time the animal product is collected for introduction into commerce.

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.

NOTE: Soil ingestion is not included in this method because any soil (and any radioactive material) included in the water being analyzed may inherently be included in the mass and activity values determined by the measurement process.

Calculation

Equation 3.4-3 shows this $Meat\_DRL_{water}$ calculation.

$$Meat\_DRL_{water,A,i,t_n} = \frac{IL_{organ,age,i} * e^{-\lambda_i t_n}}{AFDIR_A * FDC_{water} * TF_{Meat,A,i} * e^{-\lambda_i (t_h + t_m)}}$$

(Eq. 3.4-3)

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

where:

$Meat\_DRL_{water,A,i,tn}$ = Meat Derived Response Level – Water, the water concentration of radionuclide *i* in an animal's drinking water, at time t_n, that may result in the grazing animal's (*A*) meat equaling the Intervention Level for that radionuclide at the time it is distributed in commerce, μCi/l_{water};

$IL_{organ,age,i}$ = Intervention Level, the concentration of radionuclide *i* in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG, μCi/kg_{wet};

NOTE: Intervention Levels may be either a published FDA Derived Intervention Level (DIL) or calculated FRMAC Intervention Level (FIL) from Method 3.1.

λ_i = Decay constant for radionuclide *i*, d^{-1};

t_n = Evaluation Time, the point in time, relative to the start of the release, for which the calculation, measurement, or prediction is valid, d;

$AWDIR_A$ = Animal Water Daily Intake Rate, the daily rate at which an animal (*A*) consumes water (See Appendix C, Table 11), l_{water}/d;

FDC_{water} = Fraction of Diet Contaminated (water), the fraction of the animal's water that is contaminated (See Appendix C, Table 11), unitless;

$TF_{Meat,A,i}$ = Transfer Factor for Meat, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the meat produced by the animal (See Appendix C, Table 8-2), μCi/kg_{wet} per μCi/d;

t_h = Time to Harvest, the time from deposition until the animal product is collected, d; and,

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d.

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EXAMPLE 1

Problem: Calculate the Meat (Beef) DRL for Area measured 7 days after deposition for a cow that will graze in an area contaminated with Co-60 beginning 14 days after deposition and whose meat will be harvested 30 days after deposition.

The most conservative Intervention Level for Co-60 is 3.55E-02 µCi/kg_{wet} (1-year-old, whole body).

Equation 3.4-1 can be used to calculate the DRL.

$$Meat\_DRL_{area,A,i,t_n} = \frac{IL_{organ,age,i} * e^{-\lambda_i t_n} * WF_{t_n}}{\left[\left(\frac{CRF_{forage} * e^{-\lambda_w t_g}}{Y_{forage}} + \frac{TF_{forage,i} * MCF_{D-W,forage}}{\rho_{soil} * d_{e,forage}}\right) * AFDIR_{A,forage} + \frac{WF_{t_g} * ASDIR_A}{\rho_{soil} * d_m}\right] * FDC_{forage} * TF_{Meat,A,i} * e^{-\lambda_i (t_h + t_m)}}$$

Assuming:

$\lambda_{Co\text{-}60}$ = 3.60E-04 d^{-1},
t_n = 7 d,

WF_{7d} = 0.996,

CRF_{forage} = 0.5,
λ_w = 4.62E-02 d^{-1},

t_g = 14 d,

Y_{forage} = 0.7 kg_{wet}/m^2,
$TF_{forage,Co}$ = 4.5E-02 µCi/kg_{dry} per µCi/kg_{soil},

$MCF_{D\text{-}W,forage}$ = 0.22 kg_{dry}/kg_{wet},

ρ_{soil} = 1600 kg_{soil}/m^3,
$d_{e,forage}$ = 0.6 m,

$AFDIR_{cow,forage}$ = 50 kg_{wet}/d,
WF_{14d} = 0.993,
$ASDIR_{cow}$ = 0.5 kg_{soil}/d,
d_m = 1.0E-03 m,
FDC_{forage} = 1.0,
$TF_{Meat,cow,Co}$ = 4.3E-04 µCi/kg_{wet} per µCi/d,
t_h = 30 d, and

t_m = 20 d.

The *Meat_DRL_{area}* for Co-60 for beef equals:

$$Meat\_DRL_{area,cow,^{60}Co,7d} = \frac{3.55\text{E-}02\,\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * e^{-3.6\text{E-}04\text{d}^{-1}*7\text{d}} * 0.996}{\left[\left(\begin{array}{c}\frac{0.5 * e^{-4.62\text{E-}02\text{d}^{-1}*14\text{d}}}{0.7\,\frac{\text{kg}_{\text{wet}}}{\text{m}^2}} \\ + \frac{4.5\text{E-}02\left(\frac{\mu\text{Ci}/\text{kg}_{\text{dry}}}{\mu\text{Ci}/\text{kg}_{\text{soil}}}\right) * 0.22\,\frac{\text{kg}_{\text{dry}}}{\text{kg}_{\text{wet}}}}{1600\,\frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 0.6\text{m}}\end{array}\right) * 50\,\frac{\text{kg}_{\text{wet}}}{\text{d}} + \frac{0.993 * 0.5\,\frac{\text{kg}_{\text{soil}}}{\text{d}}}{1600\,\frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 1.0\text{E-}03\text{m}}\right] * 1.0 * 4.3\text{E-}04\left(\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} / \frac{\mu\text{Ci}}{\text{d}}\right) * e^{-3.6\text{E-}04\,\text{d}^{-1}*(30\text{d}+20\text{d})}}$$

$$= 4.39\,\frac{\mu\text{Ci}}{\text{m}^2}$$

Therefore, cows which started grazing 14 days after deposition, in areas with Co-60 contamination on the ground greater than 4.39 μCi/m^2 7 days after deposition, have the potential to produce meat (beef) that may equal the Intervention Level when that meat enters commerce 50 days after deposition. Meat that equals the Intervention Level could produce a dose that equals the PAG when consumed by a 1 year old.

EXAMPLE 2

Problem: Calculate the Meat (Beef) DRL for Mass measured 7 days after deposition for a cow that will eat fodder contaminated with Co-60 and whose meat will be harvested 30 days after deposition.

The most conservative Intervention Level for Co-60 is 3.55E-02 µCi/kg_{wet} (1-year-old, whole body).

Equation 3.4-2 can be used to calculate the DRL.

$$Meat\_DRL_{mass,A,i,t_n} = \frac{IL_{organ,age,i} * e^{-\lambda_i t_n}}{AFDIR_{A,fodder} * FDC_{fodder} * TF_{Meat,A,i} * e^{-\lambda_i (t_h + t_m)}}$$

Assuming:

$\lambda_{Co\text{-}60}$ = 3.60E-04 d^{-1},
t_n = 7 d,

$AFDIR_{cow,fodder}$ = 50 kg_{wet}/d,
FDC_{fodder} = 1.0,
$TF_{Meat,cow,Co}$ = 4.3E-04 µCi/ kg_{wet} per µCi/d,
t_h = 30 d, and

t_m = 20 d.

The $Meat\_DRL_{mass}$ for Co-60 for beef equals:

$$Meat\_DRL_{mass,cow,{}^{60}Co,7d} = \frac{3.55\text{E-}02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * e^{-3.6\text{E-}04\text{d}^{-1} * 7\text{d}}}{50\,\frac{\text{kg}_{\text{wet}}}{\text{d}} * 1 * 4.3\text{E}-04\left(\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} / \frac{\mu\text{Ci}}{\text{d}}\right) * e^{-3.6\text{E-}04\ \text{d}^{-1} * (30\text{d}+20\text{d})}}$$

$$= 1.68 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

Therefore, cows that eat fodder with Co-60 contamination greater than 1.68 µCi/kg_{wet} 7 days after deposition, have the potential to produce meat (beef) that may equal the Intervention Level when that meat enters commerce 50 days after deposition. Meat that equals the Intervention Level could produce a dose that equals the PAG when consumed by a 1-year-old.

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EXAMPLE 3

Problem: Calculate the Meat (Beef) DRL for Water measured 7 days after deposition for a cow that will drink water contaminated with Co-60 and whose meat will be harvested 30 days after deposition.

The most conservative Intervention Level for Co-60 is 3.55E-02 µCi/kg_{wet} (1-year-old, whole body).

Equation 3.4-3 can be used to calculate the DRL.

$$Meat\_DRL_{water,A,i,t_n} = \frac{IL_{organ,age,i} * e^{-\lambda_i t_n}}{AFDIR_A * FDC_{water} * TF_{Meat,A,i} * e^{-\lambda_i (t_h + t_m)}}$$

Assuming:

$\lambda_{Co\text{-}60}$ = 3.60E-04 d^{-1},
t_n = 7 d,

$AWDIR_{cow,beef}$ = 50 l_{water}/d,
FDC_{water} = 1.0,
$TF_{Meat,cow,Co}$ = 4.3E-04 µCi/ kg_{wet} per µCi/d,
t_h = 30 d, and

t_m = 20 d.

The $Meat\_DRL_{water}$ for Co-60 for beef equals:

$$Meat\_DRL_{water,cow,{}^{60}Co,7d} = \frac{3.55\text{E-}02 \frac{\mu Ci}{kg_{wet}} * e^{-3.6\text{E-}04 d^{-1} * 7d}}{50 \frac{l_{water}}{d} * 1 * 4.3\text{E-}04 \left(\frac{\mu Ci}{kg_{wet}} / \frac{\mu Ci}{d}\right) * e^{-3.6\text{E-}04\ d^{-1} * (30d + 20d)}}$$

$$= 1.68 \frac{\mu Ci}{l_{water}}$$

Therefore, cows that drink water with Co-60 contamination greater than 1.68 µCi/l 7 days after deposition, have the potential to produce meat (beef) that may equal the Intervention Level when that meat enters commerce 50 days after deposition. Meat that equals the Intervention Level could produce a dose that equals the PAG when consumed by a 1-year-old.

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METHOD 3.5 INGESTION DOSE

Application

This method has been developed to calculate the Ingestion Dose from the consumption of radioactive material, either in food, milk or water.

The Ingestion Dose:

1) Can be applied to the whole body (E) or to a specific organ (H_T)

2) Uses sample results for various food types to calculate the dose that a receptor is projected to receive over a specified time phase (generally 1 year) due to ingestion of the contaminated food.

3) Is used to define dose levels to assist decision makers in determining where it may be advisable to implement protective actions (e.g., sheltering livestock, embargos, special product handling).

Discussion

The Ingestion Dose method calculates the expected dose from consuming foods contaminated by radioactive material and is obtained by combining sample results (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):

1) Meat/Fish (Beef, Pork, Poultry, Fin Fish, Shellfish, Other Meat);

2) Crop/Produce (Leafy, Exposed, Protected, Other Produce, Breads, Cereals, Other Grains);

3) Milk (Fresh Cow's Milk, Other Dairy, Eggs); and

4) Beverages (Tap Water, Water Based Drinks, Soups, Other Beverages).

Because Ingestion Dose Coefficients include the dose contribution from daughter radionuclides that grow in after the parent is consumed, all radionuclides present at the time of consumption should be treated as parent radionuclides.

Assumptions

The following assumptions apply in addition to the Default Assumptions:

1) Dose calculations are based on samples of foods as prepared for consumption and assume a consumption period of 1 year. To compare with analytical results it may be necessary to convert to "dry weight," see Method 4.2.

2) Inadvertent ingestion of soil is not included in these methods. Activity contained in any soil present in the food would be accounted for in the sample analysis process. Inadvertent Soil Ingestion is discussed in Method 3.7.

Inputs

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

1) Data – Activity concentration (µCi/kg or µCi/l) from sample analysis data.
2) Constants – Fraction of food contaminated, daily food intake rate, ingestion dose coefficient.
3) Other Factors – Decay of radionuclides over the duration of consumption (default consumption period is 1 year).

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

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

Outputs

Final

The final output of this method is the Ingestion Dose for a diet including food sources that have been contaminated by a deposition of radioactive material.

E = Committed Effective Dose, the dose to the whole body, from the ingestion of all radionuclides in contaminated food, mrem

H_T = Committed Equivalent Dose, the dose to organ T, from the ingestion of all radionuclides in contaminated food, mrem

Intermediate

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

$IngDP$ = Ingestion Dose Parameter for a specific food type for a specific age group ($mrem \cdot d/kg_{wet}$)

Method 3.5.1 Calculation of Committed Effective Dose

The Ingestion Dose calculation includes contributions from each type of contaminated food at its individual contamination level and appropriate intake rates (averaged over each subgroup). Food contamination levels are decay adjusted over the duration of consumption (default of 1 year).

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

Equation 3.5-1 represents the final form of the Ingestion Dose calculation:

$$E_{Ing,age} = \sum_{Subgroup} \begin{pmatrix} DFIR_{subgroup,age} \\ * FFC_{subgroup} \\ * IngDP_{E,avg,age} \end{pmatrix}$$

(Eq. 3.5-1)

$$\mathrm{mrem} = \sum_{\mathrm{subgroup}} \left(\frac{\mathrm{kg_{wet}}}{\mathrm{d}} * \mathrm{unitless} * \frac{\mathrm{mrem \cdot d}}{\mathrm{kg_{wet}}} \right)$$

where:

$E_{Ing,age}$ = Committed Effective Dose from ingestion, the dose to the whole body, received by a specific age group from ingestion of all radionuclides in all contaminated food types, mrem;

$DFIR_{subgroup,age}$ = Daily Food Intake Rate for a food subgroup (as prepared for consumption, i.e. wet mass) for a specific age group. (See Appendix C, Table 10), kg_{wet}/d;

$FFC_{subgroup}$ = Fraction of Food Subgroup Contaminated, unitless;

NOTE: See Appendix C, Table 11 for default *FFC* values. If there is convincing local information that the actual *FFC* is considerably different, local authorities may decide to use a different *FFC*.

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

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

Calculation of IngDP

Equation 3.5-2 shows the calculation of the individual $IngDP_{E,f,age}$ for each type of contaminated food. These values should be averaged with all other food types in a subgroup to determine the $IngDP_{E,avg,age}$ for each food subgroup. For example, if the diet includes 3 food types from the "protected" subgroup of the crop/produce group (e.g., corn, carrots, oranges) then sum the IngDPs for each food type and divide by 3 to determine the average Ingestion Dose Parameter for the subgroup.

$$IngDP_{E,f,age} = \sum_i \left(C_{f,i} * IngDC_{E,age,i} * \frac{1-e^{-\lambda t_c}}{\lambda_i} \right)$$

(Eq. 3.5-2)

$$\frac{\text{mrem}\cdot\text{d}}{\text{kg}_{\text{wet}}} = \sum_{\text{i}} \left(\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \frac{\text{mrem}}{\mu\text{Ci}} * \frac{\text{unitless}}{\text{d}^{-1}} \right)$$

where:

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

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

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

λ_i = Decay constant for radionuclide *i*, d^{-1};

t_c = Consumption Time, the length of the consumption period (default 365 days), d;

Method 3.5.2 Calculation of Equivalent Dose to an Organ

The preceding calculations assume that the organ of interest is the whole body. The generic approach can be modified to calculate a dose for a specific organ (e.g., skin, thyroid, etc.).

To calculate the dose to a specific organ, replace the IngDC for the whole body with the IngDC for the specific organ when calculating the IngDP.

EXAMPLE 1

Problem: Calculate the Whole-Body Ingestion Dose received by an adult from consuming food contaminated with ^{137}Cs and ^{60}Co for 1 year.

Assume food samples were collected and analyzed immediately before entering commerce for several food types with results as shown below:

Table 3.5-E1

Food Type	^{60}Co (µCi/kg$_{wet}$)	^{137}Cs (µCi/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
[a] Assumes a density of 1.04 kg/l.		

E1.1 Calculating IngDP for each food type using Equation 3.5-2

Table 3.5-E2 shows the values needed to calculate the individual IngDP for each food type.

Table 3.5-E2

Radionuclide	IngDC [a] (mrem/µCi)	Λ [a] (days^{-1})	$\frac{1-e^{-\lambda t_c}}{\lambda}$ (days) [b]
^{60}Co	12.7	3.6E-04	342
^{137}Cs	50.3	6.59E-05	361
[a] Value from DCFPAK 3.0 (ICRP 60+). [b] Consumption period (t_c): 365 days			

Example IngDP calculation for Beef and IngDP values for the other contaminated food types (Table 3.5-E3):

$$IngDP_{E,Beef,Adult} = 2.5\text{E-}03\,\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * 12.7\,\frac{\text{mrem}}{\mu\text{Ci}} * 342\text{ d}$$

$$+4.0\text{E-}03\,\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * 50.3\,\frac{\text{mrem}}{\mu\text{Ci}} * 361\text{ d}$$

$$= 83.5\,\frac{\text{mrem}\cdot\text{d}}{\text{kg}_{\text{wet}}}$$

Table 3.5-E3

Food Type	Sub-group	IngDP (mrem·d/kg_{wet})
Beef	Beef	83.5
Corn	Protected Crop	21.0
Lettuce	Leafy Crop	192
Milk	Cow's Milk	63.2
Oranges	Protected Crop	3.55

E1.2 Calculating Ingestion Dose using Equation 3.5-1

Obtain the Ingestion Dose for each subgroup by multiplying the IngDP for the subgroup by the associated Daily Food Intake Rate (DFIR) and Fraction of Food Subgroup Contaminated ($FFC_{subgroup}$), and then add up the subgroup doses to obtain the Committed Effective Dose (E) as shown in Table 3.5-E4.

Table 3.5-E4

Food Type	Sub-group	Daily Food Intake Rate (kg_{wet}/d)[a]	$FFC_{subgroup}$	IngDP (mrem·d/kg_{wet})	Subgroup Ingestion Dose (mrem)
Beef	Beef	0.098	1	83.5	8.18
Corn/ Oranges	Protected Crop	0.155	1	12.3[b]	1.91
Lettuce	Leafy Crop	0.042	1	192	8.07
Milk	Cow's Milk	0.238	1	63.2	15.0
				E (∑)	**33.2**

[a] Assumes a density of 1.04 kg/l for milk.
[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.

Therefore, the Whole-Body Ingestion Dose received by an adult from consuming this food contaminated at these levels would be 33.2 mrem over a year.

E1.3 Calculating an Ingestion Dose for an individual organ or for a different age group

To calculate a Committed Equivalent Dose (H_T) for a specific organ and/or different age group, use the appropriate IngDC for the organ/age group and calculate as demonstrated above.

METHOD 3.6 PROJECTING CONTAMINATION LEVELS IN FOOD

Application

This method has been developed to project potential contamination levels in food (C_f) based on a measured or projected deposition of radioactive material on the ground.

The contamination levels in food:

1) Can be used to determine potential doses to individuals consuming the food when results from direct sampling of the food are not available.
2) Uses deposition data to project potential contamination levels in crops, milk, and meat at some time in the future, generally when the product will be distributed in commerce.
3) Is used to define dose levels to assist decision makers in determining where it may be advisable to implement protective actions (e.g., sheltering livestock, embargos, special product handling).

Discussion

This method projects the potential contamination levels in food crops harvested from contaminated ground using projected or measured deposition (areal activity) values (μCi/m^2) and for meat and milk from animals grazing on contaminated forage using deposition (μCi/m^2), eating contaminated fodder (μCi/kg) and drinking water (μCi/l) values.

Contamination levels in stored crops or animal fodder should be determined by sampling, not using these calculations.

Assumptions

The following assumptions apply in addition to the Default Assumptions:

All deposition and concentration values used are for the time of deposition (t=0).

NOTE: Data (i.e., sample results) valid for times other than the time of deposition should be back decayed and “unweathered” to the time of deposition using Method 4.3.

Inputs

The following are examples of the types of information required to perform the methods described in this section:

1) Data – Composition of the deposited radionuclide mixture (radionuclides and concentration). This information may come from predictive analysis (atmospheric dispersion models) or field data (monitoring and/or samples).

2) Constants – Crop Retention Factor, Crop Yield, Animal Daily Intake Rates (Feed, Water, Soil), soil mixing depth, mature root depth, Transfer Factors for crops, milk and meat for each radionuclide.
3) Other Factors – Decay and weathering of radionuclides during the time period under consideration, fraction of animals' diet contaminated, timing inputs.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

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

Outputs

Final

The final output of this method is the projected contamination levels in foods that have been affected by a deposition of radioactive material.

C_{crop} = Projected Contamination Level in a food Crop, the level of activity per mass in a food type harvested from contaminated ground when the crop is distributed in commerce, $\mu Ci/kg_{wet}$;

C_{milk} = Projected Contamination Level in Milk, the level of activity per volume in milk produced from animals consuming radioactive material when the milk is distributed in commerce, $\mu Ci/l_{milk}$; and

C_{meat} = Projected Contamination Level in Meat, the level of activity per mass in meat produced animals consuming radioactive material when the meat is distributed in commerce, $\mu Ci/kg_{wet}$.

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 3.5 to calculate ingestion dose when food samples are not available.

Method 3.6.1 Calculation of Contamination in Crops

Equation 3.6-1 shows the calculation for determining the amount of contamination that would be expected in a crop based on the initial deposition (areal activity) on the ground:

$$C_{crop,i} = Dp_{i,t_0} * \left(\frac{CRF_{crop} * e^{-\lambda_w t_h}}{Y_{crop}} + \frac{TF_{crop,i} * MCF_{D-W,crop}}{\rho_{soil} * d_{e,crop}} \right) * e^{-\lambda_i (t_h + t_m)}$$

(Eq. 3.6-1)

$$\frac{\mu\mathrm{Ci}}{\mathrm{kg_{wet}}} = \frac{\mu\mathrm{Ci}}{\mathrm{m^2}} * \left(\frac{\mathrm{unitless} * \mathrm{unitless}}{\frac{\mathrm{kg_{wet}}}{\mathrm{m^2}}} + \frac{\left(\frac{\mu\mathrm{Ci}}{\mathrm{kg_{dry}}} \Big/ \frac{\mu\mathrm{Ci}}{\mathrm{kg_{soil}}} \right) * \frac{\mathrm{kg_{dry}}}{\mathrm{kg_{wet}}}}{\frac{\mathrm{kg_{soil}}}{\mathrm{m^3}} * \mathrm{m}} \right) * \mathrm{unitless}$$

where:

$C_{crop,i}$ = Projected Contamination Level in a food Crop, the level of activity of radionuclide *i* per mass in a food type harvested from contaminated ground at the time it is distributed in commerce, $\mu Ci/kg_{wet}$;

Dp_{i,t_0} = Deposition, the areal activity of radionuclide *i* at the time of deposition, t_0, $\mu Ci/m^2$;

λ_i = Decay constant for radionuclide *i*, d^{-1};

CRF_{crop} = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop (See Appendix C, Table 11), unitless;

NOTE: For crops not growing above the surface at the time of deposition, the CRF=0.

λ_w = Decay constant for weathering radioactive material off plants (See Appendix C, Table 11), d^{-1};

t_h = Time to Harvest, the time from deposition until the crop is collected, d;

Y_{crop} = Crop Yield, the mass of crop grown per area of land (See Appendix C, Table 11), kg_{wet}/m^2;

$TF_{crop,i}$ = Transfer Factor for a food crop, the fraction of radionuclide *i* deposited on the growing medium that is transferred to the plant prior to collection (See Appendix C, Table 8-1), $\mu Ci/kg_{dry}$ per $\mu Ci/kg_{soil}$;

$MCF_{D-W,crop}$ = Mass Conversion Factor (dry to wet), the ratio of dry mass to wet mass for a crop (See Appendix C, Table 9-1), kg_{dry}/kg_{wet};

ρ_{soil} = Soil density (See Appendix C, Table 11), kg_{soil}/m^3;

$d_{e,crop}$ = Effective Soil Depth, the maximum of the mixing depth (d_m) and the mature root depth (d_r) for the crop (See Appendix C, Table 11), m;

NOTE: Default mixing depth is 1.0E-3 m prior to plowing and 0.15 m after plowing. Mature root depth is dependent on the type of crop, and;

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d

Method 3.6.2 Calculation of Contamination in Milk

Equation 3.6-2 shows the calculation for determining the amount of contamination that would be expected in milk based on areal contamination of forage and volumetric contamination of the fodder and drinking water of the animal at the time the animal begins consuming the contaminated forage, fodder, and/or water.

NOTE: Unless specific evidence of different values is available, the $AFDIR_{forage}$ and $AFDIR_{fodder}$ values used should sum to the default AFDIR provided in Appendix C, Table 11.

NOTE: A concentration value of zero is appropriate if any of these intake pathways is NOT contaminated.

$$C_{milk,i,A} = \left\{ \begin{array}{l} Dp_{i,t_0} * FDC_{forage} * \left[\left(\begin{array}{c} \dfrac{CRF_{forage} * e^{-\lambda_w t_g}}{Y_{forage}} \\ + \dfrac{TF_{forage,i} * MCF_{D-W,forage}}{\rho_{soil} * d_{e,forage}} \end{array} \right) * AFDIR_{A,forage} \atop + \left(WF_{t_g} * \dfrac{ASDIR_A}{\rho_{soil} * d_m} \right) \right] \\ + \left[C_{fodder} * FDC_{fodder} * AFDIR_{A,fodder} \right] + \left[C_{water} * FDC_{water} * AWDIR_A \right] \end{array} \right\} * TF_{milk,A,i} * e^{-\lambda_i (t_h + t_m)}$$

(Eq. 3.6-2)

$$\frac{\mu Ci}{l_{milk}} = \left\{ \begin{array}{l} \frac{\mu Ci}{m^2} * \text{unitless} * \left[\left(\begin{array}{c} \frac{\text{unitless}*\text{unitless}}{\frac{kg_{wet}}{m^2}} \\ + \frac{\left(\frac{\mu Ci}{kg_{dry}} / \frac{\mu Ci}{kg_{soil}}\right) * \frac{kg_{dry}}{kg_{wet}}}{\frac{kg_{soil}}{m^3} * m} \end{array} \right) * \frac{kg_{wet}}{d} + \left(\frac{\text{unitless} * \frac{kg_{soil}}{d}}{\frac{kg_{soil}}{m^3} * m} \right) \right] \\ + \left[\frac{\mu Ci}{kg_{wet}} * \text{unitless} * \frac{kg_{wet}}{d} \right] + \left[\frac{\mu Ci}{l_{water}} * \text{unitless} * \frac{l_{water}}{d} \right] \end{array} \right\} * \left(\frac{\mu Ci}{l_{milk}} / \frac{\mu Ci}{d} \right) * \text{unitless}$$

where:

$C_{milk,i,A}$ = Projected Contamination Level in Milk, the level of activity of radionuclide *i* per volume in milk produced from an animal *(A)* consuming radioactive material, $\mu Ci/l_{milk}$;

Dp_{i,t_0} = Deposition, the areal activity of radionuclide *i* at the time of deposition, t_0, $\mu Ci/m^2$;

FDC_{forage} = Fraction of Diet Contaminated (forage), the fraction of the animal's forage that is contaminated (See Appendix C, Table 11), unitless;

CRF_{forage} = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the forage (See Appendix C, Table 11), unitless;

NOTE: For crops not growing above the surface at the time of deposition, the CRF=0.

λ_w = Decay constant for weathering radioactive material off plants (See Appendix C, Table 11), d^{-1};

t_g = Time to Grazing, the time from deposition until the animal begins eating the contaminated forage, d;

Y_{forage} = Crop Yield, the mass of forage grown per area of pastureland (See Appendix C, Table 11), kg_{wet}/m^2;

$TF_{forage,i}$ = Transfer Factor for forage, the fraction of radionuclide *i* deposited on the growing medium that is transferred to the forage during the growing time (See Appendix C, Table 8-1), $\mu Ci/kg_{dry}$ per $\mu Ci/kg_{soil}$;

$MCF_{D\text{-}W,forage}$ = Mass Conversion Factor (dry to wet), the ratio of dry mass to wet mass for forage (See Appendix C, Table 9-1), kg_{dry}/kg_{wet};

ρ_{soil} = Soil density (See Appendix C, Table 11), kg_{soil}/m^3;

$d_{e,forage}$ = Effective Soil Depth, the maximum of the mixing depth (d_m) and the mature root depth (d_r) for the forage (See Appendix C, Table 11), m;

NOTE: Default mixing depth is 1.0E-3 m prior to plowing and 0.15 m after plowing.

$AFDIR_{A,forage}$ = Animal Feed Daily Intake Rate (forage), the daily rate at which an animal *(A)* consumes forage (See Appendix C, Table 11), kg_{wet}/d;

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

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

d_m = Mixing Depth (See Appendix C, Table 11), m;

$ASDIR_A$ = Animal Soil Daily Intake Rate, the daily rate at which an animal (*A*) consumes soil (See Appendix C, Table 11), kg_{soil}/d;

$C_{fodder,i}$ = Measured Contamination level of radionuclide *i* in fodder, µCi/kg_{wet};

FDC_{fodder} = Fraction of Diet Contaminated (fodder), the fraction of the animal's fodder that is contaminated (See Appendix C, Table 11), unitless;

$AFDIR_{A,fodder}$ = Animal Feed Daily Intake Rate (fodder), the daily rate at which an animal *(A)* consumes fodder (See Appendix C, Table 11), kg_{wet}/d;

$C_{water,i}$ = Measured Contamination level of radionuclide *i* in drinking water, µCi/l_{water};

FDC_{water} = Fraction of Diet Contaminated (water), the fraction of the animal's water that is contaminated (See Appendix C, Table 11), unitless;

$AWDIR_A$ = Animal Water Daily Intake Rate, the daily rate at which an animal *(A)* consumes water (See Appendix C, Table 11), l_{water}/d;

$TF_{Milk,A,i}$ = Transfer Factor for Milk, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the milk produced by the animal (See Appendix C, Table 8-2), µCi/l_{milk} per µCi/d;

λ_i = Decay constant for radionuclide *i*, d^{-1};

t_h = Time to Harvest, the time from deposition until the animal product is collected, d; and

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d.

Method 3.6.3 Calculation of Contamination in Meat

Equation 3.6-3 shows the calculation for determining the amount of contamination that would be expected in meat based on areal contamination of forage and volumetric contamination of the fodder and drinking water of the animal at the time the animal begins consuming the contaminated forage, fodder, and/or water.

NOTE: Unless specific evidence of different values is available, the $AFDIR_{forage}$ and $AFDIR_{fodder}$ values used should sum to the default AFDIR provided in Appendix C, Table 11.

NOTE: A contamination value of zero is appropriate if any of these intake pathways is NOT contaminated.

$$C_{meat,i,A} = \left\{ \begin{array}{c} Dp_{i,t_0} * FDC_{forage} * \left[\begin{array}{c} \left(\frac{CRF_{forage} * e^{-\lambda_w t_g}}{Y_{forage}} + \frac{TF_{forage,i} * MCF_{D-W,forage}}{\rho_{soil} * d_{e,forage}} \right) * AFDIR_{A,forage} \\ + \left(WF_{t_g} * \frac{ASDIR_A}{\rho_{soil} * d_m} \right) \end{array} \right] \\ + \left[C_{fodder} * FDC_{fodder} * AFDIR_{A,fodder} \right] + \left[C_{water} * FDC_{water} * AWDIR_A \right] \end{array} \right\} * TF_{meat,A,i} * e^{-\lambda_i (t_h + t_m)}$$

(Eq. 3.6-3)

$$\frac{\mu Ci}{kg_{wet}} = \left\{ \begin{array}{c} \frac{\mu Ci}{m^2} * unitless * \left[\begin{array}{c} \left(\frac{unitless * unitless}{\frac{kg_{wet}}{m^2}} + \frac{\left(\frac{\mu Ci}{kg_{dry}} / \frac{\mu Ci}{kg_{soil}} \right) * \frac{kg_{dry}}{kg_{wet}}}{\frac{kg_{soil}}{m^3} * m} \right) * \frac{kg_{wet}}{d} \\ + \left(\frac{unitless * \frac{kg_{soil}}{d}}{\frac{kg_{soil}}{m^3} * m} \right) \end{array} \right] \\ + \left[\frac{\mu Ci}{kg_{wet}} * unitless * \frac{kg_{wet}}{d} \right] + \left[\frac{\mu Ci}{l_{water}} unitless * \frac{l_{water}}{d} \right] \end{array} \right\} * \left(\frac{\mu Ci}{kg_{wet}} / \frac{\mu Ci}{d} \right) * unitless$$

where:

$C_{meat,i,A}$ = Projected Contamination Level in Meat, the level of activity of radionuclide *i* per mass in meat produced from an animal *(A)* consuming radioactive material, $\mu Ci/kg_{wet}$;

Dp_{i,t_0} = Deposition, the areal activity of radionuclide *i* at the time of deposition, t_0, $\mu Ci/m^2$;

FDC_{forage} = Fraction of Diet Contaminated (forage), the fraction of the animal's forage that is contaminated (See Appendix C, Table 11), unitless;

CRF_{forage} = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the forage (See Appendix C, Table 11), unitless;

NOTE: For crops not growing above the surface at the time of deposition, the CRF=0.

λ_w = Decay constant for weathering radioactive material off plants (See Appendix C, Table 11), d^{-1};

t_g = Time to Grazing, the time from deposition until the animal begins eating the contaminated forage, d;

Y_{forage} = Crop Yield, the mass of forage grown per area of pastureland (See Appendix C, Table 11), kg_{wet}/m^2;

$TF_{forage,i}$ = Transfer Factor for forage, the fraction of radionuclide *i* deposited on the growing medium that is transferred to the forage during the growing time (See Appendix C, Table 8-1), $\mu Ci/kg_{dry}$ per $\mu Ci/kg_{soil}$;

$MCF_{D\text{-}W,forage}$ = Mass Conversion Factor (dry to wet), the ratio of dry mass to wet mass for forage (See Appendix C, Table 9-1), kg_{dry}/kg_{wet};

ρ_{soil} = Soil density (See Appendix C, Table 11), kg_{soil}/m^3;

$d_{e,forage}$ = Effective Soil Depth, the maximum of the mixing depth (d_m) and the mature root depth (d_r) for the forage (See Appendix C, Table 11), m;

NOTE: Default mixing depth is 1.0E-3 m prior to plowing and 0.15 m after plowing.

$AFDIR_{A,forage}$ = Animal Feed Daily Intake Rate (forage), the daily rate at which an animal *(A)* consumes forage (See Appendix C, Table 11), kg_{wet}/d;

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

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

d_m = Mixing Depth (See Appendix C, Table 11), m;

$ASDIR_A$ = Animal Soil Daily Intake Rate, the daily rate at which an animal *(A)* consumes soil (See Appendix C, Table 11), kg_{soil}/d;

$C_{fodder,i}$ = Measured Contamination level of radionuclide *i* in fodder, $\mu Ci/kg_{wet}$;

FDC_{fodder} = Fraction of Diet Contaminated (fodder), the fraction of the animal's fodder that is contaminated (See Appendix C, Table 11), unitless;

$AFDIR_{A,fodder}$ = Animal Feed Daily Intake Rate (fodder), the daily rate at which an animal *(A)* consumes fodder (See Appendix C, Table 11), kg_{wet}/d;

$C_{water,i}$ = Measured Contamination level of radionuclide *i* in drinking water, $\mu Ci/l_{water}$;

FDC_{water} = Fraction of Diet Contaminated (water), the fraction of the animal's water that is contaminated (See Appendix C, Table 11), unitless;

$AWDIR_A$ = Animal Water Daily Intake Rate, the daily rate at which an animal *(A)* consumes water (See Appendix C, Table 11), l_{water}/d;

$TF_{Meat,A,i}$ = Transfer Factor for Meat, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the meat produced by the animal (See Appendix C, Table 8-2), µCi/kg_{wet} per µCi/d;

λ_i = Decay constant for radionuclide *i*, d^{-1};

t_h = Time to Harvest, the time from deposition until the animal product is collected, d; and

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d.

EXAMPLE 1

Problem: Calculate the projected contamination levels for a lettuce crop that will be harvested 30 days after deposition from an area with an initial ground concentration of ^{60}Co of 4.0E-03 µCi/m^2.

Equation 3.6-1 is to calculate the projected contamination levels in a crop:

$$C_{crop,i} = Dp_{i,t_0} * \left(\frac{CRF_{crop} * e^{-\lambda_w t_h}}{Y_{crop}} + \frac{TF_{crop,i} * MCF_{D-W,crop}}{\rho_{soil} * d_{e,crop}}\right) * e^{-\lambda_i (t_h + t_m)} \quad \text{(Eq. 3.6-1)}$$

Assuming:

$Dp_{Co\text{-}60,0d}$ = 4.0E-03 µCi/m^2,

$\lambda_{Co\text{-}60}$ = 3.60E-04 d^{-1},

$CRF_{lettuce}$ = 0.2,

λ_w = 4.62E-02 d^{-1},

t_h = 30 d,

$Y_{lettuce}$ = 2 kg$_{wet}$/m^2,

$TF_{lettuce,Co}$ = 0.17 µCi/kg$_{dry}$ per µCi/kg$_{soil}$ (leafy vegetable),

$MCF_{D\text{-}W,lettuce}$ = 0.2 kg$_{dry}$/kg$_{wet}$ (leafy vegetable),

ρ_{soil} = 1600 kg$_{soil}$/m^3,

$d_{e,lettuce}$ = 0.3 m (leafy vegetable), and

t_m = 1 d.

$$C_{lettuce,^{60}Co} = 4.0\text{E-}03\,\frac{\mu\text{Ci}}{\text{m}^2} * \left(\frac{0.2 * e^{-4.62\text{E-}02\text{d}^{-1} * 30\text{d}}}{2.0\frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \frac{0.17\left(\frac{\mu\text{Ci}}{\text{kg}_{\text{dry}}} \Big/ \frac{\mu\text{Ci}}{\text{kg}_{\text{soil}}}\right) * 0.2\frac{\text{kg}_{\text{dry}}}{\text{kg}_{\text{wet}}}}{1600\frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 0.30\text{m}}\right) * e^{-3.6\text{E-}04\ \text{d}^{-1} * (30\text{d} + 1\text{d})}$$

$$= 9.92\text{E-}05\ \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

This projected contamination level could be compared to an Intervention Level (either the FDA DIL, generic FRMAC FIL, or other incident-specific value) to determine whether this product is acceptable to introduce into commerce.

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EXAMPLE 2

Problem: Calculate the projected ^{60}Co contamination levels for cow's milk for animals that have enough clean fodder and water for 30 days whose milk will begin to be sold 90 days after deposition.

Once the clean fodder runs out, they will be fed 20% of their diet on fodder containing 1.0E-04 µCi/kg$_{wet}$. The remaining 80% of their diet will be from forage contaminated at an initial deposition of 4.0E-03 µCi/m2 and their drinking water will be contaminated with 3.0E-05 µCi/l.

Equation 3.6-2 is to calculate the projected contamination levels in milk:

$$C_{milk,i,A} = \left\{ \begin{array}{c} Dp_{i,t_0} * FDC_{forage} * \left[\begin{array}{c} \left(\begin{array}{c} \dfrac{CRF_{forage} * e^{-\lambda_w t_g}}{Y_{forage}} \\ + \dfrac{TF_{forage,i} * MCF_{D-W,forage}}{\rho_{soil} * d_{e,forage}} \end{array} \right) * AFDIR_{A,forage} \\ + \left(\dfrac{WF_{t_g}}{\rho_{soil} * d_m} \right) * ASDIR_A \end{array} \right] \\ + \left[C_{fodder} * FDC_{fodder} * AFDIR_{A,fodder} \right] + \left[C_{water} * FDC_{water} * AWDIR_A \right] \end{array} \right\} * TF_{Milk,A,i} * e^{-\lambda_i (t_h + t_m)}$$

(Eq. 3.6-2)

Assuming:

$Dp_{Co\text{-}60}$ = 4.0E-03 µCi/m^2,

FDC_{forage} = 1.0,

CRF_{forage} = 0.5,

λ_w = 4.62E-02 d^{-1},

t_g = 30 d,

Y_{forage} = 0.7 kg$_{wet}$/m^2,

$TF_{forage,Co}$ = 4.50E-02 µCi/kg$_{dry}$ per µCi/kg$_{soil}$,

$MCF_{D\text{-}W,forage}$ = 0.22 kg$_{dry}$/kg$_{wet}$,

ρ_{soil} = 1600 kg$_{soil}$/m^3,

$d_{e,forage}$ = 0.6 m,

$AFDIR_{cow,forage}$ = 40 kg$_{wet}$/d,

WF_{30d} = 0.984,

d_m = 1.0E-03 m,

$ASDIR_{cow}$ = 0.4 kg$_{soil}$/d,

$C_{fodder,\ Co\text{-}60}$ = 1.0E-04 µCi/kg$_{wet}$,

FDC_{fodder} = 1.0,

$AFDIR_{cow,fodder}$ = 10 kg$_{wet}$/d,

$C_{water,\ Co\text{-}60}$ = 3.0E-05 µCi/l$_{water}$,

FDC_{water} = 1.0,

$AWDIR_{cow,milk}$ = 60 l$_{water}$/d,

$TF_{Milk,cow,Co}$ = 1.1E-04 µCi/l$_{milk}$ per µCi/d,

$\lambda_{Co\text{-}60}$ = 3.60E-04 d^{-1},

t_h = 90 d, and

t_m = 2 d.

NOTE: *ASDIR* adjusted by the same factor (80%) as $AFDIR_{forage}$.

$$C_{milk,{}^{60}Co,cow} = \left\{ \begin{array}{l} 4.0\text{E-}03 \frac{\mu\text{Ci}}{\text{m}^2} * 1 * \left[\begin{array}{c} \left(\begin{array}{c} \dfrac{0.5 * e^{-4.62\text{E-}02\ \text{d}^{-1} * 30\text{d}}}{0.7 \frac{\text{kg}_\text{wet}}{\text{m}^2}} \\ + \dfrac{4.5\text{E-}02 \left(\dfrac{\mu\text{Ci}/\text{kg}_\text{dry}}{\mu\text{Ci}/\text{kg}_\text{soil}} \right) * 0.22 \frac{\text{kg}_\text{dry}}{\text{kg}_\text{wet}}}{1600 \frac{\text{kg}_\text{soil}}{\text{m}^3} * 0.6\text{m}} \end{array} \right) * 40 \frac{\text{kg}_\text{wet}}{\text{d}} \\ + \left(\dfrac{0.984}{1600 \frac{\text{kg}_\text{soil}}{\text{m}^3} * 1.03\text{E-}03\text{m}} \right) * 0.4 \frac{\text{kg}_\text{soil}}{\text{d}} \end{array} \right] \\ + \left[1.0\text{E-}04 \frac{\mu\text{Ci}}{\text{kg}_\text{wet}} * 1.0 * 10 \frac{\text{kg}_\text{wet}}{\text{d}} \right] + \left[3.0\text{E-}05 \frac{\mu\text{Ci}}{l_\text{water}} * 1.0 * 60 \frac{l_\text{water}}{\text{d}} \right] \end{array} \right\} * 1.1\text{E-}04 \left(\frac{\mu\text{Ci}}{l_\text{milk}} \Big/ \frac{\mu\text{Ci}}{\text{d}} \right) * e^{-3.6\text{E-}04\ \text{d}^{-1} * (90\text{d}+2\text{d})}$$

$$= 3.44\text{E-}06 \frac{\mu\text{Ci}}{l_\text{milk}}$$

This projected contamination level could be compared to an Intervention Level (either the FDA DIL, generic FRMAC FIL, or other incident-specific value) to determine whether this product is acceptable to introduce into commerce.

EXAMPLE 3

Problem: Calculate the projected ^{60}Co contamination levels for beef for animals that have enough clean fodder and water for 30 days whose meat will be harvested 90 days after deposition.

Once the clean fodder runs out, they will be fed 20% of their diet on fodder containing 1.0E-04 µCi/kg$_{wet}$. The remaining 80% of their diet will be from forage contaminated at an initial deposition of 4.0E-03 µCi/m2 and their drinking water will be contaminated with 3.0E-05 µCi/l.

Equation 3.6-2 is to calculate the projected contamination levels in meat:

$$C_{meat,i,A} = \left\{ \begin{array}{c} Dp_{i,t_0} * FDC_{forage} * \left[\left(\begin{array}{c} \frac{CRF_{forage} * e^{-\lambda_w t_g}}{Y_{forage}} \\ + \frac{TF_{forage,i} * MCF_{D-W,forage}}{\rho_{soil} * d_{e,forage}} \end{array} \right) * AFDIR_{A,forage} + \left(\frac{WF_{t_g}}{\rho_{soil} * d_m} \right) * ASDIR_A \right] \\ + \left[C_{fodder} * FDC_{fodder} * AFDIR_{A,fodder} \right] + \left[C_{water} * FDC_{water} * AWDIR_A \right] \end{array} \right\} * TF_{Meat,A,i} * e^{-\lambda_i (t_h + t_m)}$$

(Eq. 3.6-3)

$DpCo\text{-}60$ = $4.0E\text{-}03\ \mu Ci/m2$;

FDC_{forage} = 1.0;

CRF_{forage} = 0.5;

λ_w = 4.62E-02 d^{-1};

t_g = 30 d;

Y_{forage} = 0.7 kg_{wet}/m^2;

$TF_{forage,Co}$ = 4.50E-02 $\mu Ci/kg_{dry}$ per $\mu Ci/kg_{soil}$;

$MCF_{D\text{-}W,forage}$ = 0.22 kg_{dry}/kg_{wet};

ρ_{soil} = 1600 kg_{soil}/m^3;

$d_{e,forage}$ = 0.6 m;

$AFDIR_{cow,forage}$ = 40 kg_{wet}/d;

WF_{30d} = 0.984;

d_m = 1.0E-03 m;

$ASDIR_{cow}$ = 0.4 kg_{soil}/d;

$C_{fodder,\ Co\text{-}60}$ = 1.0E-04 µCi/kg_{wet};

FDC_{fodder} = 1.0;

$AFDIR_{cow,fodder}$ = 10 kg_{wet}/d;

$C_{water,\ Co\text{-}60}$ = 3.0E-05 µCi/l_{water};

FDC_{water} = 1.0;

$AWDIR_{cow,beef}$ = 50 l_{water}/d;

$TF_{Meat,cow,Co}$ = 4.3E-04, µCi/kg_{wet} per µCi/d;

$\lambda_{Co\text{-}60}$ = 3.60E-04 d^{-1},

t_h = 90 d, and

t_m = 20 d.

NOTE: *ASDIR* adjusted by the same factor (80%) as $AFDIR_{forage}$.

$$C_{meat,{}^{60}Co,beef} = \left\{ \begin{array}{l} 4.0\text{E-}03\,\frac{\mu\text{Ci}}{\text{m}^2} * 1 * \left[\left(\dfrac{0.5 * e^{-4.62\text{E-}02\,\text{d}^{-1} * 30\text{d}}}{0.7\,\frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \dfrac{4.5\text{E-}02 \left(\frac{\mu\text{Ci}/\text{kg}_{\text{dry}}}{\mu\text{Ci}/\text{kg}_{\text{soil}}} \right) * 0.22\,\frac{\text{kg}_{\text{dry}}}{\text{kg}_{\text{wet}}}}{1600\,\frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 0.6\text{m}} \right) * 40\,\frac{\text{kg}_{\text{wet}}}{\text{d}} + \left(\dfrac{0.984}{1600\,\frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 1.03\text{E-}03\text{m}} \right) * 0.4\,\frac{\text{kg}_{\text{soil}}}{\text{d}} \right] \\ + \left[1.0\text{E-}04\,\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * 1.0 * 10\,\frac{\text{kg}_{\text{wet}}}{\text{d}} \right] + \left[3.0\text{E-}05\,\frac{\mu\text{Ci}}{1_{\text{water}}} * 1.0 * 50\,\frac{1_{\text{water}}}{\text{d}} \right] \end{array} \right\} * 4.3\text{E-}04 \left(\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} \Big/ \frac{\mu\text{Ci}}{\text{d}} \right) * e^{-3.6\text{E-}04\,\text{d}^{-1} * (90\text{d}+20\text{d})}$$

$$= 1.33\text{E-}05\,\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

This projected contamination level could be compared to an Intervention Level (either the FDA DIL, generic FRMAC FIL, or other incident-specific value) to determine whether this product is acceptable to introduce into commerce.

METHOD 3.7 DOSE FROM INADVERTENT SOIL INGESTION

Application

This method calculates the Ingestion Dose from the inadvertent consumption of soil that has been contaminated with radioactive material.

The Ingestion Dose Method:

1) Can be applied to the whole body (E) or to a specific organ (H_T)
2) Uses monitoring results of areal activity to calculate the dose that a receptor is projected to receive over a specified time phase (generally 1 year) due to ingestion of the contaminated soil.
3) Is used to define dose levels to assist decision makers in determining where it may be advisable to implement protective actions.

Discussion

This method calculates the projected dose from the inadvertent ingestion of soil contaminated by radioactive material and is calculated by evaluating ground monitoring results ($\mu Ci/m^2$). 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 following assumptions apply in addition to the Default Assumptions:

1) Default soil intake rates are 5.0E-05 kg_{soil}/day for adults and 1.0E-04 kg_{soil}/day for children (EPA11). If specific intake rates are known, use those instead of defaults.
2) 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.

Inputs

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

1) Data – Areal concentration ($\mu Ci/m^2$) from monitoring data.

2) Constants – Daily Soil Intake Rate, Ingestion Dose Coefficient.
3) Other Factors – Start and end time of period (duration of consumption) under consideration, decay and weathering of radionuclides over the duration of consumption (default consumption period is 1 year).

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

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

Outputs

Final

The final output of this method is the Ingestion Dose for soils that have been contaminated by a deposition of radioactive material.

E_{soil} = Committed Effective Dose, the dose to the whole body, from the ingestion of all radionuclides in contaminated soil, mrem

$H_{T,soil}$ = Committed Equivalent Dose, the dose to organ T from the ingestion of all radionuclides in contaminated soil, mrem

Intermediate

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

None

Method 3.7.1 Calculation of Committed Effective Dose from Inadvertent Soil Ingestion

Equation 3.7-1 shows the Ingestion Dose calculation:

$$E_{soil,age} = \frac{DSIR}{\rho_{soil} * d_m} * \sum_i \left(e^{-\lambda_i t_1} * WF_{t_1} * IngDC_{E,age,i} * WP_{i,TP} \right)$$

(Eq. 3.7-1)

$$\mathrm{mrem} = \frac{\frac{\mathrm{kg_{soil}}}{\mathrm{d}}}{\frac{\mathrm{kg_{soil}}}{\mathrm{m^3}} * \mathrm{m}} * \sum_i \left(\mathrm{unitless} * \mathrm{unitless} * \frac{\mathrm{mrem}}{\mu\mathrm{Ci}} * \frac{\mu\mathrm{Ci \cdot d}}{\mathrm{m^2}} \right)$$

where:

$E_{soil,age}$ = Committed Effective Dose from inadvertent soil ingestion, the dose to the whole body, received by a specific age group from ingestion of all radionuclides in contaminated soil, mrem;

$DSIR$ = Daily Soil Intake Rate, kg_{soil}/d;

ρ_{soil} = Soil density (See Appendix C, Table 11), kg_{soil}/m^3;

d_m = Mixing Depth (See Appendix C, Table 11), m;

WF_{t_1} = Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind) from t_0 (deposition) to t_1 (start of the time phase), unitless;

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

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

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

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

Method 3.7.2 Calculation of Equivalent Dose to an Organ

The preceding calculations assume that the organ of interest is the whole body. The generic approach can be modified to calculate a dose for a specific organ (e.g., skin, thyroid, etc.).

To calculate the dose to a specific organ, replace the IngDC for the whole body with the IngDC for the organ of interest.

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EXAMPLE 1

Problem: Calculate the Whole Body Ingestion Dose received by an adult from inadvertent consumption of soil contaminated with ^{60}Co and ^{137}Cs for 1 year, beginning 100 days after deposition.

Assume monitoring results (at initial deposition) as shown below:

^{60}Co = 2.5E-03 μCi/m^2

^{137}Cs = 4.0E-03 μCi/m^2

Equation 3.7-1 can be used to calculate the dose:

$$E_{50,soil,age} = \frac{DSIR}{\rho_{soil} * d_m} * \sum_i \left(e^{-\lambda t_1} * WF_{t_1} * IngDC_{E,age,i} * WP_{i,TP}\right)$$

Given:

$IngDC_{Co}$ = 12.7 mrem/μCi

λ_{Co} = 3.6E-04 d^{-1}

$IngDC_{Cs}$ = 50.3 mrem/μCi

λ_{Cs} = 6.29E-05 d^{-1}

t_1 = 100 d (Start of Time Phase – used in WP calculation)

t_2 = 465 d (End of Time Phase – used in WP calculation)

WF_{100d} = 0.950

Assuming:

$DSIR$ = 5.0E-05 kg$_{soil}$/d (EPA11)

ρ_{soil} = 1600 kg$_{soil}$/m^3

d_m = 1.0E-04 m (EPA89)

Calculating WP as in Appendix F, Supplement 2 yields:

WP_{Co} = 0.725 μCi•d/m^2

WP_{Cs} = 1.26 μCi•d/m^2

$$E_{50,soil,Adult} = \frac{5.0\text{E-05 } \frac{\text{kg}_{\text{soil}}}{\text{d}}}{1600\,\frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 1.0\text{E-04 m}} * \left(\begin{array}{l} 0.965 * 0.959 * 12.7\,\frac{\text{mrem}}{\mu\text{Ci}} * 0.725\,\frac{\mu\text{Ci}\cdot\text{d}}{\text{m}^2} \\ +0.994 * 0.950 * 50.3\,\frac{\text{mrem}}{\mu\text{Ci}} * 1.26\,\frac{\mu\text{Ci}\cdot\text{d}}{\text{m}^2} \end{array} \right)$$

$$= 2.13\text{E-02 mrem}$$

To calculate a Committed Equivalent Dose (H_T) for a specific organ and/or different age group, use the appropriate IngDC for the organ/age group and calculate as demonstrated above.

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METHOD 3.8 WATER DERIVED RESPONSE LEVEL

This method is currently being finalized in cooperation with the EPA.

As of the 2018 release, Turbo FRMAC© includes a Water DRL calculation using only the standard six age groups (i.e., excluding the fetus and breastfed infant), in agreement with the EPA.

Single-radionuclide DRLs calculated using the Water DRL method described in the EPA PAG Manual (EPA17) can be found in Appendix C, Table 8-3.

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SECTION 4. SUPPLEMENTAL METHODS

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INTRODUCTION TO SUPPLEMENTAL METHODS

These Methods provide supplemental calculations in support of the primary Methods described in the previous sections. The results of these methods may be used to determine alternate (non-default) input factors that may be used to calculate values that are more applicable to the incident being assessed. These methods may also be used to normalize sample data for comparison to values calculated by other methods.

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METHOD 4.1 DETERMINING RESUSPENSION FROM SAMPLES

Application

This method has been developed to calculate a Resuspension Factor based on air and deposition samples.

The Resuspension Factor (*K*):

1) Represents the ratio of activity in the air at a particular location to the activity on the ground at that location for a particular radionuclide.

   NOTE: Resuspension Factors may be different for each radionuclide in a mixture because some chemical/physical forms may be more likely to become airborne than others. Local decision makers should be consulted to determine if radionuclide-specific Resuspension Factors should be used instead of one factor for the entire mixture.

2) Is used to calculate the Resuspension Parameter (*KP*) and Deposition Inhalation Dose Parameter (*Dp_InhDP*) for each radionuclide in a release.

Discussion

This calculation is presented as an alternative to the default, time dependent, formula shown in Appendix F, Supplement 2, Equation 2 and may be used only with approval from local decision makers.

In contrast to direct measurements of air concentration (usually made at occupied locations), air and ground measurements used for determining resuspension factors must be made at or near source locations – i.e., areas of contaminated ground from which activity is being resuspended *into* occupied areas. Although it is possible that such source areas may be near (or may be the same as) occupied areas, it is also possible that the source contamination area is some distance away from the occupied area of interest.

Therefore, the location of resuspension measurements must take into account the geography and weather factors that affect the transfer of activity from the ground to the air that will end up in the occupied areas of interest. In general, resuspension measurements should be made at locations in contaminated areas that are upwind (or may be expected to be upwind) of the occupied areas of interest.

Several ground samples should be taken upwind of each air sampler in order to obtain an average value for the ground in the area covered by the air sampler. The purpose of these measurements is to obtain the general level of ground activity for comparison to the measured activity on the air filter.

There are several pitfalls to consider when deciding to use a sample based resuspension value:

1) It may be difficult to obtain accurate/representative sample-based values.
2) Hot particles may significantly skew the air sample activity results.
3) Samples are only representative of the resuspension factor for a specific point in time and space.
4) Resuspension may change over the time phase of interest as the land use changes.
5) Weathering processes and alpha-recoil energy can break apart contaminated particles creating smaller particle sizes over time potentially changing resuspension.
6) Sample based resuspension values are sensitive to many factors, including:
    - Air sampler location,
    - Wind direction relative to the air sample location, and
    - Activities being conducted in the sampling area.

Assumptions

The following default assumptions are used in this method:

None

Inputs

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

Data: Sampling Results from air and ground monitoring.

Outputs

Final

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

$K_{t,i}$ = Resuspension Factor, the ratio of the activity level in the air to the level on the ground of radionuclide *i* at the time of measurement *t*, m^{-1}.

Intermediate

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

None

Calculation

Equation 4.1-1 shows the Resuspension Factor calculation.

$$K_i = \frac{\chi_i}{Dp_i} \qquad \text{(Eq. 4.1-1)}$$

$$\mathrm{m}^{-1} = \frac{\mu\mathrm{Ci}/\mathrm{m}^3}{\mu\mathrm{Ci}/\mathrm{m}^2}$$

where:

$K_{t,i}$ = Resuspension Factor for radionuclide *i* at time *t*, m^{-1};

χ_i = Air Concentration of radionuclide *i*, $\mu Ci/m^3$; and

Dp_i = Deposition, the areal activity of radionuclide *i*, $\mu Ci/m^2$.

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EXAMPLE 1

Problem: Calculate the Resuspension Factor from sample results

At a particular sampling location, the average results for ^{137}Cs are:

Air Sampling: 2.74E-03 µCi/m^3

Ground Sampling: 2.74E+04 µCi/m^2

$$K = \frac{2.74\text{E-}03\,\frac{\mu\text{Ci}}{\text{m}^3}}{2.74\text{E+}04\,\frac{\mu\text{Ci}}{\text{m}^2}} = 1.00\text{E-}07\text{m}^{-1}$$

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METHOD 4.2 COMPARING SAMPLE RESULTS TO INGESTION PATHWAY THRESHOLDS

Application

This method provides instructions on how to compare analytical sample results of food and fodder to ILs.

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 IL. Assessment Scientists must determine when it is appropriate to apply the dry-to-wet conversion factor to sample results for comparison to the IL.

Assumptions

The FRMAC radiological assessment calculations use the default assumptions established by the FDA.

The following default assumptions are used in this method:

- Food products are intended to be eaten in a fresh or "wet" condition. This does not apply to fodder that is to be fed to livestock in a dry form.

Inputs

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

1) Data: Sampling Results from food products/fodder in terms of dry mass ($\mu Ci/kg_{dry}$).
2) Constants: Mass Conversion Factor for the food product/fodder.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

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

Outputs

Final

The final output of this method is a sample analysis result in "wet mass" that may be directly compared to an Intervention Level.

$C_{sample,i,wet}$ = Sample Contamination, the level of contamination of radionuclide *i* in an analytical sample in terms of wet mass, $\mu Ci/kg_{wet}$.

Intermediate

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

None

Calculation

Equation 4.2-1 shows the wet mass Contamination calculation.

$$C_{sample,i,wet} = C_{sample,i,dry} * MCF_{D-W,subgroup} \qquad \text{(Eq. 4.2-1)}$$

$$\frac{\mu Ci}{kg_{wet}} = \frac{\mu Ci}{kg_{dry}} * \frac{kg_{dry}}{kg_{wet}}$$

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 9-1), 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, an FDA-listed radionuclide, 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 4.2-1 should be used to calculate the wet mass Concentration.

$$C_{sample,i,wet} = C_{sample,i,dry} * MCF_{D-W,sbubgroup}$$

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 Intervention Level.

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METHOD 4.3 ADJUSTING SAMPLES FOR THE EFFECTS OF DECAY AND WEATHERING

Application

This method provides instructions on how to adjust sample results for radioactive decay and weathering.

Discussion

Generally, samples will be obtained after the initial deposition of radioactive material; this Method considers the decay and weathering that occur over time. This Method predicts the activity at the sampled location at a desired time (e.g., the Evaluation Time) so that the sample can be compared to other samples or to a value calculated in another Method (e.g., Deposition DRLs).

Caveats

1) Care must be taken when adjusting daughter radionuclide activities. It may be appropriate to "back-decay" using the decay constant of the ultimate parent to avoid potentially overestimating daughter activity.

2) The weathering function is dependent on time from deposition. If an Evaluation Time (t_n) other than time of release/deposition is desired, the sample must first be "back-weathered" to the time of deposition (t_0) and then weathered from t_0 to t_n.

3) Weathering may not be performed recursively; it must be calculated from initial deposition each time it is used (i.e., weathering for 30 days twice will not produce the same answer as weathering for 60 days).

Assumptions

To compare data sets with different reference times, it is necessary to normalize them to a common time. When normalizing data sets, decay adjustments are always applied, and weathering adjustment depends on the type of data as described in Table 4.3-1.

Table 4.3-1 Default Weathering Adjustments Based on Sample Type

Sample Type	Weather Adjust
Dose/Exposure Rate	Yes
In-Situ Gamma Spectroscopy	Yes
Ground Deposition	No

Weathering adjustment is not necessary for ground deposition samples because it is assumed that these samples are collected to a depth that captures all radionuclides from a release.

Inputs

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

Data: Sample results, collection time, and the time for which the results are valid (Reference Time).

Outputs

Final

The final output of this method is a sample result valid for the Evaluation Time.

NOTE: For demonstration purposes this method will use a ground deposition sample, but it may also be used for any sample type which is collected over an extended period (e.g., air samples).

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

Intermediate

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

None

Calculation

4.3.1 Correction for radioactive decay from Sampling Time to the Reference Time

Results provided by a laboratory may be back-decayed to different times. Determine what time the reported results are valid (Reference Time) before performing any additional decay adjustments. If the results are reported at the Sampling Time, this step is not necessary – skip to Section 4.3.2.

To back-correct a sample result valid for a Reference Time (t_r) to the Sampling Time (t_s), divide the result by the effects of radioactive decay as shown in Equation 4.3-1.

$$Dp_{i,t_s} = \frac{Dp_{i,t_r}}{e^{-\lambda_i * (t_r - t_s)}} \qquad \text{(Eq. 4.3-1)}$$

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

where:

$Dp_{i,ts}$ = Deposition, the areal activity of radionuclide *i* at time t_s, μCi/m^2;

$Dp_{i,tr}$ = Deposition, the areal activity of radionuclide *i* at time t_r, μCi/m^2;

t_s = Sampling Time, the time when the sample was collected, s;

t_r = Reference Time, the time when the sample results are valid, s; and,

λ_i = Decay constant for radionuclide *i* (or the parent for a daughter in equilibrium), s^{-1}.

4.3.2 Correction for weathering and radioactive decay from deposition to Sampling Time

Once the sample result has been corrected to the value at the Sampling Time (t_s), the value is modified by the effects of weathering and radioactive decay from the time of deposition (t_0) as shown in Equation 4.3-2:

NOTE: This equation is for times expressed in seconds. See Appendix F, Supplement 2, Section F.3.1 for a description of the default FRMAC Weathering Factor (*WF*).

$$Dp_{i,t_0} = \frac{Dp_{i,t_s}}{WF_{t_s} * e^{-\lambda_i * (t_s - t_0)}} \qquad \text{(Eq. 4.3-2)}$$

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

where:

$Dp_{i,t0}$ = Deposition, the areal activity of radionuclide i at time t_0, µCi/m^2;

$Dp_{i,ts}$ = Deposition, the areal activity of radionuclide i at time t_s, µCi/m^2;

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

> **NOTE:** See Appendix F, Supplement 2 for details on calculating WF.
>
> **NOTE:** If weathering adjustment is not needed, $WF = 1$.

t_s = Sampling Time, the time when the sample was collected, s;

t_0 = Release Time, the time the release begins. This time is usually assumed to correspond to the time of deposition, s; and,

λ_i = Decay constant for radionuclide i (or the parent for a daughter in equilibrium), s^{-1}.

4.3.3 Forward-correction for weathering and radioactive decay to the Evaluation Time

To determine the value at the Evaluation Time (t_n), apply the effects of weathering and radioactive decay as shown in Equation 4.3-3:

NOTE: This equation is for times expressed in seconds. See Appendix F, Supplement 2, Section F2.2.1 for a description of the default FRMAC Weathering Factor (*WF*).

$$Dp_{i,t_n} = Dp_{i,t_0} * WF_{t_n} * e^{-\lambda_i t_n} \qquad \text{(Eq. 4.3-3)}$$

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

where:

$Dp_{i,tn}$ = Deposition, the areal activity of radionuclide i at time t_n, µCi/m^2;

$Dp_{i,t0}$ = Deposition, the areal activity of radionuclide i at time t_0, µCi/m^2;

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

> **NOTE:** See Appendix F, Supplement 2 for details on calculating WF.
>
> **NOTE:** If weathering adjustment is not needed, $WF = 1$.

t_n = Evaluation Time, the point in time, relative to the start of the release, for which the calculation, measurement, or prediction is valid, s; and,

λ_i = Decay constant for radionuclide i (or the parent for a daughter in equilibrium), s^{-1}.

EXAMPLE 1

Problem: Determine the initial deposition activity of a sample, given:

Sample results 0.70 µCi/m^2 Cs-134 at t=180 days after deposition

Sample collected at t=150 days after deposition

t_r = 180 days (1.56E+07 s)

t_s = 150 days (1.30E+07 s)

$\lambda_{Cs\text{-}134}$ = 1.06E-08 s^{-1}

NOTE: Times should be converted to seconds to use the weathering function in Section 4.3.2.

First, back-decay the sample result to the Sampling Time:

$$Dp_{i,t_s} = \frac{0.70\frac{\mu\text{Ci}}{\text{m}^2}}{\text{e}^{-1.06\text{E-}08*(1.56\text{E}+07-1.30\text{E}+07)}} = 0.72\,\frac{\mu\text{Ci}}{\text{m}^2}$$

The deposition value at the Sampling Time is 0.72 µCi/m^2.

Then, back-decay and back-weather from the Sampling Time to deposition:

$$Dp_{i,t_0} = \frac{0.72\frac{\mu\text{Ci}}{\text{m}^2}}{\left(0.4*\text{e}^{-1.46\text{E-}08*1.30\text{E}+07}+0.6*e^{-4.44\text{E-}10*1.30\text{E}+07}\right)*e^{-1.06\text{E-}08*1.30\text{E}+07}}$$

$$= 0.89\,\frac{\mu\text{Ci}}{\text{m}^2}$$

The initial deposition value for Cs-134 is 0.89 µCi/m^2.

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METHOD 4.4 LABORATORY DETECTION REQUIREMENTS

This method describes the process for determining required laboratory detection thresholds (Critical Levels) for a variety of analytical sample types (matrices). When analyzing samples collected during an incident, one of the primary decisions that must be made is what threshold of detection should be used for each sample. Different sample matrices (i.e., water, soil, vegetation) will have different thresholds of detection. The specific questions that the sample data will answer may also affect the thresholds.

NOTE: See the FRMAC Laboratory Analysis Manual, Appendix B for details on this process.

FRMAC Assessment will supply Derived Response Levels (DRLs) and Intervention Levels (ILs) for each radionuclide in a release mixture that have been determined to be relevant to the incident, radionuclide mixture, and protective action decision being considered to Laboratory Analysis. These DRLs are converted to sample-matrix-specific Analytical Action Levels (AALs) as shown in the following table.

Table 4.4-1 DRL to AAL Conversions

Matrix	Source DRL Type	DRL Units	Conversion from DRL to AAL	AAL Units
Air	Deposition DRL "Short Term" [a]	µCi/m^2	AAL = DRL x Resuspension Factor (1E-06 m^{-1} Default)	µCi/m^3
Animal Feed	$Milk\_DRL_{mass}$ or $Meat\_DRL_{mass}$ [b]	µCi/kg_{wet}	AAL = $Milk\_DRL_{mass}$ or $Meat\_DRL_{mass}$ [b]	µCi/kg_{wet}
Food	IL	µCi/kg_{wet}	AAL = IL	µCi/kg_{wet}
Milk	IL	µCi/kg_{wet}	AAL = IL	µCi/kg_{wet}
Ground Deposition [c] **"Short Term"**	Deposition DRL "Short Term" [a]	µCi/m^2	AAL = DRL x Sample Size (0.01 m^2 Default)	µCi/sample
Ground Deposition [c] **"Long Term"**	Deposition DRL "Long Term" [d]	µCi/m^2	AAL = DRL x Sample Size (0.01 m^2 Default)	µCi/sample
Animal Water	$Milk\_DRL_{water}$ or $Meat\_DRL_{water}$ [b]	µCi/l	AAL = $Milk\_DRL_{water}$ or $Meat\_DRL_{water}$ [b]	µCi/l

Drinking Water	DRL_{water}	µCi/l	AAL = DRL_{water}	µCi/l

[a] Short Term Deposition Derived Response Levels are the minimum (most conservative) of the DRLs for the Early Phase (Total Dose) and First Year Time Phases

[b] If it is known whether the feed of concern is for milk or meat producing animals, use the respective DRL. If this is not known, use the minimum (most conservative) of the DRLs

[c] Ground Deposition samples include soil and any other material present in the sampling area (e.g., grass, leaves, sticks, rocks, etc.), not just the "dirt"

[d] Long Term Deposition Derived Response Levels are the minimum (most conservative) of the DRLs for the Early Phase (Avoidable Dose), First Year, and Second Year Time phases as well as the Crop_DRL (Time to Harvest = 0) and $Milk\_DRL_{area}$ and $Meat\_DRL_{area}$ (Time to Grazing and Time to Harvest = 0)

The calculated AAL should then be divided by the L_C/AAL Ratio (default of 10) to determine the initial Critical Level for the radionuclide being evaluated. These values are baseline values that may be modified as the incident progresses upon consultation between the Assessment and Laboratory Analysis Divisions.

METHOD 4.5 USING DEPOSITION VELOCITY TO CONVERT DATA TYPES

Application

This method provides instructions on how to convert between Integrated Air Activity ($\tilde{A}_i$) and Areal Activity (Deposition, Dp_i) using Deposition Velocity (V_d) values.

Discussion

When a plume of radioactive material passes over an area, a certain fraction of that material is deposited on the surface. The rate at which this occurs can be expressed in terms of a deposition velocity. Because different elements and chemical/physical forms have different deposition velocities (V_d), the relative activity ratios of plume-borne radionuclides may be different than the activity ratios of the ground-deposited radionuclides.

This method demonstrates how to estimate:

1) an Integrated Air Activity from a measured Deposition activity, and
2) a Deposition activity from a measured Integrated Air Activity.

Assumptions

The following default assumptions are used in this method:

1) All deposition is assumed to be dry particulates – wet deposition (increased localized deposition caused by rain or snow) is not included in this method.
2) Default Deposition Velocities (V_d) of
   - 3.0E-03 m/s, for Particulates
   - 6.5E-03 m/s for Iodine (NUREG-1940)
   - 0.0 m/s for Noble Gases which are assumed to remain airborne and are not deposited on the ground.

Inputs

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

1) Data: Integrated Air Activity (μCi•s/m^3), or Deposition (μCi/m^2).
2) Constants: Deposition Velocities for the appropriate particle size.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

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

Outputs

Final

The final output of this method is either an Integrated Air Activity or a Deposition value for the passage of a plume of radioactive material.

$\tilde{A}_i$ = Integrated air activity of radionuclide *i* in a release, µCi•s/m³.

Dp_{i,t_0} = Initial Deposition, the areal activity of radionuclide *i* at the time of deposition t_0, µCi/m²;

Intermediate

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

None

Method 4.5.1 Estimating missing data (Dpᵢ or Ãᵢ) from the known value

Calculation

Equation 4.5-1 shows the calculation of Integrated Air Activity from Deposition.

$$\tilde{A}_i = \frac{Dp_{i,t_0}}{V_\mathrm{d}} \qquad \text{(Eq. 4.5-1)}$$

$$\frac{\mu\mathrm{Ci{\cdot}s}}{\mathrm{m}^3} = \frac{\mu\mathrm{Ci}}{\mathrm{m}^2} \Big/ \frac{\mathrm{m}}{\mathrm{s}}$$

where:

$\tilde{A}_i$ = Integrated air activity of radionuclide *i* in a release, µCi•s/m³.

Dp_{i,t_0} = Initial Deposition, the areal activity of radionuclide *i* at the time of deposition t_0, µCi/m^2; and

V_d = Deposition Velocity, radionuclide-specific default, m/s.

Conversely, Equation 4.5-2 shows the calculation of Deposition from Integrated Air Activity.

$$Dp_i = \tilde{A}_i * V_d \quad \text{(Eq. 4.5-2)}$$

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

Method 4.5.2 Estimating a deposition velocity (V_d) for a mixture containing multiple particle sizes

Calculation

If the details of the particle size distribution are known and their corresponding deposition velocities, it is possible to estimate a weighted average deposition velocity using Equation 4.5-3.

$$\bar{V}_d = \sum\left(V_{d,PS} * F_{PS}\right) \quad \text{(Eq. 4.5-3)}$$

$$\frac{\text{m}}{\text{s}} = \frac{\text{m}}{\text{s}} * \text{unitless}$$

where:

$\bar{V}_d$ = Weighted Average Deposition Velocity, m/s;

$V_{d,PS}$ = Deposition Velocity for a specific particle size, m/s; and,

F_{PS} = Fraction of the mixture of a specific particle size, unitless.

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EXAMPLE 1

Problem: Calculate the Areal Activity of a radionuclide from the Integrated Air Activity.

An air sampler has reported an integrated air activity (Ã) of:

Cs-137: 1000 µCi•s/m^3

I-131: 800 µCi•s/m^3

Xe-133: 1500 µCi•s/m^3

What are the areal activities expected in the area of the air sampler?

Using Equation 4-5.2:

$$Dp_i = \tilde{A}_i * V_d$$

Table 4.5-E1

Radionuclide	Integrated Air Activity (Ã) (µCi•s/m^3)	Deposition Velocity (V_d) (m/s)	Deposition (Dp_i) (µCi/m^2)
Cs-137	1000	3.0E-03	3
I-131	800	6.5E-03	5.2
Xe-133	1500	0	0

Remember, because different elements and chemical/physical forms have different deposition velocities (V_d), the relative activity ratios of plume-borne radionuclides may be different than the activity ratios of the ground-deposited radionuclides.

EXAMPLE 2

Problem: Calculate the Weighted Average Deposition Velocity for a mix of particle sizes.

$$\bar{V}_d = \sum \left(V_{d_{PS}} * F_{PS} \right)$$

A plume contains the following particle size mixture:

Particle Size	% of mixture
1 micron	50
10 micron	40
100 micron	10

What is the weighted average deposition velocity for the mixture if you assume the following deposition velocities for individual particle sizes?

Particle Size	V_d (m/s)
1 micron	1.0E-03
10 micron	3.0E-03
100 micron	2.4E-01

$$\bar{V}_d = \sum \begin{pmatrix} 1.0\text{E-}03 \frac{\text{m}}{\text{s}} * 0.5 \\ +3.0\text{E-}03 \frac{\text{m}}{\text{s}} * 0.4 \\ +2.4\text{E-}01 \frac{\text{m}}{\text{s}} * 0.1 \end{pmatrix} = 2.6\text{E-}02 \frac{\text{m}}{\text{s}}$$

METHOD 4.6 CONVERTING “GRAB” AIR SAMPLE RESULTS TO INTEGRATED AIR VALUES

Application

This method provides instructions on how to convert “grab” air sampling results (µCi/m^3) to an integrated air concentration ($\tilde{A}$, in µCi•s/m^3) for use in the Methods in Section 1 of this manual. This method may be used for a single sample or a series of consecutive samples at a single location.

Discussion

The Assessment Methods presented in Section 1 of this manual were developed primarily in support of activities where air sampling results would be delivered in units corresponding to an integrated air concentration. It is more likely that “grab” air sample results will be available. This Method was developed to convert results from “grab” air (e.g., filter) samples, collected in the field and analyzed by a laboratory, into units corresponding to an integrated air concentration.

Caveats

1) This Method calculates the integrated air concentration for the portion of the plume that is captured by the grab air sample(s). Dose projections based on these calculations will not reflect the potential total dose if the sample(s) do not represent the entirety of the plume.

2) This Method makes no assumptions as to the position of the sampling location relative to plume centerline; it calculates the integrated air concentration at the location of the sampler. Dose projections based on these calculations will not reflect the potential total dose if the receptor is not at the sample location.

3) Potential errors in this calculation may be greater when considering radionuclides with short half-lives compared to the sample collection time and/or the time between collection and analysis.

Assumptions

The following default assumptions are used in this method:

1) The radionuclide being evaluated is a parent or a daughter that is in transient equilibrium with the parent.

Inputs

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

Data: Filter Sample Air Activity (μCi/m^3), start and end times of sample collection, and the time for which the results are valid (Reference Time).

Outputs

Final

The final output of this method is an integrated air activity value that corresponds to the sample result.

$\tilde{A}_i$ = Integrated air activity of radionuclide *i* in the release, μCi•s/m^3

Intermediate

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

None

Calculation

4.6.1 Calculating the Integrated Air Activity

Equation 4.6-1 shows the calculation to convert a grab air sample to an integrated air activity value for a given radionuclide:

Step 1: Back-decay the sample result value back to the start of the sample collection period, and

Step 2: Integrate this value over the sample collection time.

$$\tilde{A}_i = \frac{\chi_{i,t_r}}{e^{-\lambda_i * (t_r - t_s)}} * \left(\frac{1 - e^{-\lambda_i * t_\Delta}}{\lambda_i}\right) \qquad \text{(Eq. 4.6-1a)}$$

$$\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} = \frac{\mu\text{Ci}/\text{m}^3}{\text{unitless}} * \frac{\text{unitless}}{\text{s}^{-1}}$$

where:

$\tilde{A}_i$ = Integrated air activity of radionuclide *i* in the release, μCi•s/m^3;

$\chi_{i,tr}$ = Grab air sample activity of radionuclide *i* at the Reference Time for the sample (t_r), μCi/m^3;

λ_i = Decay constant for radionuclide *i* (or the parent for a daughter in equilibrium), s^{-1};

t_s = Sampling Time, the time when the sample was collected, s;

t_r = Reference Time, the time when the sample results are valid, s; and,

t_Δ = Duration of the sampling period, s.

NOTE: If the half-life of the radionuclide is long in comparison to the sample collection time and to the time between collection and analysis, Equation 4.6-1a simplifies to:

$$\tilde{A}_i = \chi_{i,t_r} * t_\Delta \quad \text{(Eq. 4.6-1b)}$$

4.6.2 Handling Reference Time

Results provided by a laboratory may be back-decayed to different times. Determine what time the reported results are valid (Reference Time) before performing any additional decay adjustments. For example, if the laboratory back-decayed the reported result to the start of the sample collection period, then Step 1 above is not necessary and Equation 4.6-1 becomes:

$$\tilde{A}_i = \chi_{i,t_s} * \left(\frac{1-e^{-\lambda_i * t_\Delta}}{\lambda_i}\right) \quad \text{(Eq. 4.6-2)}$$

$$\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} = \frac{\mu\text{Ci}}{\text{m}^3} * \frac{\text{unitless}}{\text{s}^{-1}}$$

where:

$\tilde{A}_i$ = Integrated air activity of radionuclide *i* in the release, μCi•s/m^3;

$\chi_{i,0}$ = Grab air sample activity of radionuclide *i* at the start of the sample collection period, μCi/m^3;

λ_i = Decay constant for radionuclide *i* (or the parent for a daughter in equilibrium), s^{-1};and,

t_Δ = Duration of the sampling period, s.

4.6.3 Handling consecutive samples

To determine the appropriate integrated air activity for multiple consecutive samples from a single sampling location, perform the calculation in Equation 4.6-1a for each sample and then add the individual results to get the total integrated air activity. Correct samples to their individual collection times. DO NOT correct all samples to the start time of the first sample!

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EXAMPLE 1

Problem: Calculate the Integrated Air Activity that would correspond to a grab air sample, given:

Sample results: 1 μCi/m³ Tc-99m

Sample duration: 20 min (1.2E+03 s)

Sample collection time: 4 hours after deposition (1.44E+04 s)

Sample results valid: 7 hours after deposition (2.52E+04 s)

$\lambda_{Tc\text{-}99m} = 3.2\text{E-}05\ \text{s}^{-1}$

$$\tilde{A}_i = \frac{\chi_{i,t_r}}{e^{-\lambda_i * (t_r - t_s)}} * \left(\frac{1 - e^{-\lambda_i * t_\Delta}}{\lambda_i}\right)$$

Step 1 – Back-decay the sample result to the start of the collection time.

$$\chi_{^{99\mathrm{m}}\mathrm{Tc},\mathrm{t_s}} = \frac{1\,\frac{\mu\mathrm{Ci}}{\mathrm{m}^3}}{\mathrm{e}^{-3.2\mathrm{E}\text{-}05*(2.25\mathrm{E}+04-1.44\mathrm{E}+04)}} = 1.41\,\frac{\mu\mathrm{Ci}}{\mathrm{m}^3}$$

Step 2 – Integrate this value over the sample duration.

$$\tilde{A}_{^{99\mathrm{m}}\mathrm{Tc}} = 1.41\,\frac{\mu\mathrm{Ci}}{\mathrm{m}^3} * \left(\frac{1 - e^{-3.2\mathrm{E}\text{-}05*1.2\mathrm{E}+03)}}{3.2\mathrm{E}\text{-}05\ \mathrm{s}^{-1}}\right) = 1.66\mathrm{E}+03\,\frac{\mu\mathrm{Ci}\cdot\mathrm{s}}{\mathrm{m}^3}$$

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METHOD 4.7 ACCOUNTING FOR OCCUPANCY AND SHELTERING

Application

This method has been developed to determine the effects of being sheltered inside a building for a portion of the Time Phase and of being outside the contaminated area for another portion of the Time Phase. The effects of occupancy and sheltering can be applied to any or all of the four Primary Dose Pathways as needed.

Discussion

Default FRMAC methodology assumes that the receptor is outdoors in the contaminated area continuously during the time phase under consideration without any protective measures (e.g., shielding or respiratory protection). This method allows for the inclusion of Occupancy Factors and Building Protection Factors which may reduce the Total Dose received by a receptor in a contaminated area.

Occupancy Factors

Occupancy Factors account for the fact that, during different portions of the Time Phase, receptors may be:

- outdoors (unsheltered) in the contaminated area;
- sheltered inside a structure in the contaminated area; and,
- absent from the contaminated area.

Occupancy Factors are needed for the fraction of time spent outside in the contaminated area and for the time spent sheltered inside a building in the contaminated area.

Building Protection Factors

Building Protection Factors (BPFs) account for the fact that being sheltered inside a structure may reduce the dose to an individual in an area of contamination. BPFs for both Inhalation and External Exposure to radioactive material can be applied to the appropriate Dose Parameters for each of the four Primary Dose Pathways described in Method 1.1. (See Appendix C, Table 6-1 for default FRMAC BPFs.)

NOTE: BPFs will have no effect on Groundshine or Resuspension Inhalation doses for Time Phases where the Inside Occupancy Factor is Zero (the receptor is assumed to be outdoors (unsheltered) for the entire Time Phase.)

Assumptions

This method assumes that:

- the receptor may be sheltered inside a structure for a portion of the Time Phase under consideration;
- the receptor may leave the contaminated area for a portion of the Time Phase under consideration; and,
- if Plume Dose Pathways are being included in the assessment the receptor is present and remains in the same location (inside or outside) for the entirety of the plume.

Inputs

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

1) Dose Parameters for each of the four primary dose pathways for each radionuclide in the mixture, based on the start and end times of the time phase (calculated using Method 1.1).
2) Other Factors – Building Protection Factor (BPF) for the type of building being assessed; Occupancy Factors for time spent outside in the contaminated area (OF_{out}) and for time spent inside a building in the contaminated area (OF_{in}).

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

Outputs

Final

The final output of this method is the Total Dose Parameter for a radionuclide for a Time Phase modified to include the effects of Occupancy and Building Protection.

$TDP_{i,\,TP,\,Sh}$ = Sheltered Total Dose Parameter, the sum of the doses from radionuclide *i*, over the time phase under consideration (*TP*), from the pathways included in the assessment, modified by Occupancy and Building Protection, mrem;

Intermediate

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

Pl_InhDP_{Sh} = Sheltered Plume Inhalation Dose Parameter for each radionuclide (mrem)

Pl_ExDP_{Sh} = Sheltered Plume External Dose Parameter for each radionuclide (mrem)

Dp_InhDP_{Sh} = Sheltered Deposition Inhalation Dose Parameter for each radionuclide (mrem)

Dp_ExDP_{Sh} = Sheltered Deposition External Dose Parameter for each radionuclide (mrem)

Calculation

Once the default Dose Parameters for the Primary Dose Pathways have been calculated (See Method 1.1), the effects of occupancy and sheltering on the Total Projected Dose to a receptor may be calculated by applying Occupancy and Building Protection Factors to the appropriate Dose Parameters. This Sheltered Total Dose Parameter is then used to calculate the appropriate DRLs that reflect the occupancy and sheltering assumptions.

Modifying the Total Dose Parameter for each Radionuclide in a Release for the Effects of Occupancy and Sheltering

The Total Dose Parameter (TDP) represents the dose from the pathways included in the assessment and is obtained by adding the Dose Parameters for the selected Primary Dose Pathways. The default TDP is calculated using Equation 1.1-3 from Method 1.1.

$$TDP_{i,TP} = Pl\_InhDP_{i,TP} + Pl\_ExDP_{i,TP}$$

$$+Dp\_InhDP_{i,TP} + Dp\_ExDP_{i,TP} \quad \text{(Eq. 1.1-3)}$$

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

The sheltering-modified TDP is calculated by modifying each component Dose Parameter as shown in the following sections.

4.7.1 Modifying the Plume Inhalation Dose Parameter (Plume Inhalation Pathway) to Account for Sheltering

The Plume Inhalation Dose Parameter (Pl_InhDP) is modified by dividing the default Dose Parameter calculated in Method 1.1 by the Building Protection Factor for Inhalation.

$$Pl\_InhDP_{i,TP,Sh} = \frac{Pl\_InhDP_{i,TP}}{BPF_{Pl,Inh}} \quad \text{(Eq. 4.7-1)}$$

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

where:

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

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

$BPF_{Pl,Inh}$ = Building Protection Factor for Plume Inhalation, a factor to account for the reduction in Inhalation Dose due to being inside a building, unitless.

4.7.2 Modifying the Plume External Dose Parameter (Submersion Exposure Pathway) to Account for Sheltering

The Plume External Dose Parameter (Pl_ExDP) is modified by dividing the default Dose Parameter calculated in Method 1.1 by the Building Protection Factor for External Exposure.

$$Pl\_ExDP_{i,TP,Sh} = \frac{Pl\_ExDP_{i,TP}}{BPF_{Pl,Ex}} \qquad \text{(Eq. 4.7-2)}$$

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

where:

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

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

$BPF_{Pl,Ex}$ = Building Protection Factor for Plume External Exposure, a factor to account for the reduction in External Dose due to being inside a building, unitless.

4.7.3 Modifying the Deposition Inhalation Dose Parameter (Resuspension Inhalation Pathway) to Account for Occupancy and Sheltering

The Deposition Inhalation Dose Parameter (Dp_InhDP) is modified by accounting for the effects of Occupancy and Sheltering as shown in Equation 4.7-3.

$$Dp\_InhDP_{i,TP,Sh} = Dp\_InhDP_{i,TP} * \left(OF_{out} + \frac{OF_{In}}{BPF_{Dp,Inh}}\right) \qquad \text{(Eq. 4.7-3)}$$

$$\text{mrem} = \text{mrem} * \left(\text{unitless} + \left[\frac{\text{unitless}}{\text{unitless}}\right]\right)$$

where:

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

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

OF_{out} = Outside Occupancy Factor, the fraction of the Time Phase spent outdoors in the contaminated area, unitless;

OF_{in} = Inside Occupancy Factor, the fraction of the Time Phase spent inside a building in the contaminated area, unitless;

NOTE: These Occupancy Factors will not sum to one (1) if the receptor is absent from the contaminated area during any part of the Time Phase under consideration.

$BPF_{Dp,Inh}$ = Building Protection Factor for Deposition Inhalation, a factor to account for the reduction in Inhalation Dose due to being inside a building, unitless.

4.7.4 Modifying the Deposition External Dose Parameter (Groundshine Exposure Pathway) to Account for Occupancy and Sheltering

The Deposition External Dose Parameter (Dp_ExDP) is modified by accounting for the effects of Occupancy and Sheltering as shown in Equation 4.7-4.

$$Dp\_ExDp_{i,TP,Sh} = Dp\_ExDp_{i,TP} * \left(OF_{out} + \frac{OF_{In}}{BPF_{Dp,Ex}}\right) \quad \text{(Eq. 4.7-4)}$$

$$\text{mrem} = \text{mrem} * \left(\text{unitless} + \left[\frac{\text{unitless}}{\text{unitless}}\right]\right)$$

where:

$Dp\_ExDP_{i, TP, Sh}$ = Sheltered Deposition External Dose Parameter, the external dose from groundshine from radionuclide *i* over the time phase under consideration (*TP*) including the effects of Occupancy and Sheltering, mrem;

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

OF_{out} = Outside Occupancy Factor, the fraction of the Time Phase spent outside in the contaminated area, unitless;

OF_{in} = Inside Occupancy Factor, the fraction of the Time Phase spent inside a building in the contaminated area, unitless;

NOTE: These Occupancy Factors will not sum to one (1) if the receptor is absent from the contaminated area during any part of the Time Phase under consideration.

$BPF_{Dp,Ex}$ = Building Protection Factor for Deposition External Exposure, a factor to account for the reduction in External Dose due to being inside a building, unitless.

4.7.5 Calculating the Sheltered Total Dose Parameter

The Sheltered Total Dose Parameter (TDP_{Sh}) is calculated by summing the Sheltered Dose Parameters from the selected Primary Dose Pathways as shown in Equation 4.7-5.

$$TDP_{i,TP,Sh} = Pl\_InhDP_{i,TP,Sh} + Pl\_ExDP_{i,TP,Sh} + Dp\_InhDP_{i,TP,Sh} + Dp\_ExDP_{i,TP,Sh}$$

(Eq. 4.7-5)

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

where:

$TDP_{i,\ TP,\ Sh}$ = Sheltered Total Dose Parameter, the sum of the doses from radionuclide *i*, over the time phase under consideration (*TP*), from the pathways included in the assessment modified by Occupancy and Sheltering, mrem;

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

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

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

$Dp\_ExDP_{i, TP, Sh}$ = Sheltered Deposition External Dose Parameter, the external dose from groundshine from radionuclide *i* over the time phase under consideration (*TP*) including the effects of Occupancy and Sheltering, mrem.

EXAMPLE 1

Problem: Calculate the Sheltered Total Dose Parameter for the Early Phase (Total Dose) Time Phase (0-96 hours) using the Dose Parameters calculated in Method 1.1, Example 1.

Default calculations for Early Phase (Total Dose) use all four of the Primary Dose Pathways.

Assuming:

1) The receptor is:
   - unsheltered (outdoors) in the contaminated area for 6 hours/day (OF_{Out} = 0.25)
   - sheltered in a building in the contaminated area for 9 hours/day (OF_{In} = 0.375)
   - absent from the contamination area for 9 hours/day
2) The building has:
   - a Building Protection Factor for Deposition External Exposure of 4
   - a Building Protection Factor for Deposition Inhalation of 1
   - a Building Protection Factor for Plume External Exposure of 4
   - a Building Protection Factor for Plume Inhalation of 1

These assumptions may not reflect realistic conditions during the Early Phase, but were chosen to demonstrate all aspects of this Method.

Table 1.1-E8 from Method 1.1, Example 1 shows the Pathway Dose Parameters calculated using default assumptions:

Table 1.1-E8

Radionuclide	Pl_InhDP (mrem)	Pl_ExDP (mrem)	Dp_InhDP EP(TD) (mrem)	Dp_ExDP EP(TD) (mrem)	TDP EP(TD) (mrem)
Co-60	1.05E+01	2.93E-01	5.82E-02	4.81	**1.57E+01**
Gd-148	5.92E+03	0	3.29E+01	0	**5.95E+03**
Sr-90	5.50E+01	3.64E-04	3.06E-01	5.15E-03	**5.54E+01**
Y-90	2.14E+00	2.93E-03	1.19E-02	3.47E-01	**2.51**

E1.1 Calculating Pl_InhDP_{Sh} (Equation 4.7-1)

Example Pl_InhDP_{Sh} calculation for Co-60 and Pl_InhDP_{Sh} values for the radionuclide mixture for the Early Phase (Total Dose) time phase.

$$Pl\_InhDP_{Sh_{60_{Co}}} = \frac{1.05\text{E+01 mrem}}{1} = 1.05\text{E+01mrem}$$

Table 4.7-E1

Radionuclide	Pl_InhDP (mrem)	Building Protection Factor for Plume Inhalation	Pl_InhDP_{Sh} (mrem)
Co-60	1.05E+01	1	1.05E+01
Gd-148	5.92E+03	1	5.92E+03
Sr-90	5.50E+01	1	5.50E+01
Y-90	2.14E+00	1	2.14E+00

E1.2 Calculating Pl_ExDP_{Sh} (Equation 4.7-2)

Example Pl_ExDP_{Sh} calculation for Co-60 and Pl_ExDP_{Sh} values for the radionuclide mixture for the Early Phase (Total Dose) time phase.

$$Pl\_ExDP_{Sh_{60_{Co}}} = \frac{2.93\text{E-}01 \text{ mrem}}{4} = 7.33\text{E-}02 \text{ mrem}$$

Table 4.7-E2

Radionuclide	Pl_ExDP (mrem)	Building Protection Factor for Plume External Exposure	Pl_ExDP_{Sh} (mrem)
Co-60	2.93E-01	4	7.33E-02
Gd-148	0	4	0
Sr-90	3.64E-04	4	9.10E-05
Y-90	2.93E-03	4	7.33E-04

E1.3 Calculating Dp_InhDP_{Sh} (Equation 4.7-3)

Example Dp_InhDP_{Sh} calculation for Co-60 and Dp_InhDP_{Sh} values for the radionuclide mixture for the Early Phase (Total Dose) time phase.

$$Dp\_InhDP_{Sh_{60_{Co}}} = 5.82\text{E-}02 \text{ mrem} * \left(0.25 + \left(\frac{0.375}{1}\right)\right) = 3.64\text{E-}02 \text{ mrem}$$

Table 4.7-E3

Radionuclide	Dp_InhDP EP(TD) (mrem)	Building Protection Factor for Deposition Inhalation	OF_{Out}	OF_{In}	Dp_InhDP_{Sh} EP(TD) (mrem)
Co-60	5.82E-02	1	0.25	0.375	3.64E-02
Gd-148	3.29E+01	1	0.25	0.375	2.06E+01
Sr-90	3.06E-01	1	0.25	0.375	1.91E-01
Y-90	1.19E-02	1	0.25	0.375	7.44E-03

E1.4 Calculating Dp_ExDP_{Sh} (Equation 4.7-4)

Example Dp_ExDP_{Sh} calculation for Co-60 and Dp_ExDP_{Sh} values for the radionuclide mixture for the Early Phase (Total Dose) time phase.

$$Dp\_ExDP_{Sh_{60_{Co}}} = 4.81 \text{ mrem} * \left(0.25 + \left(\frac{0.375}{4}\right)\right) = 1.65 \text{ mrem}$$

Table 4.7-E4

Radionuclide	Dp_ExDP EP(TD) (mrem)	Building Protection Factor for Deposition External Exposure	OF_{Out}	OF_{In}	Dp_ExDP_{Sh} EP(TD) (mrem)
Co-60	4.81	4	0.25	0.375	1.65E+00
Gd-148	0	4	0.25	0.375	0
Sr-90	5.15E-03	4	0.25	0.375	1.77E-03
Y-90	3.47E-01	4	0.25	0.375	1.19E-01

E1.5 Calculating TDP_{Sh} (Eq 4.7-5)

Example TDP_{Sh} calculation for Co-60 and TDP_{Sh} values for the radionuclide mixture for the Early Phase (Total Dose) time phase.

$$TDP_{Sh_{60_{Co}}} = 1.05\text{E}01 \text{ mrem} + 7.33\text{E-}02 \text{ mrem} + 3.64\text{E-}02 \text{ mrem} + 1.65 \text{ mrem}$$

$$= 1.23\text{E+}01 \text{ mrem}$$

Table 4.7-E5

Radionuclide	PI_InhDP_{Sh} (mrem)	PI_ExDP_{Sh} (mrem)	Dp_InhDP_{Sh} EP(TD) (mrem)	Dp_ExDP_{Sh} EP(TD) (mrem)	TDP_{Sh} EP(TD) (mrem)
Co-60	1.05E+01	7.33E-02	3.64E-02	1.65E+00	**1.23E+01**
Gd-148	5.92E+03	0	2.06E+01	0	**5.94E+03**
Sr-90	5.50E+01	9.10E-05	1.91E-01	1.77E-03	**5.52E+01**
Y-90	2.14E+00	7.33E-04	7.44E-03	1.19E-01	**2.27E+00**

The Sheltered Total Dose Parameters for the individual radionuclides can then be used to calculate the Mixture Total Dose Parameter and Derived Response Levels as shown in Method 1.1.

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EXAMPLE 2

Problem: Calculate the Sheltered Total Dose Parameter for the First-Year Time Phase (12-8772 hours) using the Dose Parameters calculated in Method 1.1, Example 2.

Note: Default calculations for the First Year use only the two ground Primary Dose Pathways.

Assuming:

1) The receptor is:
   - unsheltered (outside) in the contaminated area for 6 hours/day (OF_{Out} = 0.25)
   - sheltered in a building in the contaminated area for 9 hours/day (OF_{In} = 0.375)
   - absent from the contamination area for 9 hours/day
2) The building has:
   - a Building Protection Factor for Deposition Inhalation of 1
   - a Building Protection Factor for Deposition External Exposure of 4

Pathway Dose Parameters from Method 1.1, Example 2:

Table 1.1-E17

Radionuclide	Dp_InhDP First Year (mrem)	Dp_ExDP First Year (mrem)	TDP First Year (mrem)
Co-60	2.32E-01	3.78E+02	**3.79E+02**
Gd-148	1.32E+02	0	**1.32E+02**
Sr-90	1.23	4.26E-01	**1.65**
Y-90	4.77E-02	2.86E+01	**2.86E+01**

E2.1 Calculating Dp_InhDP_{Sh} (Equation 4.7-3)

Example Dp_InhDP_{Sh} calculation for Co-60 and Dp_InhDP_{Sh} values for the radionuclide mixture for the First Year time phase.

$$Dp\_InhDP_{Sh_{^{60}Co}} = 2.32\text{E-01 mrem} * \left(0.25 + \left(\frac{0.375}{1}\right)\right) = 1.45\text{E-01mrem}$$

Table 4.7-E6

Radionuclide	Dp_InhDP First Year (mrem)	Building Protection Factor for Deposition Inhalation	OF_{Out}	OF_{In}	Dp_InhDP_{Sh} First Year (mrem)
Co-60	2.32E-01	1	0.25	0.375	1.45E-01
Gd-148	1.32E+02	1	0.25	0.375	8.25E+01
Sr-90	1.23	1	0.25	0.375	7.69E-01
Y-90	4.77E-02	1	0.25	0.375	2.98E-02

E2.2 Calculating Dp_ExDP_{Sh} (Equation 4.7-4)

Example Dp_ExDP_{Sh} calculation for Co-60 and Dp_ExDP_{Sh} values for the radionuclide mixture for the First Year time phase.

$$Dp\_ExDP_{Sh_{60_{Co}}} = 3.78\text{E+02 mrem} * \left(0.25 + \left(\frac{0.375}{4}\right)\right) = 1.30\text{E+02 mrem}$$

Table 4.7-E7

Radionuclide	Dp_ExDP First Year (mrem)	Building Protection Factor for Deposition External Exposure	OF_{Out}	OF_{In}	Dp_ExDP_{Sh} First Year (mrem)
Co-60	3.78E+02	4	0.25	0.375	1.30E+02
Gd-148	0	4	0.25	0.375	0
Sr-90	4.26E-01	4	0.25	0.375	1.46E-01
Y-90	2.86E+01	4	0.25	0.375	9.83

E2.3 Calculating TDP_{Sh} (Eq 4.7-5)

Example TDP_{Sh} calculation for Co-60 and TDP_{Sh} values for the radionuclide mixture for the First Year time phase.

$$TDP_{Sh_{60_{Co}}} = 1.45\text{E-01 mrem} + 1.3\text{E+02 mrem} = 1.3\text{E+02 mrem}$$

Table 4.7-E8

Radionuclide	Dp_InhDP_{Sh} First Year (mrem)	Dp_ExDP_{Sh} First Year (mrem)	TDP_{Sh} First Year (mrem)
Co-60	1.45E-01	1.30E+02	**1.30E+02**
Gd-148	8.25E+01	0	**8.25E+01**
Sr-90	7.69E-01	1.46E-01	**9.15E-01**
Y-90	2.98E-02	9.83	**9.86E+00**

The Sheltered Total Dose Parameters for the individual radionuclides can then be used to calculate the Mixture Total Dose Parameter and Derived Response Levels as shown in Method 1.1.

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METHOD 4.8 ADMINISTRATION OF POTASSIUM IODIDE (KI)

Application

This method has been developed to calculate Integrated Air, Deposition, Dose Rate and Exposure Rate Derived Response Levels (DRLs) to support decisions to administer Potassium Iodide (KI) in response to releases of iodine radionuclides. DRLs can be based upon either integrated air activity ($DRL_{\tilde{A}}$) or areal activity (DRL_{Dp}) as described in Methods 1.1 and 1.2.

Discussion

This Method is a variation of the standard DRL calculations presented in Methods 1.1 and 1.2. It differs in that only the dose to the thyroid from iodine radionuclides is included in the dose calculation.

NOTE: DRLs may be calculated for any radionuclide present in the release, including non-iodine radionuclides. This can be useful when other radionuclides may be easier to detect than iodine radionuclides (e.g., Cs-137) and can be used as a "marker" to indicate how much iodine is present. See Example 2 of this Method for more explanation of this concept.

Assumptions

The following are exceptions to the Default Assumptions described in Section 1:

1) The receptor of interest is the 1-year-old child.
2) The organ of interest is the thyroid.
   NOTE: The 1-year-old age group is expected to receive the largest dose to the thyroid from exposure to iodine radionuclides. Therefore, it is recommended that the 1-year-old age group is considered when considering the administration of prophylactic KI. (EPA17)
3) This Method only considers the dose to the receptor's thyroid from iodine radionuclides.

The following assumptions apply in addition to the Default Assumptions described in Section 1:

1) Because of the short-term effectiveness of KI, this method assumes that the Time Phase of interest is the Early Phase (specifically 0-96 hours).
2) Administration of KI as a protective action is only effective in reducing the dose from iodine radionuclides that are taken into the body. Therefore, this method only considers the two inhalation dose pathways of the Primary Dose Pathways.

Inputs

There are no additional inputs beyond the Default Inputs above.

Appendix C provides the FRMAC default values for selected inputs. Users are urged to use the default inputs until site-specific values become available through consultations with the Advisory Team.

Outputs

Final

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

$DRL_{\tilde{A}}$ = Integrated Air Derived Response Level, the integrated air activity ($\tilde{A}$) of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration *(TP)*, µCi•s/m^3.

DRL_{Dp} = Deposition Derived Response Level, the areal activity, at time t_n, of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration *(TP)*, µCi/m^2.

DRL_{DR} = Dose Rate Derived Response Level, the external dose rate one meter above the ground, at time t_n, at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), mrem/h.

DRL_{XR} = Exposure Rate Derived Response Level, the external exposure rate one meter above the ground, at time t_n, at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*), mR/h. (See Method 1.2 for instructions on calculating an Exposure Rate DRL using a Dose Rate DRL.)

$DRL_{\alpha,\tilde{A}}$ = Integrated Air Alpha Derived Response Level, the integrated air alpha activity of the mixture at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration *(TP)*, µCi$_\alpha$•s/m^3. (See Method 1.3 for instructions on calculating an Integrated Air Alpha DRL using radionuclide-specific Integrated Air DRLs.)

$DRL_{\alpha,Dp,tn}$ = Deposition Alpha Derived Response Level, the areal alpha activity of the mixture, at time t_n, of the mixture at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration *(TP)*, µCi$_\alpha$/m^2. (See Method 1.3 for instructions on calculating a Deposition Air Alpha DRL using radionuclide-specific Deposition DRLs.)

$DRL_{\beta,\tilde{A}}$ = Integrated Air Beta Derived Response Level, the integrated air beta activity of the mixture at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration *(TP)*, $\mu Ci_{\beta} \cdot s/m^3$. (See Method 1.4 for instructions on calculating an Integrated Air Beta DRL using radionuclide-specific Integrated Air DRLs.)

$DRL_{\beta,Dp,tn}$ = Deposition Beta Derived Response Level, the areal beta activity of the mixture, at time t_n, at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration *(TP)*, $\mu Ci_{\beta}/m^2$. (See Method 1.4 for instructions on calculating a Deposition Air Beta DRL using radionuclide-specific Deposition DRLs.)

Intermediate

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

$MTDP_{Iodine}$ = Iodine Mixture Total Dose Parameter for all iodine radionuclides (mrem)

TDP = Total Dose Parameter for each radionuclide (mrem)

Dp_InhDP = Deposition Inhalation Dose Parameter for each radionuclide (mrem)

Pl_InhDP = Plume Inhalation Dose Parameter for each radionuclide (mrem)

Dp_MExDF = Deposition Mixture External Dose Factor (mrem/h)

Calculation

Calculate the DRLs as shown in Equations 1.1-1 and 1.1-2 from Method 1.1 and Equation 1.2-1 from Method 1.2, using the Iodine Mixture Total Dose Parameter ($MTDP_{Iodine}$) calculated below.

The $MTDP_{Iodine}$ is calculated following these steps:

1. Calculate the Dp_InhDP and Pl_InhDP for each iodine radionuclide for the 0-96 hour time phase for the 1-year-old thyroid. (Equations 1.1-4 and 1.1-6 from Method 1.1)
2. Sum these to calculate the TDP for each iodine radionuclide. (Equation 1.1-3 from Method 1.1)
3. Sum these for all iodine radionuclides to calculate the $MTDP_{Iodine}$.

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EXAMPLE 1

Problem: Calculate the KI Administration (Thyroid Equivalent Dose) Integrated Air, Deposition, and Dose Rate DRLs for the Early Phase (Total Dose) Time Phase (0-96 hours) for the Following Mixture released from a Nuclear Power Plant for an Evaluation Time (t_n) of 12 hours, including the dose from the two inhalation pathways applicable to KI administration.

Table 4.8-E1

Radionuclide	Integrated Air Activity (µCi•s/m³)	$t_{1/2}$ [a] (s)
I-131	1.0E-01	6.93E+05
I-132	2.0E-03	8.26E+03
I-133	1.5E-01	7.49E+04
I-135	5.0E-02	2.37E+04
[a] Values from DCFPAK 3.0.		

The default Early Phase (Total Dose) Time Phase includes all four Primary Dose Pathways. However; for the purposes of evaluating KI administration, only the two inhalation dose pathways are considered.

NOTE: Because this mixture is released from a Nuclear Power Plant, the defaults for Physical Form and Deposition Velocity from Appendix F, Supplement 4 should be used (as shown below).

Form	Partition	V_d (m/s)
Methyl Iodide/Non-reactive Gas (CH_3I)	45%	0
Iodine Vapor/Reactive Gas (I_2)	30%	6.4E-03
Particulate	25%	6.5E-03

For resuspension dose calculations, all deposited iodine Vapor/Reactive Gas is assumed to be converted to 1-micron particulate.

E1.1 Calculating Pl_InhDP (Equation 1.1-4)

This calculation requires the Inhalation Dose Coefficient (InhDC), and the Light Exercise Breathing Rate (BR_{LE}) for the 1-year-old of 9.72E-05 m³/s.

Example Pl_InhDP calculation for the particulate form of I-131 and Pl_InhDP values for the radionuclide mixture for the Early Phase (Total Dose) time phase. (Integrated Air values obtained by applying the Partitioning fractions to the values in Table 4.8-E1.)

$$Pl\_InhDP_{^{131}I_{Part}} = 5.29\text{E+03}\,\frac{\text{mrem}}{\mu\text{Ci}} * 2.5\text{E-02}\,\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * 9.72\text{E-05}\,\frac{\text{m}^3}{\text{s}} = 1.29\text{E-02 mrem}$$

Table 4.8.E2

Radionuclide	Physical Form	InhDC [a] (mrem/μCi)	Integrated Air Activity (μCi•s/m^3)	PI_InhDP (mrem)
I-131	Particulate	5.29E+03	2.50E-02	1.29E-02
	Vapor	1.20E+04	3.00E-02	3.50E-02
	Methyl	9.36E+03	4.50E-02	4.09E-02
	Total			**8.88E-02**
I-132	Particulate	6.03E+01	5.00E-04	2.93E-06
	Vapor	1.40E+02	6.00E-04	8.16E-06
	Methyl	1.22E+02	9.00E-04	1.07E-05
	Total			**2.18E-05**
I-133	Particulate	1.30E+03	3.75E-02	4.74E-03
	Vapor	2.96E+03	4.50E-02	1.29E-02
	Methyl	2.34E+03	6.75E-02	1.54E-02
	Total			**3.30E-02**
I-135	Particulate	2.58E+02	1.25E-02	3.13E-04
	Vapor	5.92E+02	1.50E-02	8.63E-04
	Methyl	4.81E+02	2.25E-02	1.05E-03
	Total			**2.23E-03**

[a] From DCFPAK 3.0 (ICRP 60+). Particulate Dose Coefficients are for 1-micron particles. If particle size is known to be other than 1 micron, choose appropriate value.

[b] The light exercise breathing rate (for the 1-year-old) is used because it is assumed that the individual will be actively seeking to exit the plume.

E1.2 Calculating Dp_InhDP (Equation 1.1-6)

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

E1.2.1 Calculating the Deposition values

For mixtures involving multiple physical forms, the deposition value is calculated by multiplying the integrated air concentration by the appropriate deposition velocity. All deposited material is treated as particulate for calculation of dose.

Table 4.8-E3 shows the calculation of the deposition values for this mix.

Radionuclide	Physical Form	Integrated Air Activity (µCi•s/m³)	V_d (m/s)	Deposition (µCi/m²)
I-131	Particulate	2.5E-02	6.5E-03	1.63E-04
	Vapor	3.0E-02	6.4E-03	1.92E-04
	Methyl	4.5E-02	0	0
	Total			**3.55E-04**
I-132	Particulate	5.0E-04	6.5E-03	3.25E-06
	Vapor	6.0E-04	6.4E-03	3.84E-06
	Methyl	9.0E-04	0	0
	Total			**7.09E-06**
I-133	Particulate	3.75E-02	6.5E-03	2.44E-04
	Vapor	4.5E-02	6.4E-03	2.88E-04
	Methyl	6.75E-02	0	0
	Total			**5.32E-04**
I-135	Particulate	1.25E-02	6.5E-03	8.13E-05
	Vapor	1.5E-02	6.4E-03	9.60E-05
	Methyl	2.25E-02	0	0
	Total			**1.77E-04**

E1.2.2 Calculating the Resuspension Parameter (See Appendix F, Supplement 2, Equation 3c)

Example KP calculation for I-131 and KP values for the radionuclide mixture for the Early Phase (Total Dose) time phase.

$$KP_{^{131}I} = 3.55\text{E-}04\,\frac{\mu\text{Ci}}{\text{m}^2} * \left[\begin{array}{c} \frac{1.0\text{E-}05*\left(e^{(-3.46\text{E+}05*(1.00\text{E-}06+8.1\text{E-}07))}-e^{(-0*(1.00\text{E-}06+8.1\text{E-}07))}\right)}{-(1.00\text{E-}06+8.1\text{E-}07)} \\ +\frac{7.0\text{E-}09*\left(e^{(-3.46\text{E+}05*(1.00\text{E-}06+2.31\text{E-}08))}-e^{(-0*(1.00\text{E-}06+2.31\text{E-}08))}\right)}{-(1.00\text{E-}06+2.31\text{E-}08)} \\ +\frac{1.0\text{E-}09*\left(e^{(-3.46\text{E+}05*(1.00\text{E-}06))}-e^{(-0*(1.00\text{E-}06))}\right)}{-(1.00\text{E-}06)} \end{array} \right] \frac{\text{s}}{\text{m}}$$

$$= 9.12\text{E-}04\,\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3}$$

Table 4.8-E4

Radionuclide	Deposition ($\mu Ci/m^2$)	λ_i [a] (s^{-1})	t_1 (s)	t_2 (s)	KP_i – EP(TD) [b] ($\mu Ci \cdot s/m^3$)
I-131	3.55E-04	1.00E-06	0	3.46E+05	9.12E-04
I-132	7.09E-06	8.39E-05	0	3.46E+05	8.38E-07
I-133	5.32E-04	9.26E-06	0	3.46E+05	5.12E-04
I-135	1.77E-04	2.93E-05	0	3.46E+05	5.89E-05

[a] Values from DCFPAK 3.0.
[b] Values approximated using equations in Appendix F, Supplement 2.

E1.2.3 Calculating the Dp_InhDP

Example Dp_InhDP calculation for I-131 and Dp_InhDP values for the radionuclide mixture for the Early Phase (Total Dose) time phase.

$$DP\_InhDP_{^{131}I} = 5.29\text{E+03}\,\frac{\text{mrem}}{\mu\text{Ci}} * 9.12\text{E-04}\,\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} * 5.98\text{E-05}\,\frac{\text{m}^3}{\text{s}} = 2.89\text{E-04 mrem}$$

Table 4.8-E5

Radionuclide	InhDC [a] (mrem/μCi)	KP_i – EP(TD) ($\mu Ci \cdot s/m^3$)	Breathing Rate (Activity-averaged) [b] (m^3/s)	Dp_InhDP EP(TD) (mrem)
I-131	5.29E+03	9.12E-04	5.98E-05	**2.89E-04**
I-132	6.03E+01	8.38E-07	5.98E-05	**3.02E-09**
I-133	1.30E+03	5.12E-04	5.98E-05	**3.98E-05**
I-135	2.58E+02	5.89E-05	5.98E-05	**9.09E-07**

[a] Value from DCFPAK 3.0 (ICRP 60+) for 1-micron particles. If particle size is known to be other than 1 micron, choose appropriate value.
[b] Activity-averaged breathing rate for the 1-year-old child.

E1.3 Calculating TDP (Eq 1.1-3)

Example TDP calculation for I-131 and TDP values for the radionuclide mixture for the Early Phase (Total Dose) time phase, using only the two inhalation dose pathways applicable to KI administration decisions.

$$TDP_{^{131}I} = 8.88\text{E-02 mrem} + 2.89\text{E-04 mrem} = 8.91\text{E-02 mrem}$$

Table 4.8-E6

Radionuclide	Pl_InhDP (mrem)	Dp_InhDP EP(TD) (mrem)	TDP EP(TD) (mrem)
I-131	8.88E-02	2.89E-04	**8.91E-02**
I-132	2.18E-05	3.02E-09	**2.18E-05**
I-133	3.30E-02	3.98E-05	**3.31E-02**
I-135	2.23E-03	9.09E-07	**2.23E-03**

E1.4 Calculating $MTDP_{Iodine}$ (Equation 1.1-8)

The Iodine Mixture Total Dose Parameter includes the dose contributions from the pathways included in the assessment for all iodine radionuclides in the mixture, and is calculated by summing the TDPs for each iodine radionuclide in the mixture.

Table 4.8-E7

Radionuclide	TDP - EP(TD) (mrem)
I-131	8.91E-02
I-132	2.18E-05
I-133	3.31E-02
I-135	2.23E-03
$MTDP_{Iodine}$ =	**1.24E-01**

E1.5 Calculating the Derived Response Levels

E1.5.1 Calculating $DRL_{\tilde{A}}$ (Equation 1.1-1)

Example $DRL_{\tilde{A}}$ calculation for I-131 and $DRL_{\tilde{A}}$ values for the radionuclide mixture for the Early Phase (Total Dose) Time Phase with an Evaluation Time (t_n) of 12 hours.

PAG = 5000 mrem (1-year-old Thyroid)
$MTDP_{Iodine}$ = 1.24E-01 mrem

$$DRL_{\tilde{A}_{131_I}} = \frac{5000\ \text{mrem} * 1.0\text{E-}01\,\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3}}{1.24\text{E-}01\text{mrem}} = 4.02\text{E+}03\,\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3}$$

This means that a I-131 Integrated Air Activity of 4.02E+03 µCi•s/m^3 in the plume would indicate that the entire mixture has the potential to cause a Thyroid Equivalent Dose over the Early Phase equal to the PAG of 5000 mrem to the 1-year-old child.

Table 4.8-E8

Radionuclide	Integrated Air Activity (µCi•s/m³)	EP(TD) $DRL_{\tilde{A}}$ [a] (µCi•s/m³)
I-131	1.0E-01	**4.02E+03**
I-132	2.0E-03	**8.04E+01**
I-133	1.5E-01	**6.03E+03**
I-135	5.0E-02	**2.01E+03**
[a] Because this method uses a time integrated air activity, there is no need to account for decay during sample collection.		

E1.5.2 Calculating DRL_{Dp} (Equation 1.1-2)

Example DRL_{Dp} calculation for I-131 and DRL_{Dp} values for the radionuclide mixture for the Early Phase (Total Dose) Time Phase with an Evaluation Time (t_n) of 12 hours.

PAG = 5000 mrem (1-year-old Thyroid)
$MTDP_{Iodine}$ = 1.24E-03 mrem

$$DRL_{Dp_{131_I}} = \frac{5000\text{ mrem}*\left(3.55\text{E-}04\frac{\mu\text{Ci}}{\text{m}^2}*e^{-9.98\text{E-}07*(12*3600)}\right)*0.9997}{1.24\text{E-}01\text{ mrem}} = 1.36\text{E+}01\,\frac{\mu\text{Ci}}{\text{m}^2}$$

This means that a I-131 Areal Activity of 13.6 µCi/m² 12 hours after deposition would indicate that the entire mixture has the potential to cause a Thyroid Equivalent Dose over the Early Phase equal to the PAG of 5000 mrem to the 1-year-old child.

Table 4.8-E9

Radionuclide	$Dp_{i,t0}$ (µCi/m²)	λ_i [a] (s⁻¹)	$WF_{12\,h}$ [b] (unitless)	EP(TD) DRL_{Dp} (µCi/m²)
I-131	3.55E-04	1.00E-06	0.9997	**1.36E+01**
I-132	7.09E-06	8.39E-05	0.9997	**7.60E-03**
I-133	5.32E-04	9.26E-06	0.9997	**1.43E+01**
I-135	1.77E-04	2.93E-05	0.9997	**2.01E+00**
[a] Values from DCFPAK 3.0.				
[b] $WF_{12\text{ hours}} = 0.4 * e^{-1.46\text{E-}08*(12*3600)} + 0.6 * e^{-4.44\text{E-}10*(12*3600)} = 0.9997$				
See Appendix F, Supplement 2 for details on calculating WF.				

E1.5.3 Calculating DRL_{DR} (Equation 1.2-1)

Calculating the Deposition Mixture External Dose Factor (Dp_MExDF) (Equation 1.2-2)

To calculate the DRL_{DR} at 12 hours after deposition, we must decay the deposited mixture to the Evaluation Time. Then we use those activities to calculate the Dp_MExDF at the Evaluation Time using Equation 1.2-2.

Table 4.8-E10 shows the calculation of the Dp_MExDF for the mixture at the Evaluation Time including daughter ingrowth. (Shaded radionuclides are original parents.)

Table 4.8-E10

Radionuclide	$Dp_{i,12\ hours}$ (µCi/m²)	$WF_{12\ h}$ [a] (unitless)	Dp_ExDC [b] (mrem•m²) per (µCi•h)	GRF (unitless)	$Dp_{i,tn}$ x WF x Dp_ExDC x GRF (mrem/h)
I-131	3.40E-04	0.9997	4.86E-03	0.82	1.35E-06
Xe-131m	1.18E-07	0.9997	2.17E-04	0.82	2.10E-11
I-132	1.89E-07	0.9997	2.90E-02	0.82	4.49E-09
I-133	3.57E-04	0.9997	8.29E-03	0.82	2.43E-06
Xe-133	2.72E-05	0.9997	5.41E-04	0.82	1.21E-08
Xe-133m	1.84E-06	0.9997	4.70E-04	0.82	7.09E-10
Xe-133	6.53E-08	0.9997	5.41E-04	0.82	2.90E-11
I-135	4.99E-05	0.9997	1.96E-02	0.82	8.02E-07
Xe-135	4.55E-05	0.9997	3.33E-03	0.82	1.24E-07
Cs-135	1.39E-14	0.9997	6.74E-07	0.82	7.68E-21
Xe-135m	8.60E-06	0.9997	5.53E-03	0.82	3.90E-08
Cs-135	4.05E-17	0.9997	6.74E-07	0.82	2.24E-23
Xe-135	9.00E-06	0.9997	3.33E-03	0.82	2.46E-08
Cs-135	2.63E-15	0.9997	6.74E-07	0.82	1.45E-21
				Dp_MExDF	**4.79E-06**

[a] See Appendix F, Supplement 2 for details on calculating WF.
[b] Values from DCFPAK 3.0 (ICRP 60+).

Comparing the Dp_MExDF to the PAG to Calculate the DRL (Equation 1.2-1)

PAG = 5000 mrem (1-year-old Thyroid)
Dp_MExDF = 4.79E-06 mrem/h
$MTDP_{Iodine}$ = 1.24E-01 mrem

$$DRL_{DR} = \frac{5000\ \text{mrem} * 4.79\text{E-}06\ \frac{\text{mrem}}{\text{h}}}{1.24\text{E-}01\ \text{mrem}} = 1.93\text{E-}01\ \frac{\text{mrem}}{\text{h}}$$

This means that a Dose Rate, 12 hours after deposition, of 0.193 mrem/h would indicate that the entire mixture has the potential to cause a Thyroid Equivalent Dose over the Early Phase equal to the PAG of 5000 mrem to the 1-year-old child.

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EXAMPLE 2

Problem: Calculate the KI Administration (Thyroid Equivalent Dose) Integrated Air, Deposition, and Dose Rate DRLs for the Early Phase (Total Dose) Time Phase (0-96 hours) for the Following Mixture released from a Nuclear Power Plant for an Evaluation Time (t_n) of 12 hours, including the dose from the two inhalation pathways applicable to KI administration.

NOTE: This mixture contains the same iodine concentrations as Example 1. Adding Ba-137m, Cs-137, Sr-90 and Y-90 (all as parents) to the mix.

Table 4.8-E11

Radionuclide	Integrated Air Activity (µCi•s/m^3)	$t_{1/2}$ [a] (s)
Ba-137m	3.7E-02	1.53E+02
Cs-137	4.5E-02	9.52E+08
I-131	1.0E-01	6.93E+05
I-132	2.0E-03	8.26E+03
I-133	1.5E-01	7.49E+04
I-135	5.0E-02	2.37E+04
Sr-90	7.0E-04	9.09E+08
Y-90	9.9E-06	2.31E+05

[a] Values from DCFPAK 3.0.

Because the iodine concentrations are the same as Example 1 and the other radionuclides do not contribute iodine dose to the thyroid, we can use the $MTDP_{Iodine}$ (1.24E-01 mrem) from Example 1 and immediately calculate the DRLs.

E2.1 Calculating the Derived Response Levels

E2.1.1 Calculating $DRL_{\tilde{A}}$ (Equation 1.1-1)

Example $DRL_{\tilde{A}}$ calculation for Cs-137 and $DRL_{\tilde{A}}$ values for the radionuclide mixture for the Early Phase (Total Dose) Time Phase with an Evaluation Time (t_n) of 12 hours.

PAG = 5000 mrem (1-year-old Thyroid)
$MTDP_{Iodine}$ = 1.24E-01 mrem

$$DRL_{\tilde{A}_{^{137}Cs}} = \frac{5000\ \text{mrem} * 4.5\text{E-}02 \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3}}{1.24\text{E-}01\text{mrem}} = 1.81\text{E+}03\ \frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3}$$

This means that a Cs-137 Integrated Air Activity of 1.81E+03 µCi•s/m^3 in the plume would indicate that the entire mixture has the potential to cause a Thyroid Equivalent Dose over the Early Phase equal to the PAG of 5000 mrem to the 1-year-old child.

Table 4.8-E12

Radionuclide	Integrated Air Activity (µCi•s/m³)	EP(TD) DRL$_{\tilde{A}}$ [a] (µCi•s/m³)
Ba-137m	3.7E-02	**1.49E+03**
Cs-137	4.5E-02	**1.81E+03**
I-131	1.0E-01	**4.02E+03**
I-132	2.0E-03	**8.04E+01**
I-133	1.5E-01	**6.03E+03**
I-135	5.0E-02	**2.01E+03**
Sr-90	7.0E-04	**2.81E+01**
Y-90	9.9E-06	**3.98E-01**

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

NOTE: The iodine DRLs have not changed from Example 1, again because the added radionuclides do not contribute any iodine dose to the thyroid.

E2.1.2 Calculating DRL$_{Dp}$ (Equation 1.1-2)

Example DRL$_{Dp}$ calculation for Cs-137 and DRL$_{Dp}$ values for the radionuclide mixture for the Early Phase (Total Dose) Time Phase with an Evaluation Time (t_n) of 12 hours.

First, we need to calculate the Areal Activities of Cs-137 and Sr-90.

Table 4.8-E13

Radionuclide	Physical Form	Integrated Air Activity (µCi•s/m³)	V$_d$ (m/s)	Deposition (µCi/m²)
Ba-137m	Particulate	3.7E-02	3.0E-03	1.11E-04
Cs-137	Particulate	4.5E-02	3.0E-03	1.35E-04
Sr-90	Particulate	7.0E-04	3.0E-03	2.10E-06
Y-90	Particulate	9.9E-06	3.0E-03	2.97E-08

Now, we can use the Deposition values to calculate the DRLs.

PAG = 5000 mrem (1-year-old Thyroid)
MTDP$_{\text{Iodine}}$ = 1.24E-03 mrem

$$DRL_{Dp_{137Cs}} = \frac{5000\ \text{mrem} * \left(1.35\text{E-}04 \frac{\mu\text{Ci}}{\text{m}^2} * e^{-7.28\text{E-}10*(12*3600)}\right) * 0.9997}{1.24\text{E-}01\ \text{mrem}} = 5.42\,\frac{\mu\text{Ci}}{\text{m}^2}$$

This means that a Cs-137 Areal Activity of 5.42 µCi/m² 12 hours after deposition would indicate that the entire mixture has the potential to cause a Thyroid Equivalent Dose from iodine over the Early Phase equal to the PAG of 5000 mrem to the 1-year-old child.

Table 4.8-E14

Radionuclide	$Dp_{i,t0}$ (µCi/m²)	λ_i [a] (s^{-1})	$WF_{12\ h}$ [b] (unitless)	EP(TD) DRL_{Dp} (µCi/m²)
Ba-137m	1.11E-04	4.53E-03	0.9997	**4.57E-85**
Cs-137	1.35E-04	7.28E-10	0.9997	**5.42E+00**
I-131	3.55E-04	1.00E-06	0.9997	**1.36E+01**
I-132	7.09E-06	8.39E-05	0.9997	**7.60E-03**
I-133	5.32E-04	9.26E-06	0.9997	**1.43E+01**
I-135	1.77E-04	2.93E-05	0.9997	**2.01E+00**
Sr-90	2.10E-06	7.63E-10	0.9997	**8.44E-02**
Y-90	2.97E-08	3.00E-06	0.9997	**1.05E-03**

[a] Values from DCFPAK 3.0.

[b] $WF_{12\ \text{hours}} = 0.4 * e^{-1.46\text{E-08}*(12*3600)} + 0.6 * e^{-4.44\text{E-10}*(12*3600)} = 0.9997$

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

NOTE: The iodine DRLs have not changed from Example 1, again because the added radionuclides do not contribute any iodine dose to the thyroid.

E1.5.3 Calculating DRL_{DR} (Equation 1.2-1)

Calculating the Deposition Mixture External Dose Factor (Dp_MExDF) (Equation 1.2-2)

To calculate the DRL_{DR} at 12 hours after deposition, we must decay the deposited mixture to the Evaluation Time. Then we use those activities to calculate the Dp_MExDF at the Evaluation Time using Equation 1.2-2.

Table 4.8-E15 shows the calculation of the Dp_MExDF for the mixture at the Evaluation Time including daughter ingrowth. (Shaded radionuclides are original parents.)

Table 4.8-E15

Radionuclide	$Dp_{i,12\ hours}$ (µCi/m²)	$WF_{12\ h}$ [a] (unitless)	Dp_ExDC [b] (mrem•m²) per (µCi•h)	GRF (unitless)	$Dp_{i,tn}$ x WF x Dp_ExDC x GRF (mrem/h)
Ba-137m	1.30E-89	0.9997	7.69E-03	0.82	8.20E-92
Cs-137	1.35E-04	0.9997	4.17E-05	0.82	4.61E-09
Ba-137m	1.27E-04	0.9997	7.69E-03	0.82	8.01E-07
I-131	3.40E-04	0.9997	4.86E-03	0.82	1.35E-06
Xe-131m	1.18E-07	0.9997	2.17E-04	0.82	2.10E-11
I-132	1.89E-07	0.9997	2.90E-02	0.82	4.49E-09
I-133	3.57E-04	0.9997	8.29E-03	0.82	2.43E-06
Xe-133	2.72E-05	0.9997	5.41E-04	0.82	1.21E-08
Xe-133m	1.84E-06	0.9997	4.70E-04	0.82	7.09E-10
Xe-133	6.53E-08	0.9997	5.41E-04	0.82	2.90E-11
I-135	4.99E-05	0.9997	1.96E-02	0.82	8.02E-07
Xe-135	4.55E-05	0.9997	3.33E-03	0.82	1.24E-07
Cs-135	1.39E-14	0.9997	6.74E-07	0.82	7.68E-21
Xe-135m	8.60E-06	0.9997	5.53E-03	0.82	3.90E-08
Cs-135	4.05E-17	0.9997	6.74E-07	0.82	2.24E-23
Xe-135	9.00E-06	0.9997	3.33E-03	0.82	2.46E-08
Cs-135	2.63E-15	0.9997	6.74E-07	0.82	1.45E-21
Sr-90	2.10E-06	0.9997	2.18E-05	0.82	3.75E-11
Y-90	2.56E-07	0.9997	1.47E-03	0.82	3.08E-10
Y-90	2.61E-08	0.9997	1.47E-03	0.82	3.15E-11
				Dp_MExDF	**5.59E-06**

[a] See Appendix F, Supplement 2 for details on calculating WF.
[b] Values from DCFPAK 3.0 (ICRP 60+).

Comparing the Dp_MExDF to the PAG to Calculate the DRL (Equation 1.2-1)

PAG = 5000 mrem (1-year-old Thyroid)
Dp_MExDF = 5.59E-06 mrem/h
$MTDP_{Iodine}$ = 1.24E-01 mrem

$$DRL_{DR} = \frac{5000\ \text{mrem} * 5.59\text{E-}06\,\frac{\text{mrem}}{\text{h}}}{1.24\text{E-}01\ \text{mrem}} = 2.25\text{E-}01\,\frac{\text{mrem}}{\text{h}}$$

This means that a Dose Rate, 12 hours after deposition, of 0.225 mrem/h would indicate that the entire mixture has the potential to cause a Thyroid Equivalent Dose over the Early Phase equal to the PAG of 5000 mrem to the 1-year-old child.

APPENDIX A. GLOSSARY

Acute Dose	The dose delivered over a period of 30 days.
Acute Dose Coefficient	The Effective or Equivalent Dose received over 30 days per unit intake (mrem/µCi).
Areal Activity	The amount of radioactive material per area (e.g., $\mu Ci/m^2$).
Avoidable Dose	The projected dose that can be avoided by taking protective actions.
Chronic Dose	The dose delivered over a period of 50-70 years.
Chronic Dose Coefficient	The Effective or Equivalent Dose received over 50-70 years per unit intake (mrem/µCi).
Committed Effective Dose (E)	The sum of the committed equivalent doses following intake (inhalation or ingestion) of a radionuclide to each organ multiplied by a tissue weighting factor.
Committed Equivalent Dose (H_T)	The equivalent dose to a specific organ following intake (inhalation or ingestion). It does not include contributions from external dose.
DCFPAK (Dose Coefficient File Package)	An electronic database containing dose coefficients from ICRP Dosimetry Models.
Deposition	The contamination on the surface of the ground.
Derived Response Level (DRL)	A level of radioactivity in an environmental medium that would be expected to produce a dose equal to its corresponding Protective Action Guide (PAG).
Early Phase	The period at the beginning of a nuclear incident when immediate decisions for effective use of protective actions are required and must be based primarily on predictions of radiological conditions in the environment. This phase may last from hours to days. For the purpose of dose projection, it is assumed to last for four days.
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 adult 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.
Groundshine	External 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 subsequently published.

Intermediate Phase	The period beginning after the incident source and releases have been brought under control and reliable environmental measurements are available for use as a basis for decisions on additional protective actions and extending until these protective actions have terminated. This phase may overlap the early phase and late phase and may last from weeks to many months. For the purposes of dose projection, it is assumed to last for one year.
Intervention Level (IL)	The concentration of a radionuclide in food that could lead to an individual receiving a dose equal to the PAG. This manual discusses two types of ILs: FDA-Established Derived Intervention Levels (DILs) and FRMAC-calculated FRMAC Intervention Levels (FILs).
Late Phase	The period beginning when recovery actions designed to reduce radiation levels in the environment to permanently acceptable levels are commenced, and ending when all recovery actions have been completed. This phase may extend from months to years.
Mixture	The nuclide ratio (relative abundance) of the radionuclides in a release.
Pathways	The paths radionuclides follow from the source through the environment, including vegetation and animals, to reach an individual or a population.
Primary Dose Pathways	The four main exposure pathways used in projecting doses for Public Protection calculations. These pathways are: Plume Pathways (airborne material) • Inhalation of plume-borne material • External exposure from plume submersion Ground Pathways (deposited material) • Inhalation of resuspended material • External exposure from groundshine
Protective Action Guide (PAG)	The projected dose, from an accidental release of radioactive material, where specific actions to reduce or avoid dose are warranted.
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 breathing zone of material originally deposited onto surfaces.
Submersion	To be surrounded or engulfed by the radioactive cloud.
Total Dose	The projected dose that begins at the start of the release
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, forage or water.

Turn-Back Limit Guidance given to emergency workers to ensure that they do not exceed their dose limit for the shift. This guidance is usually implemented via an integrated dose reading on a self-reading dosimeter, an exposure rate, or a deposition concentration indicating that the emergency worker should move to a less contaminated area.

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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APPENDIX B. LIST OF VARIABLES

TERM	UNITS	DEFINITION	METHODS
$AFDIR_{A,fodder}$	$\frac{kg_{wet}}{d}$	Animal Feed Daily Intake Rate (fodder), the daily rate at which an animal *(A)* consumes fodder.	3.3, 3.4, 3.6, Appendix C
$AFDIR_{A,forage}$	$\frac{kg_{wet}}{d}$	Animal Feed Daily Intake Rate (forage), the daily rate at which an animal *(A)* consumes forage.	3.3, 3.4, 3.6, Appendix C
$\tilde{A}_i$	$\frac{\mu Ci \cdot s}{m^3}$	Integrated air activity of radionuclide *i* in a release.	1.1, 2.3, 4.5
APF	unitless	Assigned Protection Factor, the level of respiratory protection that a respirator is expected to provide. (Default of 1 when no respirators are used.) **NOTE:** Consult Health and Safety personnel for appropriate values for APF.	2.1, 2.2, 2.3, Appendix C
$ASDIR_A$	$\frac{kg_{soil}}{d}$	Animal Soil Daily Intake Rate, the daily rate at which an animal *(A)* consumes soil.	3.3, 3.4, 3.6, Appendix C
$AWDIR_A$	$\frac{L}{d}$	Animal Water Daily Intake Rate, the daily rate at which an animal *(A)* consumes water.	3.3, 3.4, 3.6, Appendix C
$BPF_{Dp,Ex}$	unitless	Building Protection Factor for Deposition External Exposure, a factor to account for the reduction in External Dose due to being inside a building.	4.7
$BPF_{Dp,Inh}$	unitless	Building Protection Factor for Deposition Inhalation, a factor to account for the reduction in Inhalation Dose due to being inside a building.	4.7
$BPF_{Pl,Ex}$	unitless	Building Protection Factor for Plume External Exposure, a factor to account for the reduction in External Dose due to being inside a building.	4.7
$BPF_{Pl,Inh}$	unitless	Building Protection Factor for Plume Inhalation, a factor to account for the reduction in Inhalation Dose due to being inside a building.	4.7
BR_{AA}	$\frac{m^3}{s}$	Activity-Averaged Breathing Rate, the average volume of air breathed per unit time by an adult male (ICRP94, Table B.16B).	1.1, Appendix C
BR_{LE}	$\frac{m^3}{s}$	Light Exercise Breathing Rate, the volume of air breathed per unit time by an adult male during light exercise (ICRP94, Table 6).	1.1, 2.2, 2.3, Appendix C

TERM	UNITS	DEFINITION	METHODS
$C_{crop,i}$	$\frac{\mu Ci}{kg_{wet}}$	Projected Contamination level in a food crop, the level of activity of radionuclide *i* per mass in a food type harvested from contaminated ground at the time it is distributed in commerce.	3.6
$C_{f,i}$	$\frac{\mu Ci}{kg_{wet}}$	Food Contamination, the level of contamination of radionuclide *i* in a specific food type (f) at the time it is distributed in commerce. (May also be expressed in µCi/L.)	3.5
$C_{fodder,i}$	$\frac{\mu Ci}{kg_{wet}}$	Measured Contamination level of radionuclide *i* in fodder.	3.6
$C_{meat,i,A}$	$\frac{\mu Ci}{kg_{wet}}$	Projected Contamination Level in Meat, the level of activity of radionuclide *i* per mass in meat produced from an animal *(A)* consuming radioactive material.	3.6
$C_{milk,i,A}$	$\frac{\mu Ci}{L}$	Projected Contamination Level in Milk, the level of activity of radionuclide *i* per volume in milk produced from an animal *(A)* consuming radioactive material.	3.6
CRF_{crop}	unitless	Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop.	3.2, 3.6, Appendix C
CRF_{forage}	unitless	Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the forage.	3.3, 3.4, 3.6, Appendix C
$Crop\_DRL_{i,tn}$	$\frac{\mu Ci}{m^2}$	Ingestion Derived Response Level for Crop, the areal activity, at time t_n, of radionuclide *i* that may cause the crop growing in that area to equal the applicable Intervention Level at the time it is distributed in commerce.	3.2, Appendix C
C_S	$\frac{\mu Ci}{kg_{soil}}$	Measured Contamination level of radionuclide *i* in soil.	3.6
$C_{sample,dry}$	$\frac{\mu Ci}{kg_{dry}}$	Sample Contamination, the level of contamination of radionuclide *i* in a sample in terms of dry mass.	4.2
$C_{sample,wet}$	$\frac{\mu Ci}{kg_{wet}}$	Sample Contamination, the level of contamination of radionuclide *i* in a sample in terms of wet mass.	4.2
$C_{water,i}$	$\frac{\mu Ci}{L}$	Measured Contamination level of radionuclide *i* in drinking water.	3.6

TERM	UNITS	DEFINITION	METHODS
$d_{e,crop}$	m	Effective Soil Depth, the maximum of the mixing depth (d_m) and the mature root depth (d_r) for the crop.	3.2, 3.6
$d_{e,forage}$	m	Effective Soil Depth, the maximum of the mixing depth (d_m) and the mature root depth (d_r) for the forage.	3.3, 3.4, 3.6
d_m	m	Mixing Depth.	3.2, 3.3, 3.4, 3.6, 3.7, Appendix C
d_r	m	Mature Root Depth.	3.2, 3.3, 3.4, 3.6, Appendix C
$DFIR_{age}$	$\frac{\mathrm{kg_{wet}}}{\mathrm{d}}$	Daily Food Intake Rate, the daily intake rate (as prepared for consumption, i.e. wet mass) for a specific age group.	3.1, Appendix C
$DFIR_{subgroup,age}$	$\frac{\mathrm{kg_{wet}}}{\mathrm{d}}$	Daily Food Intake Rate for a food subgroup (as prepared for consumption, i.e. wet mass) for a specific age group.	3.5, Appendix C
DIL	$\frac{\mu\mathrm{Ci}}{\mathrm{kg_{wet}}}$	Derived Intervention Level, the concentration of radionuclide *i* in food at which the ingestion dose to the most sensitive population (age group) and target organ would equal the applicable ingestion PAG.	3.1, 3.2, 3.3, 3.4, Appendix C
DL_{TP}	mrem	Dose Limit, the dose that the worker is allowed to receive for the work shift.	2.1, 2.2, 2.3
Dp_ExDC_i	$\frac{\mathrm{mrem} \cdot \mathrm{m^2}}{\mu\mathrm{Ci} \cdot \mathrm{h}}$	Deposition External Dose Coefficient, the external dose rate from radionuclide *i* per unit activity deposited on the ground. *Units may either be in seconds or hours, depending on the Method.*	1.1, 1.2, Appendix C
$Dp\_ExDP_{i,TP}$	mrem	Deposition External Dose Parameter, the external dose from groundshine from radionuclide *i*, over the time phase under consideration *(TP)*.	1.1, 2.1, 2.2, 4.7 Appendix C
$Dp\_InhDP_{i,TP}$	mrem	Deposition Inhalation Dose Parameter, the committed dose from radionuclide *i* deposited on the ground from the inhalation of the resuspended fraction of the radionuclide over the time phase under consideration *(TP)*.	1.1, 2.1, 2.2, 4.7 Appendix C

TERM	UNITS	DEFINITION	METHODS
Dp_MExDF	$\frac{\text{mrem}}{\text{h}}$	Deposition Mixture External Dose Factor, the external dose rate one meter above the ground at time t_n from a radionuclide mixture deposited on the ground.	1.2, 2.3
Dp_i	$\frac{\mu\text{Ci}}{\text{m}^2}$	Deposition, the activity of radionuclide *i* per unit area of ground (areal activity).	1.1, 1.2, 3.6, 4.1, 4.5
$DRL_{\tilde{A},i,TP}$	$\frac{\mu\text{Ci}}{\text{m}^2}$	Integrated Air Derived Response Level, the integrated air activity ($\tilde{A}$) of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the PAG or worker DL over the time phase under consideration *(TP)*.	1.1, 1.3, 1.4, 2.3, Appendix C
$DRL_{Dp,i,TP}$	$\frac{\mu\text{Ci}}{\text{m}^2}$	Deposition Derived Response Level, the areal activity, at time t_n, of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the PAG or worker DL over the time phase under consideration *(TP)*.	1.1, 1.3, 1.4, 2.3, Appendix C
$DRL_{DR,TP}$	$\frac{\text{mrem}}{\text{h}}$	Dose Rate Derived Response Level, the external dose rate one meter above the ground, at time t_n, at which the total dose from *all radionuclides* in a release would equal the PAG or worker DL over the time phase under consideration *(TP)*.	1.2, 1.5, 2.3, Appendix C
$DRL_{XR,TP}$	$\frac{\text{mR}}{\text{h}}$	Exposure Rate Derived Response Level, the external exposure rate one meter above the ground, at time t_n, at which the total dose from *all radionuclides* in a release would equal the PAG or worker DL over the time phase under consideration *(TP)*.	1.2, 1.5, 2.3
$DRL_{\alpha,\tilde{A},TP}$	$\frac{\mu\text{Ci}_\alpha \cdot \text{s}}{\text{m}^3}$	Air Alpha Derived Response Level, the integrated air alpha activity of the mixture at which the total dose from *all radionuclides* in a release would equal the PAG or worker DL over the time phase under consideration *(TP)*.	1.3, 2.3

TERM	UNITS	DEFINITION	METHODS
$DRL_{\alpha,Dp,TP}$	$\frac{\mu Ci_{\alpha}}{m^2}$	Deposition Alpha Derived Response Level, the areal alpha activity of the mixture, at time t_n, of the mixture at which the total dose from *all radionuclides* in a release would equal the PAG or worker DL over the time phase under consideration *(TP)*.	1.3, 2.3
$DRL_{\beta,\tilde{A},TP}$	$\frac{\mu Ci_{\beta} \cdot s}{m^3}$	Air Beta Derived Response Level, the integrated air beta activity of the mixture at which the total dose from *all radionuclides* in a release would equal the PAG or worker DL over the time phase under consideration *(TP)*.	1.4, 2.3
$DRL_{\beta,Dp,TP}$	$\frac{\mu Ci_{\beta}}{m^2}$	Deposition Beta Derived Response Level, the areal beta activity of the mixture, at time t_n, at which the total dose from *all radionuclides* in a release would equal the PAG or worker DL over the time phase under consideration *(TP)*.	1.4, 2.3
DSIR	$\frac{kg_{soil}}{d}$	Daily Soil Intake Rate, the amount of soil inadvertently ingested by humans in a day.	3.7
$E_{Ing,age}$	mrem	Committed Effective Dose from ingestion, the dose to the whole body, received by a specific age group from ingestion of all radionuclides in all contaminated food types, mrem;	3.5
E_{soil}	mrem	Committed Effective Dose from inadvertent soil ingestion, the dose to the whole body from the ingestion of all radionuclides in contaminated soil.	3.7
ExDR	$\frac{mrem}{h}$	External dose rate, the external dose rate from materials deposited on the ground.	1.5, 2.1
$ExDR_a$	$\frac{mrem}{h}$	External dose rate at time t_a (hours after detonation).	1.7
$ExDR_b$	$\frac{mrem}{h}$	External dose rate at time t_b (hours after detonation).	1.7
$ExDR_r$	$\frac{mrem}{h}$	Reference external dose rate at 1 hour after nuclear detonation.	1.7
$ExDR_{r,PAG}$	$\frac{mrem}{h}$	Reference external dose rate at 1 hour after nuclear detonation which would produce a dose equal to the PAG over the time phase under consideration.	1.7

TERM	UNITS	DEFINITION	METHODS
$ExDR_t$	$\frac{\text{mrem}}{\text{h}}$	External dose rate at time *t* (hours after detonation).	1.7
$ExTDCF_{TP}$	$\frac{\text{mrem}_{\text{inh+external}}}{\text{mrem}_{\text{external}}}$	External to Total Dose Conversion Factor, the ratio of the total dose (inhalation + external) to the external dose from a release of radioactive material over the time phase under consideration *(TP)*. **NOTE:** This value is used to convert a measurement from a self-reading dosimeter into a dose which includes the dose from inhalation of resuspended material.	2.1, 2.2
F_{PS}	unitless	Fraction of the mixture of a specific particle size.	4.5
$FDC_{age,i}$	unitless	Fraction of Diet Contaminated, the fraction of a human's diet that is contaminated with radionuclide *i*.	3.1, Appendix C
FDC_{fodder}	unitless	Fraction of Diet Contaminated (fodder), the fraction of the animal's fodder that is contaminated.	3.3, 3.4, 3.6, Appendix C
FDC_{forage}	unitless	Fraction of Diet Contaminated (forage), the fraction of the animal's forage that is contaminated.	3.3, 3.4, 3.6, Appendix C
FDC_{water}	unitless	Fraction of Diet Contaminated (water), the fraction of the animal's water that is contaminated.	3.3, 3.4, 3.6, Appendix C
$FFC_{subgroup}$	unitless	Fraction of Food Subgroup contaminated by radionuclide *i*.	3.5, Appendix C
$FIL_{organ.age,i}$	$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$	FRMAC Intervention Level, the concentration of radionuclide *i* in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG.	3.1, 3.2, 3.3, 3.4, Appendix C
GRF	unitless	Ground Roughness Factor, a constant (0.82) that compensates for the fact that the external exposure is not coming from an infinite flat plane (An02).	1.1, 1.2
H_T	mrem	Committed Equivalent Dose, the dose to organ *T* from the ingestion of all radionuclides in contaminated food.	3.5
$H_{T,soil}$	mrem	Committed Equivalent Dose from inadvertent soil ingestion, the dose to organ *T* from the ingestion of soil.	3.7

TERM	UNITS	DEFINITION	METHODS
$IL_{organ,age,i}$	$\frac{\mu Ci}{kg_{wet}}$	Intervention Level, the concentration of radionuclide *i* in food at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to equal the applicable ingestion PAG, $\mu Ci/kg_{wet}$. **NOTE:** Intervention Levels may be either a published FDA Derived Intervention Level (DIL) or calculated FRMAC Intervention Level (FIL) from Method 3.1.	3.1, 3.2, 3.3, 3.4
$IngDC_{organ.age.i}$	$\frac{mrem}{\mu Ci}$	Ingestion Dose Coefficient, the ingestion pathway dose coefficient for the target organ for a specific age group for radionuclide *i*.	3.1, 3.5, 3.7
$IngDP_{organ,avg,age}$	$\frac{mrem \cdot d}{kg_{wet}}$	Average Ingestion Dose Parameter for a food subgroup, the average of the individual *IngDPs* for each type of contaminated food in a subgroup for a specific age group.	3.5
$IngDP_{organ.f.age}$	$\frac{mrem \cdot d}{kg_{wet}}$	Ingestion Dose Parameter, the committed effective dose received from ingestion of all radionuclides in a specific food type (*f*) by a specific age group.	3.5
$InhDC_i$	$\frac{mrem}{\mu Ci}$	Inhalation Dose Coefficient, the committed dose coefficient for inhalation of radionuclide *i*.	1.1, Appendix C
KIPF	unitless	Potassium Iodide Protection Factor, the protection factor for thyroid dose from iodine radionuclides (Default of 1 when KI is not administered). **NOTE:** Consult Health and Safety personnel for appropriate values for KIPF.	2.1, 2.2, 2.3
$KP_{i,TP}$	$\frac{\mu Ci \cdot s}{m^3}$	Resuspension Parameter, value that adjusts the airborne radioactivity level of radionuclide *i* over the time phase under consideration *(TP)* for radioactive decay and in-growth and the resuspension factor.	1.1, Appendix F
K	m^{-1}	Resuspension Factor, the fraction of radioactive material transferred from the surface to the breathing zone at given time *t* after initial deposition.	4.1, Appendix F
$MCF_{D\text{-}W,crop}$	$\frac{kg_{dry}}{kg_{wet}}$	Mass Conversion Factor (dry to wet), the ratio of dry mass to wet mass for a crop.	3.2, 3.6, 4.2, Appendix C
$MCF_{D\text{-}W,\,forage}$	$\frac{kg_{dry}}{kg_{wet}}$	Mass Conversion Factor (dry to wet), the ratio of dry mass to wet mass for forage.	3.3, 3.4, 3.6, Appendix C

TERM	UNITS	DEFINITION	METHODS
$Meat\_DRL_{area,A,i,tn}$	$\frac{\mu Ci}{m^2}$	Meat Derived Response Level – Area, the areal activity, at time t_n, of radionuclide *i* present in a grazing area that may cause the grazing animal's (*A*) meat to equal the applicable Intervention Level at the time it is distributed in commerce.	3.4, Appendix C
$Meat\_DRL_{mass,A,i,tn}$	$\frac{\mu Ci}{kg_{wet}}$	Meat Derived Response Level – Mass, the mass concentration of radionuclide *i* in animal fodder, at time t_n, that may result in the grazing animal's (*A*) meat equaling the Intervention Level for that radionuclide at the time it is distributed in commerce.	3.4, Appendix C
$Meat\_DRL_{water,A,i,tn}$	$\frac{uCi}{L}$	Meat Derived Response Level – Water, the water concentration of radionuclide *i* in an animal's drinking water, at time t_n, that may result in the grazing animal's (*A*) meat equaling the Intervention Level for that radionuclide at the time it is distributed in commerce.	3.4, Appendix C
$Milk\_DRL_{area,A,i,tn}$	$\frac{\mu Ci}{m^2}$	Milk Derived Response Level – Area, the areal activity, at time t_n, of radionuclide *i* present in a grazing area that may cause the grazing animal's (*A*) milk to equal the applicable Intervention Level at the time it is distributed in commerce.	3.3, Appendix C
$Milk\_DRL_{mass,A,i,tn}$	$\frac{\mu Ci}{kg_{wet}}$	Milk Derived Response Level – Mass, the mass concentration of radionuclide *i* in animal fodder, at time t_n, that may result in the grazing animal's (*A*) milk equaling the Intervention Level for that radionuclide at the time it is distributed in commerce.	3.3, Appendix C
$Milk\_DRL_{water,A,i,tn}$	$\frac{\mu Ci}{L}$	Milk Derived Response Level – Water, the water concentration of radionuclide *i* in an animal's drinking water, at time t_n, that may result in the grazing animal's (*A*) milk equaling the Intervention Level for that radionuclide at the time it is distributed in commerce.	3.3, Appendix C
$MTDP_{TP}$	mrem	Mixture Total Dose Parameter, the sum of the doses from *all radionuclides* in a release, over the time phase under consideration *(TP)*, from the pathways included in the assessment.	1.1, 1.2

TERM	UNITS	DEFINITION	METHODS
$MTDP_{Worker,TP}$	mrem	Worker Mixture Total Dose Parameter, the sum of the doses from *all radionuclides* in a release, over the time phase under consideration *(TP)*, from the pathways included in the assessment, in which the inhalation dose parameters may be adjusted for the use of Potassium Iodide and/or Respiratory Protection	2.2, 2.3
NF_DRL	$\frac{\text{mrem}}{\text{h}}$	Nuclear Fallout Derived Response Level, the external dose rate, at time t_n, at which the external dose from *all radionuclides* in a fallout deposition mixture would equal the PAG for the time phase under consideration.	1.7
OF_{In}	unitless	Inside Occupancy Factor, the fraction of the Time Phase spent inside a building in the contaminated area	4.7
OF_{Out}	unitless	Outside Occupancy Factor, the fraction of the Time Phase spent outside in the contaminated area	4.7
Pl_ExDC_i	$\frac{\text{mrem} \cdot \text{m}^3}{\mu\text{Ci} \cdot \text{s}}$	Plume External Dose Coefficient, the external dose rate from submersion in radionuclide *i* in the plume.	1.1, Appendix C
$Pl\_ExDP_{i,TP}$	mrem	Plume External Dose Parameter, the external dose from submersion from plume-borne radionuclide *i* over the time phase under consideration *(TP)*.	1.1, 4.7 Appendix C
$Pl\_InhDP_{i,TP}$	mrem	Plume Inhalation Dose Parameter, the committed dose from the inhalation of plume-borne radionuclide *i* over the time phase under consideration (*TP*).	1.1, 4.7 Appendix C
PPD_{TP}	mrem	Projected Public Dose, the sum of the doses of the selected dose pathways, over the time phase under consideration, from the radionuclide mixture.	1.5
ST	h	Stay Time, how long the worker will be allowed to work in the contaminated area.	2.1
t_0	NA	Release Time, the time the release begins. This time is usually assumed to correspond to the time of deposition.	1.1, 1.2, 3.6, 3.7, 4.3, 4.5, Appendix F
t_1	s or h	Start Time, the start of the time phase (integration period) under consideration.	1.1, 1.7, 2.2, 3.7, Appendix F

TERM	UNITS	DEFINITION	METHODS
t_2	s or h	End Time, the end of the time phase (integration period) under consideration.	1.1, 1.7, 2.2, 2.7, Appendix F
t_a, t_b	h	Time after a nuclear detonation at which a measurement is made.	1.7
TBL_D_{TP}	$mrem_{external}$	Turn-Back Limit for External Dose, the external dose, as recorded by the self-reading dosimeter, received from a radionuclide mixture over the time phase under consideration *(TP)* that indicates that a worker may have reached their DL.	2.2
TBL_X_{TP}	mR	Turn-Back Limit for External Exposure, the external exposure, as recorded by a self-reading exposure meter, received from a radionuclide mixture over the time phase under consideration *(TP)* that indicates that a worker may have reached their DL.	2.2
$TBL_{\alpha,TP}$	$\frac{\mu Ci_\alpha}{m^2}$	Alpha Turn-Back Limit, the alpha contamination level that should not be exceeded to ensure the worker does not exceed their DL for the work shift.	2.2
$TBL_{\beta,TP}$	$\frac{\mu Ci_\beta}{m^2}$	Beta Turn-Back Limit, the beta contamination level that should not be exceeded to ensure the worker does not exceed their DL for the work shift.	2.2
$TBL_{DR,TP}$	$\frac{mrem}{h}$	Dose Rate Turn-Back Limit, the external dose rate one meter above the ground that should not be exceeded to ensure the worker does not exceed their DL for the work shift.	2.2
$TBL_{XR,TP}$	$\frac{mR}{h}$	Exposure Rate Turn-Back Limit, the external exposure rate one meter above the ground that should not be exceeded to ensure the worker does not exceed their DL for the work shift.	2.2
t_c	d	Consumption Time, the length of the food consumption period.	3.1, 3.5
TDP_{TP}	mrem	Total Dose Parameter, the sum of the doses from radionuclide *i*, over the time phase under consideration *(TP)*, from the pathways included in the assessment	1.1, 1.5, Appendix C

TERM	UNITS	DEFINITION	METHODS
$TF_{crop,i}$	$\frac{\mu Ci / kg_{dry}}{\mu Ci / kg_{soil}}$	Transfer Factor for a food crop, the fraction of radionuclide i deposited on the growing medium that is transferred to the plant prior to collection. **NOTE:** Transfer Factors for plants are in terms of edible dry plants (PNNL20).	3.2, 3.6, Appendix C
$TF_{forage,i}$	$\frac{\mu Ci / kg_{dry}}{\mu Ci / kg_{soil}}$	Transfer Factor for forage, the fraction of radionuclide *i* deposited on the growing medium that is transferred to the forage.	3.3, 3.4, 3.6, Appendix C
$TF_{Meat,A,i}$	$\frac{\mu Ci / kg_{wet}}{\mu Ci / d}$	Transfer Factor for meat, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the meat of the animal.	3.4, 3.6, Appendix C
$TF_{Milk,A,i}$	$\frac{\mu Ci / L_{milk}}{\mu Ci / d}$	Transfer Factor for milk, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the milk produced by the animal.	3.3, 3.6, Appendix C
t_g	d	Time to Grazing, the time from deposition until the animal begins eating the contaminated forage	3.3, 3.4, 3.6
t_h	d	Time to Harvest, the time from deposition until the crop or animal product is collected.	3.2, 3.3, 3.4, 3.6
t_m	d	Time to Market, the number of days from harvest to consumption.	3.2, 3.3, 3.4, 3.6, Appendix C
t_n	s, h, d	Evaluation Time, the point in time, relative to the start of the release, for which the calculation, measurement, or prediction is valid.	1.1, 1.2, 1.3, 1.4, 1.5, 1.7, 3.2, 3.3, 3.4, 4.3
t_r	s	Reference Time, the time when the sample results are valid.	4.3, 4.6
t_s	s	Sampling Time, the time when the sample was collected.	4.3, 4.6
t_Δ	s	Duration of the sample period.	4.6
V_d	m/s	Deposition velocity for a specific particle size.	4.5
$\overline{V}_d$	m/s	Weighted average deposition velocity.	4.5

TERM	UNITS	DEFINITION	METHODS
WF	unitless	Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind)	1.1, 1.2, 2.3, 3.2, 3.3, 3.4, 3.6, 3.7, Appendix F
WP_{TP}	$\frac{\mu Ci \cdot s}{m^2}, \frac{\mu Ci \cdot hr}{m^2}$	Weathering Parameter, the adjustment for radioactive decay and in-growth and the time-dependent weathering effects that change the amount of a radionuclide available to cause direct exposure or to be ingested over the time phase under consideration *(TP)*.	1.1, 2.2, 3.7, Appendix F
x	unitless	Power function exponent, the value that represents the decay of fallout radioactivity at a given location. Default =1.2.	1.7
$XDCF_A$	$\frac{mrem}{mR}$	Exposure to Dose Conversion Factor (acute), the constant used to convert external exposure (mR) to midline (bone marrow) dose (mrem).	1.2, 2.1, 2.2
$XDCF_C$	$\frac{mrem}{mR}$	Exposure to Dose Conversion Factor (chronic), the constant used to convert external exposure (mR) to deep tissue (1 cm) dose (mrem).	1.2, 2.1, 2.2
Y_{crop}	$\frac{kg_{wet}}{m^2}$	Crop Yield, the mass of crop grown per area of land.	3.2, 3.6, Appendix C
Y_{forage}	$\frac{kg_{wet}}{m^2}$	Crop Yield, the mass of forage grown per area of pastureland.	3.3, 3.4, 3.6, Appendix C
$Y_{\alpha,i}$	$\frac{\mu Ci_{\alpha}}{\mu Ci_{nt}}$	Yield, the alpha activity per total (nuclear transformation) activity of radionuclide *i*.	1.3, 2.2, 2.3
$Y_{\beta,i}$	$\frac{\mu Ci_{\beta}}{\mu Ci_{nt}}$	Yield, the beta activity per total (nuclear transformation) activity of radionuclide *i*.	1.4, 2.2, 2.3
λ_i	s^{-1} or d^{-1}	Decay constant for radionuclide *i*.	Most Methods, Appendix C, Appendix F
λ_w	d^{-1}	Decay constant for weathering radioactive material off plants.	3.2, 3.3, 3.4, 3.6, Appendix C
ρ_{milk}	$\frac{kg_{wet}}{L_{milk}}$	Milk density.	3.3, Appendix C

TERM	UNITS	DEFINITION	METHODS
ρ_{soil}	$\frac{\text{kg}_{\text{soil}}}{\text{m}^3}$	Soil density.	3.2, 3.3, 3.4, 3.6, 3.7, Appendix C
χ_i	$\frac{\mu\text{Ci}}{\text{m}^3}$	Air concentration of radionuclide *i*.	4.1

APPENDIX C. DATA TABLES

Effective Date

Table 1. Radiological Data [1]

Parent Radionuclide	$t_{1/2}$ (d)	λ (d^{-1})	Dp_ExDC [a] (Groundshine) (mrem·m²/µCi·h)	Pl_ExDC [b] (Submersion) (mrem·m³/µCi·h)	InhDC [b] (Inhalation) (mrem/µCi)
Am-241	1.58E+05	4.39E-06	2.90E-04	8.95E-03	1.54E+05
Ba-140	1.28E+01	5.44E-02	3.55E-02	1.81E+00	2.34E+01
Ce-141	3.25E+01	2.13E-02	9.28E-04	4.17E-02	1.18E+01
Ce-144	2.85E+02	2.43E-03	2.38E-03	4.33E-02	1.33E+02
Cf-252	9.66E+02	7.17E-04	5.75E-03	2.97E-01	7.33E+04
Cm-242	1.63E+02	4.26E-03	8.90E-06	5.19E-05	1.92E+04
Cm-244	6.61E+03	1.05E-04	7.79E-06	5.33E-05	9.84E+04
Co-60	1.93E+03	3.60E-04	3.06E-02	1.59E+00	3.77E+01
Cs-134	7.54E+02	9.19E-04	1.97E-02	9.42E-01	2.48E+01
Cs-136	1.32E+01	5.27E-02	2.65E-02	1.31E+00	4.55E+00
Cs-137	1.10E+04	6.29E-05	7.30E-03	3.39E-01	1.73E+01
Gd-153	2.40E+02	2.88E-03	1.23E-03	4.14E-02	7.73E+00
I-129	5.73E+09	1.21E-10	2.65E-04	3.81E-03	1.33E+02
I-131	8.02E+00	8.64E-02	4.86E-03	2.26E-01	2.73E+01
I-132	9.56E-02	7.25E+00	2.90E-02	1.39E+00	3.47E-01
I-133	8.67E-01	8.00E-01	8.29E-03	3.70E-01	5.44E+00
I-134	3.65E-02	1.90E+01	3.32E-02	1.61E+00	1.67E-01
I-135	2.74E-01	2.53E+00	2.05E-02	1.05E+00	1.20E+00
Ir-192	7.38E+01	9.39E-03	1.03E-02	4.81E-01	1.93E+01
Kr-85	3.93E+03	1.76E-04	NA [c]	3.21E-03	NA [d]
Kr-85m	1.87E-01	3.71E+00	NA [c]	9.12E-02	NA [d]
Kr-87	5.30E-02	1.31E+01	NA [c]	5.29E-01	NA [d]
Kr-88	1.18E-01	5.86E+00	NA [c]	1.79E+00	6.69E-02
La-140	1.68E+00	4.13E-01	2.86E-02	1.48E+00	4.00E+00
Mo-99	2.75E+00	2.52E-01	3.82E-03	1.60E-01	3.38E+00
Nb-95	3.50E+01	1.98E-02	9.67E-03	4.65E-01	5.48E+00
Np-237	7.83E+08	8.85E-10	3.02E-03	1.35E-01	8.40E+04
Np-239	2.36E+00	2.94E-01	2.16E-03	9.79E-02	3.45E+00
Pm-147	9.58E+02	7.23E-04	3.74E-07	1.15E-04	1.83E+01
Pu-238	3.20E+04	2.16E-05	7.98E-06	4.48E-05	1.71E+05
Pu-239	8.81E+06	7.87E-08	4.08E-06	5.02E-05	1.86E+05
Pu-241	5.24E+03	1.32E-04	5.92E-08	2.54E-06	3.33E+03
Ra-226	5.84E+05	1.19E-06	2.23E-02	1.10E+00	1.29E+04
Ru-103	3.93E+01	1.77E-02	6.32E-03	2.94E-01	9.00E+00

Parent Radionuclide	$t_{1/2}$ (d)	λ (d^{-1})	Dp_ExDC [a] (Groundshine) (mrem·m²/µCi·h)	Pl_ExDC [b] (Submersion) (mrem·m³/µCi·h)	InhDC [b] (Inhalation) (mrem/µCi)
Ru-106	3.74E+02	1.86E-03	4.61E-03	1.43E-01	1.03E+02
Sb-127	3.85E+00	1.80E-01	9.19E-03	4.22E-01	6.68E+00
Sb-129	1.83E-01	3.78E+00	2.01E-02	9.52E-01	1.01E+00
Se-75	1.20E+02	5.79E-03	4.74E-03	2.21E-01	3.77E+00
Sr-89	5.05E+01	1.37E-02	9.16E-04	5.85E-03	2.26E+01
Sr-90	1.05E+04	6.59E-05	1.49E-03	1.18E-02	1.37E+02
Sr-91	4.01E-01	1.73E+00	1.41E-02	6.43E-01	1.39E+00
Te-129m	3.36E+01	2.06E-02	1.75E-03	4.60E-02	2.43E+01
Te-131m	1.25E+00	5.55E-01	1.95E-02	9.49E-01	3.98E+00
Te-132	3.20E+00	2.16E-01	3.28E-02	1.55E+00	7.94E+00
Tm-170	1.29E+02	5.39E-03	3.32E-04	4.33E-03	2.58E+01
Xe-131m	1.18E+01	5.85E-02	NA [c]	4.76E-03	NA [d]
Xe-133	5.24E+00	1.32E-01	NA [c]	1.82E-02	NA [d]
Xe-133m	2.19E+00	3.17E-01	NA [c]	1.72E-02	NA [d]
Xe-135	3.81E-01	1.82E+00	NA [c]	1.47E-01	NA [d]
Xe-138	9.78E-03	7.09E+01	NA [c]	7.29E-01	NA [d]
Y-91	5.85E+01	1.18E-02	9.90E-04	8.01E-03	2.63E+01
Yb-169	3.20E+01	2.16E-02	3.93E-03	1.59E-01	9.36E+00
Zr-95	6.40E+01	1.08E-02	3.06E-02	1.47E+00	2.98E+01

[a] Values generated using DCFPAK 3.0.

[b] Values include dose contributions from all daughters that meet the equilibrium rules (e.g., Cs-137 includes contribution from Ba-137m).

[c] Noble Gases are assumed to not deposit and therefore have no Groundshine dose component.

[d] Noble Gases have not been assigned Inhalation Dose Coefficients, unless daughter present in equilibrium has an Inhalation Dose Coefficient.

Table 2-1. PAGs

Time Phase	Protective Action	Limit (rem)	Comments
Early	Sheltering-in-place or evacuation of the public [a]	TED 1-5	Projected dose[b] over 4 days. Evacuation (or, for some situations, sheltering-in-place) should be initiated when projected dose is 1 rem
	Supplementary administration of prophylactic drugs – KI [c]		KI is most effective if taken prior to exposure. May require approval of state medical officials (or in accordance with established emergency plans).
		5 [d]	Pregnant or Lactating Women, Children 0-18 years.
		10 [d]	Adults 18-40 years.
		500 [d]	Adults over 40 years.
First Year	Relocation of the public [e]	2 [f]	Projected dose[b] over one year.
	Apply simple dose reduction techniques [g]	<2	These protective actions should be taken to reduce doses to as low as practicable levels.
Second Year	Relocation of the public [e]	0.5 [f]	Projected dose[b] in the second and subsequent years.
Ingestion	See current FDA guidance.	0.5 CED 5 H_T	Due to ingestion of contaminated food in one year. Whichever is more limiting (Whole Body or Organ).
Drinking Water	See current EPA guidance.	0.1 0.5	0.1 rem for one year to the most sensitive populations (e.g., infants, children, pregnant women and nursing women). 0.5 rem for one year to the general population.

Sources: EPA17, Table 2-1 and Table 4-1 and FDA01.

[a] Should begin at 1 rem if advantageous except when practical or safety considerations warrant using 5 rem; take whichever action (or combination of actions) that results in the lowest exposure for the majority of the population. Sheltering may begin at lower levels if advantageous.

[b] Projected dose is the sum of the effective dose from external radiation exposure (e.g., groundshine and plume submersion) and the committed effective dose from inhaled radioactive material.

[c] Provides thyroid protection from radioactive iodines only. See FDA01.

[d] Thyroid dose. The 1-year-old age group is expected to receive the largest dose to the thyroid from exposure to radioactive iodine. Therefore, it is recommended that the 1-year-old age group is considered when considering the administration of prophylactic KI.

[e] People 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) may be evaluated individually.

[f] The dose that would be received, by default, in the absence of shielding from structures or the application of dose reduction techniques. These PAGs may not provide adequate protection from some long-lived radionuclides. Incident-specific factors should be considered.

[g] Simple dose reduction techniques include scrubbing or flushing hard surfaces, minor removal of soil from spots where radioactive materials have concentrated and spending more time than usual indoors or in other low exposure rate areas.

Table 2-2. Emergency Worker Guidelines

TED [a] (rem)	Activity	Condition
5	All occupational exposures.	All reasonably achievable actions have been taken to minimize dose.
10 [b]	Protecting valuable property necessary for public welfare (e.g., a power plant).	Exceeding 5 rem unavoidable and all appropriate actions taken to reduce dose. Monitoring available to project or measure dose.
25 [c]	Lifesaving or protection of large populations.	Exceeding 5 rem unavoidable and all appropriate actions taken to reduce dose. Monitoring available to project or measure dose.
>25	Lifesaving or protection of large populations.	Only with an understanding of the potential acute effects of radiation to the exposed responder (see Table 3-1) and only when the benefits of the action clearly exceed the associated risks.

Source: EPA17, Table 3-1

[a] In addition to the listed TED guidelines, Turbo FRMAC includes default dose limits of 500 mrem for whole body, 1 rem for thyroid, and 5 rem for other organs in agreement with FRMAC Health & Safety.

[b] For potential doses >5 rem, medical monitoring programs should be considered.

[c] In the case of a very large incident, such as an IND, incident commanders may need to consider raising the property and lifesaving response worker guidelines to prevent further loss of life and massive spread of destruction.

Table 2-3. Default Time Phases

The table below represents the FRMAC default approach to establishing Time Phases and the inclusion of Dose Pathways. These defaults may be modified to accommodate incident-specific circumstances.

Time Phase	Start (t_1)	End (t_2)	Evaluation Time [a] (t_n)	Dose Pathways Included
Early (Total Dose)	0	96 hours	12 hours	Plume [b] and Ground [c]
Early (Avoidable Dose)	12 hours	108 hours	12 hours	Ground Only
First Year	12 hours	8772 hours (Day 365 + 12 hours)	12 hours	Ground Only
Second Year	Day 365	Day 730	12 hours	Ground Only
50 Years [d]	12 hours	Year 50	12 hours	Ground Only

[a] All Time Phases should use the same t_n if results are to be plotted on the same data product.

[b] Plume Dose Pathways include Plume Inhalation and Plume Submersion.

[c] Ground Dose Pathways include Inhalation of resuspended material and Groundshine.

[d] EPA has removed the 5 rem/50 year Relocation PAG in the revised PAG Manual. FRMAC still includes this to enable calculations bound to previous version of the PAG Manual.

Table 3-1. Acute Radiation Syndrome[a]

Feature or Illness	Effects of Whole Body Absorbed Dose from external radiation or internal absorption (Dose range in rad)				
	0-100	100-200	200-600	600-800	>800
Nausea, Vomiting	None	5-50%	50-100%	75-100%	90-100%
Time of Onset		3-6 h	2-4 h	1-2 h	<1 h to minutes
Duration		<24 h	<24 h	<48 h	<48 h
Lymphocyte Count	Unaffected	Minimally Decreased	<1000 at 24 h	<500 at 24 h	Decreases within hours
Central Nervous System Function	No Impairment	No Impairment	Cognitive Impairment for 6-20 h	Cognitive Impairment for >20 h	Rapid incapacitation
Mortality	None	Minimal	Low with aggressive therapy	High	Very High: Significant neurological symptoms indicate lethal dose

Source: EPA17, Table 2.3 - Medical Management of Radiological Casualties, Second Edition, Armed Forces Radiobiology Research Institute. Bethesda, MD, April 2003.

[a] Percentage of people receiving whole-body doses within a few hours expected to experience acute health effects.

Table 3-2. Acute Doses to Organs

Organ	Dose Threshold (rad)	Early Health Effects
Bone Marrow (hematopoietic syndrome)	50	Marrow depression
Small Intestine (gastrointestinal syndrome)	50 100 800	Vomiting Diarrhea Lethality
Skin	200	Transient erythema
Thyroid	300	Hypothyroidism
Lung [a]	600	Pneumonitis
Bone	1000	Osteonecrosis

Source Me95

[a] The lung dose includes an RBE of 10 applied to the high Linear Energy Transfer (alpha) dose conversion factors.

Table 4. Dose Parameters and DRLs

This series of Tables contains the Dose Parameters and DRLs for the Assessment Working Group's list of radionuclides. Values are provided for the 5 default Time Phases (Early (Total Dose), Early (Avoidable Dose), First Year, Second Year and 50 Year.) Values for noble gases are only provided for Plume Dose Parameters and Early Phase (Total Dose) DRLs because noble gases are assumed to **not deposit** on the ground. All values calculated using DCFPAK 3.0. Appendix F, Supplement 3 provides a crosswalk showing where values found in the 1992 EPA PAG Manual may be found in the following tables.

These values are **only appropriate** when all of the following are true:

- the default Time Phases and Evaluation Times shown in Table 2-3 are used,
- the organ of interest is the Whole Body relating to a PAG for an Effective Dose,
- the mixture of interest contains only 1 radionuclide (and associated daughters).

  NOTE: Daughter radionuclides that meet the equilibrium rules (see Section 1, Default Assumptions) are assumed to be at equilibrium at deposition. Other daughters start at zero and are grown in over the Time Phase. Dose contribution from each daughter is included.

These values can be obtained for other assumptions using the Turbo FRMAC© software.

The terms contained in this series of Tables are defined below and on the next page:

Dose Parameters		
Dp_ExDP	$\frac{\text{mrem} \cdot \text{m}^2}{\mu\text{Ci}}$	Deposition External Dose Parameter, the external dose from groundshine, over the time phase under consideration (*TP*), per unit activity of radionuclide *i*.
Dp_InhDP	$\frac{\text{mrem} \cdot \text{m}^2}{\mu\text{Ci}}$	Deposition Inhalation Dose Parameter, the committed dose, over the time phase under consideration (*TP*), per unit activity of radionuclide *i* deposited on the ground from the inhalation of the resuspended fraction of the radionuclide.
Pl_ExDP	$\frac{\text{mrem} \cdot \text{m}^3}{\mu\text{Ci} \cdot \text{s}}$	Plume External Dose Parameter, the external dose from submersion, over the time phase under consideration (*TP*), per unit activity of plume-borne radionuclide *i*.
Pl_InhDP	$\frac{\text{mrem} \cdot \text{m}^3}{\mu\text{Ci} \cdot \text{s}}$	Plume Inhalation Dose Parameter, the committed dose, over the time phase under consideration (*TP*), from inhalation per unit activity of plume-borne radionuclide *i*.

Note:

Dose Parameters are expressed in different units than those found in the Methods Sections. The values in the Methods are calculated using the TOTAL amount of each radionuclide present in a release while the values shown here have been normalized to a "unit activity" for each radionuclide. For example, the Dp_ExDP would have units of mrem in Method 1.1 and mrem per μCi/m^2 (mrem·m^2/μCi) in these Tables.

The values in the tables account for the contributions of daughter radionuclides at their appropriate equilibrium or in-growth concentration (e.g., Ba-140 includes the contribution of 1 "unit" of Ba-140 and 1.15 "units" of La-140 and Am-241 includes the contribution of the amount of Np-237 that grows in over the Time Phase.)

DRLs		
DRL_{Dp}	$\frac{\mu Ci}{m^2}$	Deposition Derived Response Level, the areal activity, at time t_n, of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the Protective Action Guide (PAG) over the time phase under consideration (*TP*).
$DRL_{\tilde{A}}$	$\frac{\mu Ci \cdot s}{m^3}$	Integrated Air Derived Response Level, the integrated air activity ($\tilde{A}$) of radionuclide *i* at which the total dose from *all radionuclides* in a release would equal the Protective Action Guide (PAG) over the time phase under consideration (*TP*).
DRL_{DR}	$\frac{mrem}{hr}$	Dose Rate Derived Response Level, the external dose rate, at time t_n, at which the total dose from *all radionuclides* in a release would equal the PAG over the time phase under consideration (*TP*).
Note: DRLs in these tables were calculated assuming a deposition velocity of 3.0E-03 m/s, except for iodine radionuclides, for which 6.5E-03 m/s was used.		

Table 4-1. Plume Dose Parameters [a,b]

Parent Radionuclide	Pl_ExDP (mrem·m³/µCi·s)	Pl_InhDP (mrem·m³/µCi·s)
Am-241	2.49E-06	6.43E+01
Ba-140	5.03E-04	9.74E-03
Ce-141	1.16E-05	4.94E-03
Ce-144	1.20E-05	5.56E-02
Cf-252	8.25E-05	3.05E+01
Cm-242	1.44E-08	8.02E+00
Cm-244	1.48E-08	4.10E+01
Co-60	4.40E-04	1.57E-02
Cs-134	2.62E-04	1.03E-02
Cs-136	3.63E-04	1.90E-03
Cs-137	9.43E-05	7.21E-03
Gd-153	1.15E-05	3.22E-03
I-129	1.06E-06	5.54E-02
I-131	6.29E-05	1.14E-02
I-132	3.85E-04	1.45E-04
I-133	1.03E-04	2.27E-03
I-134	4.48E-04	6.97E-05
I-135	2.92E-04	4.98E-04
Ir-192	1.34E-04	8.05E-03
Kr-85	8.92E-07	NA
Kr-85m	2.53E-05	NA
Kr-87	1.47E-04	NA
Kr-88	4.98E-04	2.79E-05
La-140	4.11E-04	1.67E-03
Mo-99	4.44E-05	1.41E-03
Nb-95	1.29E-04	2.28E-03
Np-237	3.75E-05	3.50E+01
Np-239	2.72E-05	1.44E-03
Pm-147	3.20E-08	7.62E-03
Pu-238	1.24E-08	7.13E+01
Pu-239	1.39E-08	7.75E+01
Pu-241	7.07E-10	1.39E+00

Parent Radionuclide	Pl_ExDP (mrem·m³/µCi·s)	Pl_InhDP (mrem·m³/µCi·s)
Ra-226	3.05E-04	5.38E+00
Ru-103	8.18E-05	3.75E-03
Ru-106	3.96E-05	4.30E-02
Sb-127	1.17E-04	2.79E-03
Sb-129	2.64E-04	4.23E-04
Se-75	6.14E-05	1.57E-03
Sr-89	1.62E-06	9.43E-03
Sr-90	3.29E-06	5.71E-02
Sr-91	1.78E-04	5.78E-04
Te-129m	1.28E-05	1.01E-02
Te-131m	2.64E-04	1.66E-03
Te-132	4.31E-04	3.31E-03
Tm-170	1.20E-06	1.08E-02
Xe-131m	1.32E-06	NA
Xe-133	5.07E-06	NA
Xe-133m	4.77E-06	NA
Xe-135	4.07E-05	NA
Xe-138	2.02E-04	NA
Y-91	2.22E-06	1.10E-02
Yb-169	4.40E-05	3.90E-03
Zr-95	4.08E-04	1.24E-02

Note:

[a] Plume Dose Parameters (External and Inhalation) are the same for all Time Phases that include the entirety of the plume and are zero for Time Phases that do not include plume passage (e.g., Second Year).

[b] Noble Gases have not been assigned Inhalation Dose Coefficients and therefore have no Inhalation Dose Parameter, unless daughter present in equilibrium has an Inhalation Dose Coefficient.

Table 4-2a. Early Phase (Total Dose) Deposition Dose Parameters

Parent Radionuclide	Dp_ExDP (mrem·m²/µCi)	Dp_InhDP (mrem·m²/µCi)
Am-241	2.28E-02	1.20E+02
Ba-140	2.51E+00	1.63E-02
Ce-141	7.00E-02	8.81E-03
Ce-144	1.86E-01	1.03E-01
Cf-252	4.52E-01	5.67E+01
Cm-242	6.94E-04	1.48E+01
Cm-244	6.13E-04	7.62E+01
Co-60	2.41E+00	2.92E-02
Cs-134	1.55E+00	1.91E-02
Cs-136	1.88E+00	3.19E-03
Cs-137	5.74E-01	1.34E-02
Gd-153	9.59E-02	5.96E-03
I-129	2.08E-02	1.03E-01
I-131	3.23E-01	1.81E-02
I-132	7.88E-02	1.05E-05
I-133	2.00E-01	1.35E-03
I-134	3.43E-02	1.95E-06
I-135	1.86E-01	1.02E-04
Ir-192	7.97E-01	1.47E-02
La-140	1.10E+00	1.57E-03
Mo-99	1.89E-01	1.69E-03
Nb-95	7.31E-01	4.09E-03
Np-237	2.37E-01	6.51E+01
Np-239	9.98E-02	1.63E-03
Pm-147	2.94E-05	1.41E-02
Pu-238	6.27E-04	1.32E+02
Pu-239	3.21E-04	1.44E+02
Pu-241	4.86E-06	2.58E+00
Ra-226	1.75E+00	1.00E+01
Ru-103	4.80E-01	6.74E-03
Ru-106	3.61E-01	7.97E-02
Sb-127	5.15E-01	3.79E-03

Parent Radionuclide	Dp_ExDP (mrem·m²/μCi)	Dp_InhDP (mrem·m²/μCi)
Sb-129	1.05E-01	7.91E-05
Se-75	3.69E-01	2.89E-03
Sr-89	7.01E-02	1.71E-02
Sr-90	1.17E-01	1.06E-01
Sr-91	1.61E-01	2.92E-04
Te-129m	1.32E-01	1.81E-02
Te-131m	6.49E-01	2.99E-03
Te-132	1.72E+00	4.20E-03
Tm-170	2.58E-02	1.98E-02
Y-91	7.60E-02	1.99E-02
Yb-169	2.96E-01	6.96E-03
Zr-95	2.36E+00	2.26E-02

Table 4-2b. Early Phase (Total Dose) DRLs

Parent Radionuclide	92 PAG Manual DCF Equivalent for Deposition (mrem·m²/µCi)	DRL_{Dp} (µCi/m²)	92 PAG Manual DCF Equivalent for Integrated Air (mrem·m³/µCi·s)	$DRL_{\tilde{A}}$ (µCi•s/m³)	DRL_{DR} (mrem/h)
Am-241	2.16E+04	4.64E-02	6.50E+01	1.55E+01	1.10E-05
Ba-140	5.94E+00	1.64E+02	1.80E-02	5.61E+04	4.77E+00
Ce-141	1.73E+00	5.72E+02	5.20E-03	1.93E+05	4.36E-01
Ce-144	1.88E+01	5.31E+01	5.60E-02	1.77E+04	1.03E-01
Cf-252	1.02E+04	9.76E-02	3.10E+01	3.26E+01	4.60E-04
Cm-242	2.69E+03	3.71E-01	8.10E+00	1.24E+02	2.71E-06
Cm-244	1.38E+04	7.27E-02	4.10E+01	2.42E+01	4.64E-07
Co-60	7.83E+00	1.28E+02	2.30E-02	4.26E+04	3.21E+00
Cs-134	5.09E+00	1.96E+02	1.50E-02	6.54E+04	3.17E+00
Cs-136	2.64E+00	3.69E+02	7.90E-03	1.26E+05	8.03E+00
Cs-137	3.02E+00	3.31E+02	9.10E-03	1.10E+05	1.98E+00
Gd-153	1.18E+00	8.46E+02	3.50E-03	2.82E+05	8.51E-01
I-129	8.65E+00	1.16E+02	5.60E-02	1.78E+04	2.51E-02
I-131	2.11E+00	4.55E+02	1.40E-02	7.31E+04	1.81E+00
I-132	1.60E-01	1.66E+02	1.00E-03	9.60E+05	3.96E+00
I-133	5.66E-01	1.18E+03	3.70E-03	2.72E+05	8.09E+00
I-134	1.14E-01	6.53E-01	7.40E-04	1.35E+06	1.78E-02
I-135	3.07E-01	9.17E+02	2.00E-03	5.01E+05	1.82E+01
Ir-192	3.54E+00	2.81E+02	1.10E-02	9.41E+04	2.38E+00
Kr-85	NA	NA	8.90E-07	1.12E+09	NA
Kr-85m	NA	NA	2.50E-05	3.95E+07	NA
Kr-87	NA	NA	1.50E-04	6.81E+06	NA
Kr-88	NA	NA	5.30E-04	1.90E+06	NA
La-140	1.80E+00	4.53E+02	5.40E-03	1.86E+05	1.06E+01
Mo-99	6.75E-01	1.31E+03	2.00E-03	4.94E+05	4.09E+00
Nb-95	1.54E+00	6.43E+02	4.60E-03	2.17E+05	5.10E+00
Np-237	1.17E+04	8.51E-02	3.50E+01	2.84E+01	2.11E-04
Np-239	5.90E-01	1.46E+03	1.80E-03	5.65E+05	2.59E+00
Pm-147	2.55E+00	3.91E+02	7.70E-03	1.30E+05	1.20E-04
Pu-238	2.39E+04	4.18E-02	7.20E+01	1.40E+01	2.74E-07

Parent Radionuclide	92 PAG Manual DCF Equivalent for Deposition (mrem·m²/µCi)	DRL_{Dp} (µCi/m²)	92 PAG Manual DCF Equivalent for Integrated Air (mrem·m³/µCi·s)	$DRL_{\tilde{A}}$ (µCi•s/m³)	DRL_{DR} (mrem/h)
Pu-239	2.60E+04	3.85E-02	7.80E+01	1.28E+01	1.29E-07
Pu-241	4.66E+02	2.15E+00	1.40E+00	7.15E+02	1.05E-07
Ra-226	1.81E+03	5.54E-01	5.40E+00	1.85E+02	1.01E-02
Ru-103	1.77E+00	5.61E+02	5.30E-03	1.89E+05	2.91E+00
Ru-106	1.48E+01	6.75E+01	4.40E-02	2.25E+04	2.55E-01
Sb-127	1.49E+00	6.15E+02	4.50E-03	2.24E+05	4.63E+00
Sb-129	3.34E-01	4.52E+02	1.00E-03	9.98E+05	7.47E+00
Se-75	9.17E-01	1.09E+03	2.70E-03	3.64E+05	4.23E+00
Sr-89	3.23E+00	3.07E+02	9.70E-03	1.03E+05	2.31E-01
Sr-90	1.92E+01	5.19E+01	5.80E-02	1.73E+04	6.33E-02
Sr-91	4.13E-01	1.02E+03	1.20E-03	8.07E+05	1.18E+01
Te-129m	3.53E+00	2.80E+02	1.10E-02	9.44E+04	4.03E-01
Te-131m	1.29E+00	5.86E+02	3.90E-03	2.58E+05	9.50E+00
Te-132	2.98E+00	3.01E+02	8.90E-03	1.12E+05	8.10E+00
Tm-170	3.64E+00	2.74E+02	1.10E-02	9.17E+04	7.46E-02
Xe-131m	NA	NA	1.30E-06	7.57E+08	NA
Xe-133	NA	NA	5.10E-06	1.97E+08	NA
Xe-133m	NA	NA	4.80E-06	2.10E+08	NA
Xe-135	NA	NA	4.10E-05	2.46E+07	NA
Xe-138	NA	NA	2.00E-04	4.94E+06	NA
Y-91	3.75E+00	2.65E+02	1.10E-02	8.89E+04	2.15E-01
Yb-169	1.62E+00	6.11E+02	4.90E-03	2.06E+05	1.97E+00
Zr-95	6.65E+00	1.50E+02	2.00E-02	5.01E+04	3.75E+00

NOTE: Values for noble gases are only provided for Integrated Air because they are assumed to **not deposit** on the ground.

Table 4-3a. Early Phase (Avoidable Dose) Deposition Dose Parameters

Parent Radionuclide	Dp_ExDP (mrem·m²/µCi)	Dp_InhDP (mrem·m²/µCi)
Am-241	2.28E-02	1.15E+02
Ba-140	2.44E+00	1.54E-02
Ce-141	6.92E-02	8.42E-03
Ce-144	1.86E-01	9.91E-02
Cf-252	4.52E-01	5.47E+01
Cm-242	6.92E-04	1.43E+01
Cm-244	6.12E-04	7.36E+01
Co-60	2.41E+00	2.82E-02
Cs-134	1.55E+00	1.85E-02
Cs-136	1.83E+00	3.00E-03
Cs-137	5.74E-01	1.29E-02
Gd-153	9.58E-02	5.74E-03
I-129	2.08E-02	9.94E-02
I-131	3.10E-01	1.67E-02
I-132	2.10E-03	2.71E-07
I-133	1.36E-01	8.71E-04
I-134	2.55E-06	1.40E-10
I-135	6.34E-02	2.78E-05
Ir-192	7.93E-01	1.41E-02
La-140	8.96E-01	1.23E-03
Mo-99	1.67E-01	1.43E-03
Nb-95	7.24E-01	3.91E-03
Np-237	2.37E-01	6.28E+01
Np-239	8.61E-02	1.36E-03
Pm-147	2.94E-05	1.36E-02
Pu-238	6.27E-04	1.28E+02
Pu-239	3.20E-04	1.39E+02
Pu-241	4.91E-06	2.49E+00
Ra-226	1.75E+00	9.65E+00
Ru-103	4.76E-01	6.45E-03
Ru-106	3.61E-01	7.69E-02
Sb-127	4.71E-01	3.35E-03

Parent Radionuclide	Dp_ExDP (mrem·m²/µCi)	Dp_InhDP (mrem·m²/µCi)
Sb-129	1.60E-02	2.97E-05
Se-75	3.67E-01	2.78E-03
Sr-89	6.96E-02	1.64E-02
Sr-90	1.17E-01	1.02E-01
Sr-91	6.81E-02	1.99E-04
Te-129m	1.31E-01	1.73E-02
Te-131m	5.03E-01	2.83E-03
Te-132	1.55E+00	3.64E-03
Tm-170	7.55E-02	1.91E-02
Y-91	2.93E-01	6.65E-03
Yb-169	2.34E+00	2.17E-02
Zr-95	7.55E-02	1.91E-02

Table 4-3b. Early Phase (Avoidable Dose) DRLs

Parent Radionuclide	DRL_{Dp} (μCi/m²)	$DRL_{\tilde{A}}$ (μCi•s/m³)	DRL_{DR} (mrem/h)
Am-241	8.66E+00	2.89E+03	2.06E-03
Ba-140	3.96E+02	1.36E+05	1.15E+01
Ce-141	1.27E+04	4.29E+06	9.70E+00
Ce-144	3.51E+03	1.17E+06	6.83E+00
Cf-252	1.81E+01	6.04E+03	8.55E-02
Cm-242	7.00E+01	2.34E+04	5.11E-04
Cm-244	1.36E+01	4.53E+03	8.68E-05
Co-60	4.11E+02	1.37E+05	1.03E+01
Cs-134	6.39E+02	2.13E+05	1.03E+01
Cs-136	5.31E+02	1.82E+05	1.15E+01
Cs-137	1.70E+03	5.68E+05	1.02E+01
Gd-153	9.84E+03	3.28E+06	9.89E+00
I-129	8.32E+03	1.28E+06	1.81E+00
I-131	2.93E+03	4.72E+05	1.17E+01
I-132	1.27E+04	7.32E+07	3.02E+02
I-133	4.91E+03	1.13E+06	3.36E+01
I-134	2.91E+04	6.02E+10	7.92E+02
I-135	4.44E+03	2.42E+06	8.81E+01
Ir-192	1.23E+03	4.13E+05	1.04E+01
La-140	9.06E+02	3.71E+05	2.13E+01
Mo-99	5.24E+03	1.98E+06	1.64E+01
Nb-95	1.36E+03	4.58E+05	1.08E+01
Np-237	1.59E+01	5.29E+03	3.92E-02
Np-239	9.87E+03	3.81E+06	1.75E+01
Pm-147	7.31E+04	2.44E+07	2.24E-02
Pu-238	7.82E+00	2.61E+03	5.12E-05
Pu-239	7.20E+00	2.40E+03	2.41E-05
Pu-241	4.01E+02	1.34E+05	1.97E-05
Ra-226	8.77E+01	2.92E+04	1.60E+00
Ru-103	2.05E+03	6.91E+05	1.07E+01
Ru-106	2.28E+03	7.62E+05	8.63E+00
Sb-127	1.93E+03	7.03E+05	1.45E+01

Parent Radionuclide	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)	DRL_{DR} (mrem/h)
Sb-129	9.43E+03	2.08E+07	1.56E+02
Se-75	2.69E+03	9.00E+05	1.05E+01
Sr-89	1.15E+04	3.88E+06	8.68E+00
Sr-90	4.56E+03	1.52E+06	5.56E+00
Sr-91	6.17E+03	4.88E+06	7.14E+01
Te-129m	6.68E+03	2.25E+06	9.60E+00
Te-131m	1.50E+03	6.58E+05	2.43E+01
Te-132	5.78E+02	2.15E+05	1.55E+01
Tm-170	2.23E+04	7.44E+06	6.05E+00
Y-91	1.05E+04	3.52E+06	8.52E+00
Yb-169	3.30E+03	1.11E+06	1.06E+01
Zr-95	4.21E+02	1.41E+05	1.06E+01

Table 4-4a. First Year Deposition Dose Parameters

Parent Radionuclide	Dp_ExDP (mrem·m²/µCi)	Dp_InhDP (mrem·m²/µCi)
Am-241	1.91E+00	4.80E+02
Ba-140	1.24E+01	3.92E-02
Ce-141	8.27E-01	2.76E-02
Ce-144	1.05E+01	3.98E-01
Cf-252	3.34E+01	2.25E+02
Cm-242	3.04E-02	5.61E+01
Cm-244	5.03E-02	3.05E+02
Co-60	1.89E+02	1.17E-01
Cs-134	1.11E+02	7.58E-02
Cs-136	9.55E+00	7.75E-03
Cs-137	4.75E+01	5.36E-02
Gd-153	5.06E+00	2.29E-02
I-129	1.74E+00	4.13E-01
I-131	1.05E+00	3.59E-02
I-132	2.10E-03	2.71E-07
I-133	1.50E-01	8.99E-04
I-134	2.55E-06	1.40E-10
I-135	6.35E-02	2.78E-05
Ir-192	1.99E+01	5.22E-02
La-140	1.11E+00	1.44E-03
Mo-99	2.62E-01	1.98E-03
Nb-95	9.27E+00	1.30E-02
Np-237	1.98E+01	2.61E+02
Np-239	1.24E-01	1.88E-03
Pm-147	2.17E-03	5.61E-02
Pu-238	5.23E-02	5.31E+02
Pu-239	2.68E-02	5.77E+02
Pu-241	1.85E-03	1.04E+01
Ra-226	1.46E+02	4.01E+01
Ru-103	6.78E+00	2.19E-02
Ru-106	2.22E+01	3.11E-01
Sb-127	9.19E-01	5.60E-03

Parent Radionuclide	Dp_ExDP (mrem·m²/µCi)	Dp_InhDP (mrem·m²/µCi)
Sb-129	1.78E-02	7.90E-05
Se-75	1.33E+01	1.07E-02
Sr-89	1.25E+00	5.77E-02
Sr-90	9.68E+00	4.25E-01
Sr-91	7.90E-02	5.60E-04
Te-129m	1.61E+00	5.70E-02
Te-131m	6.96E-01	6.37E-03
Te-132	2.67E+00	5.34E-03
Tm-170	9.77E-01	7.38E-02
Y-91	1.55E+00	6.87E-02
Yb-169	3.45E+00	2.17E-02
Zr-95	5.20E+01	7.88E-02

Table 4-4b. First Year DRLs

Parent Radionuclide	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)	DRL_{DR} (mrem/h)
Am-241	4.15E+00	1.38E+03	9.89E-04
Ba-140	1.57E+02	5.36E+04	4.56E+00
Ce-141	2.31E+03	7.80E+05	1.76E+00
Ce-144	1.84E+02	6.13E+04	3.58E-01
Cf-252	7.74E+00	2.58E+03	3.65E-02
Cm-242	3.56E+01	1.19E+04	2.60E-04
Cm-244	6.55E+00	2.18E+03	4.18E-05
Co-60	1.06E+01	3.52E+03	2.65E-01
Cs-134	1.80E+01	6.02E+03	2.92E-01
Cs-136	2.04E+02	6.98E+04	4.43E+00
Cs-137	4.21E+01	1.40E+04	2.52E-01
Gd-153	3.93E+02	1.31E+05	3.95E-01
I-129	9.27E+02	1.43E+05	2.01E-01
I-131	1.76E+03	2.82E+05	7.00E+00
I-132	2.54E+04	1.46E+08	6.04E+02
I-133	8.88E+03	2.04E+06	6.07E+01
I-134	5.83E+04	1.20E+11	1.58E+03
I-135	8.88E+03	4.85E+06	1.76E+02
Ir-192	9.98E+01	3.34E+04	8.45E-01
La-140	1.47E+03	6.01E+05	3.44E+01
Mo-99	6.67E+03	2.52E+06	2.09E+01
Nb-95	2.13E+02	7.18E+04	1.69E+00
Np-237	7.12E+00	2.37E+03	1.76E-02
Np-239	1.37E+04	5.28E+06	2.42E+01
Pm-147	3.43E+04	1.14E+07	1.05E-02
Pu-238	3.76E+00	1.26E+03	2.46E-05
Pu-239	3.46E+00	1.15E+03	1.16E-05
Pu-241	1.93E+02	6.43E+04	9.46E-06
Ra-226	1.07E+01	3.57E+03	1.96E-01
Ru-103	2.91E+02	9.80E+04	1.51E+00
Ru-106	8.86E+01	2.96E+04	3.35E-01
Sb-127	1.98E+03	7.21E+05	1.49E+01

Parent Radionuclide	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)	DRL_{DR} (mrem/h)
Sb-129	1.69E+04	3.72E+07	2.79E+02
Se-75	1.50E+02	5.00E+04	5.82E-01
Sr-89	1.52E+03	5.09E+05	1.14E+00
Sr-90	1.98E+02	6.60E+04	2.41E-01
Sr-91	1.06E+04	8.38E+06	1.23E+02
Te-129m	1.19E+03	3.99E+05	1.70E+00
Te-131m	2.16E+03	9.50E+05	3.50E+01
Te-132	6.71E+02	2.49E+05	1.80E+01
Tm-170	1.90E+03	6.34E+05	5.16E-01
Y-91	1.23E+03	4.12E+05	9.96E-01
Yb-169	5.70E+02	1.92E+05	1.84E+00
Zr-95	3.82E+01	1.28E+04	9.58E-01

Table 4-5a. Second Year Deposition Dose Parameters

Parent Radionuclide	Dp_ExDP (mrem·m²/µCi)	Dp_InhDP (mrem·m²/µCi)
Am-241	1.64E+00	4.23E+00
Ba-140	2.61E-08	9.81E-14
Ce-141	2.96E-04	2.10E-08
Ce-144	3.71E+00	1.04E-03
Cf-252	2.22E+01	1.38E+00
Cm-242	5.71E-03	8.14E-02
Cm-244	4.18E-02	2.56E+00
Co-60	1.43E+02	8.57E-04
Cs-134	6.82E+01	4.19E-04
Cs-136	3.71E-08	3.64E-14
Cs-137	4.00E+01	4.59E-04
Gd-153	1.52E+00	4.79E-05
I-129	1.50E+00	3.65E-03
I-131	8.12E-13	6.03E-19
I-132	NA	NA
I-133	1.51E-23	1.09E-133
I-134	NA	NA
I-135	1.25E-12	2.30E-14
Ir-192	5.54E-01	5.49E-06
La-140	3.84E-66	3.12E-72
Mo-99	1.92E-10	1.59E-11
Nb-95	5.76E-03	1.80E-08
Np-237	1.71E+01	2.31E+00
Np-239	6.19E-09	1.37E-06
Pm-147	1.44E-03	3.43E-04
Pu-238	4.47E-02	4.64E+00
Pu-239	2.31E-02	5.10E+00
Pu-241	4.10E-03	9.49E-02
Ra-226	1.26E+02	3.69E-01
Ru-103	9.25E-03	7.24E-08
Ru-106	9.72E+00	1.08E-03
Sb-127	3.59E-04	2.07E-07

Parent Radionuclide	Dp_ExDP (mrem·m²/µCi)	Dp_InhDP (mrem·m²/µCi)
Sb-129	9.22E-07	7.10E-11
Se-75	1.38E+00	5.67E-06
Sr-89	7.18E-03	9.61E-07
Sr-90	8.14E+00	3.63E-03
Sr-91	1.28E-04	1.83E-08
Te-129m	7.43E-04	5.71E-08
Te-131m	1.42E-13	1.12E-19
Te-132	1.28E-34	1.80E-40
Tm-170	1.17E-01	4.69E-05
Y-91	1.76E-02	2.51E-06
Yb-169	1.10E-03	1.45E-08
Zr-95	8.58E-01	4.46E-06

Table 4-5b. Second Year DRLs

Parent Radionuclide	DRL_{Dp} (μCi/m²)	$DRL_{\tilde{A}}$ (μCi•s/m³)	DRL_{DR} (mrem/h)
Am-241	8.51E+01	2.84E+04	2.03E-02
Ba-140	1.87E+10	6.39E+12	5.43E+08
Ce-141	1.67E+06	5.63E+08	1.27E+03
Ce-144	1.34E+02	4.49E+04	2.62E-01
Cf-252	2.12E+01	7.08E+03	1.00E-01
Cm-242	5.73E+03	1.91E+06	4.18E-02
Cm-244	1.92E+02	6.41E+04	1.23E-03
Co-60	3.49E+00	1.17E+03	8.78E-02
Cs-134	7.33E+00	2.44E+03	1.18E-01
Cs-136	1.31E+10	4.49E+12	2.85E+08
Cs-137	1.25E+01	4.17E+03	7.47E-02
Gd-153	3.28E+02	1.10E+05	3.30E-01
I-129	3.32E+02	5.10E+04	7.21E-02
I-131	5.90E+14	9.48E+16	2.35E+12
I-132	NA	NA	NA
I-133	2.21E+25	5.08E+27	1.51E+23
I-134	NA	NA	NA
I-135	1.10E+14	6.02E+16	2.19E+12
Ir-192	8.98E+02	3.01E+05	7.60E+00
La-140	1.06E+68	4.34E+70	2.49E+66
Mo-99	2.12E+12	8.02E+14	6.65E+09
Nb-95	8.60E+04	2.90E+07	6.82E+02
Np-237	2.57E+01	8.58E+03	6.37E-02
Np-239	3.15E+08	1.21E+11	5.57E+05
Pm-147	2.81E+05	9.36E+07	8.61E-02
Pu-238	1.07E+02	3.55E+04	6.98E-04
Pu-239	9.75E+01	3.25E+04	3.26E-04
Pu-241	5.05E+03	1.68E+06	2.48E-04
Ra-226	3.95E+00	1.32E+03	7.20E-02
Ru-103	5.36E+04	1.80E+07	2.78E+02
Ru-106	5.14E+01	1.71E+04	1.94E-01
Sb-127	1.27E+06	4.63E+08	9.57E+03

Parent Radionuclide	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)	DRL_{DR} (mrem/h)
Sb-129	8.19E+07	1.81E+11	1.35E+06
Se-75	3.60E+02	1.20E+05	1.40E+00
Sr-89	6.91E+04	2.32E+07	5.19E+01
Sr-90	6.14E+01	2.05E+04	7.48E-02
Sr-91	1.64E+06	1.30E+09	1.90E+04
Te-129m	6.66E+05	2.24E+08	9.56E+02
Te-131m	2.67E+15	1.17E+18	4.32E+13
Te-132	3.51E+36	1.30E+39	9.43E+34
Tm-170	4.25E+03	1.42E+06	1.15E+00
Y-91	2.82E+04	9.47E+06	2.29E+01
Yb-169	4.50E+05	1.52E+08	1.45E+03
Zr-95	5.79E+02	1.94E+05	1.45E+01

Table 4-6a. Fifty Year Deposition Dose Parameters

Parent Radionuclide	Dp_ExDP (mrem·m²/µCi)	Dp_InhDP (mrem·m²/µCi)
Am-241	4.53E+01	5.44E+02
Ba-140	1.24E+01	3.92E-02
Ce-141	8.28E-01	2.76E-02
Ce-144	1.64E+01	3.99E-01
Cf-252	1.13E+02	2.28E+02
Cm-242	4.25E-02	5.64E+01
Cm-244	6.42E-01	3.26E+02
Co-60	1.06E+03	1.20E-01
Cs-134	3.14E+02	7.66E-02
Cs-136	9.55E+00	7.75E-03
Cs-137	7.60E+02	5.83E-02
Gd-153	7.28E+00	2.30E-02
I-129	4.28E+01	4.71E-01
I-131	1.05E+00	3.59E-02
I-132	2.10E-03	2.71E-07
I-133	1.50E-01	8.99E-04
I-134	2.55E-06	1.40E-10
I-135	6.35E-02	2.78E-05
Ir-192	2.05E+01	5.22E-02
La-140	1.11E+00	1.44E-03
Mo-99	2.62E-01	1.98E-03
Nb-95	9.27E+00	1.30E-02
Np-237	4.86E+02	2.98E+02
Np-239	1.24E-01	1.91E-03
Pm-147	7.28E-03	5.69E-02
Pu-238	1.09E+00	5.93E+02
Pu-239	6.57E-01	6.58E+02
Pu-241	8.43E-01	1.22E+01
Ra-226	3.59E+03	4.90E+01
Ru-103	6.79E+00	2.19E-02
Ru-106	4.03E+01	3.13E-01
Sb-127	9.19E-01	5.60E-03

Parent Radionuclide	Dp_ExDP (mrem·m²/µCi)	Dp_InhDP (mrem·m²/µCi)
Sb-129	1.78E-02	7.90E-05
Se-75	1.49E+01	1.07E-02
Sr-89	1.26E+00	5.77E-02
Sr-90	1.52E+02	4.61E-01
Sr-91	7.91E-02	5.60E-04
Te-129m	1.61E+00	5.70E-02
Te-131m	6.96E-01	6.37E-03
Te-132	2.67E+00	5.34E-03
Tm-170	1.11E+00	7.38E-02
Y-91	1.57E+00	6.87E-02
Yb-169	3.45E+00	2.17E-02
Zr-95	5.29E+01	7.88E-02

Table 4-6b. Fifty Year DRLs

Parent Radionuclide	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)	DRL_{DR} (mrem/h)
Am-241	8.48E+00	2.83E+03	2.02E-03
Ba-140	3.91E+02	1.34E+05	1.14E+01
Ce-141	5.78E+03	1.95E+06	4.40E+00
Ce-144	2.97E+02	9.92E+04	5.79E-01
Cf-252	1.47E+01	4.89E+03	6.91E-02
Cm-242	8.83E+01	2.95E+04	6.44E-04
Cm-244	1.53E+01	5.11E+03	9.78E-05
Co-60	4.73E+00	1.58E+03	1.19E-01
Cs-134	1.59E+01	5.30E+03	2.57E-01
Cs-136	5.09E+02	1.74E+05	1.11E+01
Cs-137	6.57E+00	2.19E+03	3.93E-02
Gd-153	6.84E+02	2.28E+05	6.88E-01
I-129	1.16E+02	1.78E+04	2.51E-02
I-131	4.39E+03	7.06E+05	1.75E+01
I-132	6.34E+04	3.66E+08	1.51E+03
I-133	2.22E+04	5.10E+06	1.52E+02
I-134	1.46E+05	3.01E+11	3.96E+03
I-135	2.22E+04	1.21E+07	4.40E+02
Ir-192	2.43E+02	8.13E+04	2.05E+00
La-140	3.66E+03	1.50E+06	8.61E+01
Mo-99	1.67E+04	6.31E+06	5.23E+01
Nb-95	5.33E+02	1.80E+05	4.23E+00
Np-237	6.38E+00	2.13E+03	1.58E-02
Np-239	3.42E+04	1.32E+07	6.05E+01
Pm-147	7.78E+04	2.60E+07	2.39E-02
Pu-238	8.41E+00	2.80E+03	5.50E-05
Pu-239	7.59E+00	2.53E+03	2.54E-05
Pu-241	3.82E+02	1.27E+05	1.88E-05
Ra-226	1.37E+00	4.58E+02	2.51E-02
Ru-103	7.27E+02	2.45E+05	3.77E+00
Ru-106	1.23E+02	4.10E+04	4.64E-01
Sb-127	4.94E+03	1.80E+06	3.72E+01

Parent Radionuclide	DRL_{Dp} ($\mu Ci/m^2$)	$DRL_{\tilde{A}}$ ($\mu Ci \bullet s/m^3$)	DRL_{DR} (mrem/h)
Sb-129	4.22E+04	9.31E+07	6.97E+02
Se-75	3.35E+02	1.12E+05	1.30E+00
Sr-89	3.77E+03	1.27E+06	2.83E+00
Sr-90	3.28E+01	1.09E+04	3.99E-02
Sr-91	2.65E+04	2.09E+07	3.06E+02
Te-129m	2.96E+03	9.98E+05	4.25E+00
Te-131m	5.40E+03	2.37E+06	8.75E+01
Te-132	1.68E+03	6.23E+05	4.51E+01
Tm-170	4.21E+03	1.41E+06	1.14E+00
Y-91	3.04E+03	1.02E+06	2.46E+00
Yb-169	1.42E+03	4.80E+05	4.59E+00
Zr-95	9.38E+01	3.15E+04	2.36E+00

Table 5 is primarily intended to support KI administration decisions and only includes dose from Plume Inhalation. A Nuclear Power Plant release is the most likely release scenario to provide sufficient warning to a population prepared in advance with KI. Therefore, values for all three chemical/physical forms likely to be included in a release have been tabulated.

Table 5. Thyroid Inhalation Dose Parameters

Radionuclide	Form	Pl_InhDP (mrem•m^3)/(µCi•s)	
		Children 0-18 year[a]	Adult
I-125	Particulate	2.59E-01	1.60E-01
	Iodine Vapor	6.61E-01	4.30E-01
	Methyl Iodide	5.16E-01	3.35E-01
I-129	Particulate	1.53E+00	1.10E+00
	Iodine Vapor	3.92E+00	2.95E+00
	Methyl Iodide	3.06E+00	2.30E+00
I-131	Particulate	5.14E-01	2.27E-01
	Iodine Vapor	1.16E+00	6.06E-01
	Methyl Iodide	9.10E-01	4.73E-01
I-132	Particulate	5.86E-03	2.10E-03
	Iodine Vapor	1.36E-02	5.65E-03
	Methyl Iodide	1.19E-02	4.92E-03
I-133	Particulate	1.26E-01	4.38E-02
	Iodine Vapor	2.87E-01	1.17E-01
	Methyl Iodide	2.27E-01	9.29E-02
I-134	Particulate	1.11E-03	4.00E-04
	Iodine Vapor	2.62E-03	1.08E-03
	Methyl Iodide	2.62E-03	1.08E-03
I-135	Particulate	2.51E-02	8.89E-03
	Iodine Vapor	5.75E-02	2.38E-02
	Methyl Iodide	4.68E-02	1.94E-02

[a] Dose Parameter displayed is for the most restrictive age group, which is the 1-year-old for all but I-125 and I-129, for which it is the 10-year-old.

Protection Factors are the ratio of the unsheltered dose to the sheltered dose. For example, a Factor of 20 would reduce an unsheltered dose of 100 rem to a sheltered dose of 5 rem.

Sheltered dose refers to the dose measured within a building (or other structure) when the surrounding environment and/or building is contaminated with radioactive material (the contamination does not need to be uniform). The definition of the unsheltered dose varies with the type of environmental contamination considered:

Deposited Radioactive Material: The unsheltered dose refers to the groundshine dose measured 1 m above an infinite, flat plane uniformly contaminated with radioactive material.

Airborne Radioactive Material (Cloud Submersion): The unsheltered dose refers to the dose measured at a location 1 m above the ground and surrounded by a semi-infinite (bounded by the earth) cloud of radioactive material that has a uniform concentration.

These are recommended default values. For more information, see LLNL16. Logarithmic functions have been developed to customize the protection factors for specific gamma energies, see RP16.

Table 6-1. Default Building Protection Factors for Public Protection Decisions

Building Type	Cloud Submersion Protection Factor	Deposition Protection Factor
One- and two- story single-family residential building[1]		
Above Basement	1.5	2.5
Basement	3	10
Heavy Construction Building[2,3,4]		
Above Basement	5	50
Basement	5	600

[1] RP16.

[2] Buildings constructed from brick or concrete with relatively thick (0.2 to 1+ m) walls and roofs and large, both in height and footprint. May include large multi-family (e.g., apartment), office and industrial buildings.

[3] Cloud submersion protection factors from EPA78

[4] Deposition protection factors from LLNL16

Table 6-2. Surface Deposition Protection Factors for Vehicles

Vehicle	Representative Shielding Factor [a]
Cars on fully contaminated road	1.7
Cars on fully decontaminated 2-lane road	2.5
Trains	2.5

[a] Bu77

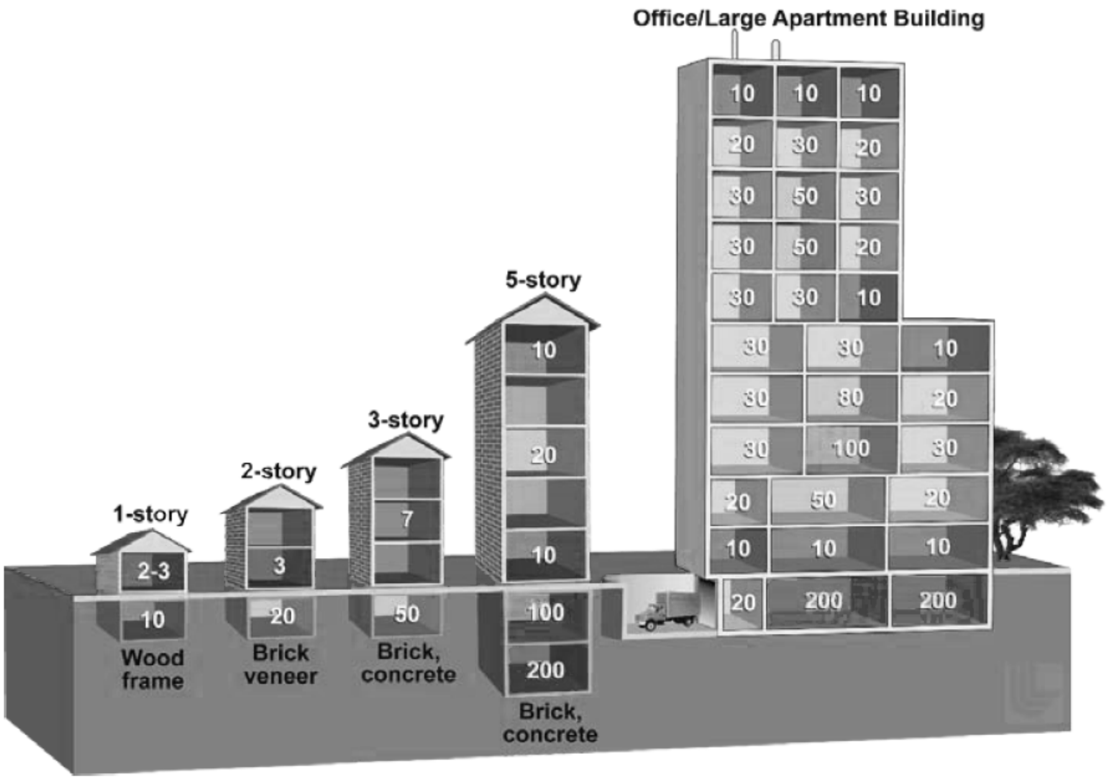

Figure 6-1. Approximate Protection Factors for locations in different Building Types

Source: LLNL09

Table 6-3. Assigned Protection Factors

Respirator Type	Quarter mask	Half mask	Full facepiece	Helmet/ Hood	Loose-fitting facepiece
Air-Purifying Respirator	5	10	50	--	--
Powered Air-Purifying Respirator	--	50	1000	1000 [a]	25
Supplied-Air Respirator					
Demand mode	--	10	50	--	--
Continuous flow mode	--	50	1000	1000 [a]	25
Pressure-demand	--	50	1000	--	--
Self-Contained Breathing Apparatus					
Demand mode	--	10	50	50	--
Pressure-demand	--	--	10,000	10,000	--

Source: OSHA09, Table I

[a] Assigned Protection Factor (APF) of 1,000 only with demonstrated Workplace Protection Factor study. Otherwise, APF is 25

Table 6-4. Resuspension Multiplication Factors

Condition	Multiplier
Rural conditions, light-medium winds	x1
Arid Climate	x10
Urban conditions, light traffic, light pedestrian activity	x10
Urban conditions, heavy traffic	x100
Ploughing in dry conditions	x100
High winds	Additional factor x2

Source: NRPB02, Table 3

Table 7. Breathing Rates by Age Group

This table lists the breathing rates for all age groups from ICRP Publication 66 (ICRP94).

Age Group	Activity								Total Volume	Activity Avg. Rate
	Sleeping		Sitting		Light Exercise		Heavy Exercise			
	Rate m^3/h	Time h/day	Rate m^3/h	Time h/day	Rate m^3/h	Time h/day	Rate m^3/h	Time h/day	m^3/day	m^3/h
3 month	0.09	17.0	NA	NA	0.19	7.0	NA	NA	**2.86**	**0.12**
1 year	0.15	14.0	0.22	3.33	0.35	6.67	NA	NA	**5.20**	**0.22**
5 year old	0.24	12.0	0.32	4.0	0.57	8.0	NA	NA	**8.76**	**0.37**
10 year old	0.31	10.0	0.38	4.67	1.12	9.33	NA	NA	**15.28**	**0.64**
15 year old (m)	0.42	10.0	0.48	5.5	1.38	7.5	2.92	1.0	**20.10**	**0.84**
15 year old (f)	0.35	10.0	0.4	7.0	1.3	6.75	2.57	0.25	**15.72**	**0.66**
Adult (m) (Sedentary)	0.45	8.5	0.54	5.5	1.5	9.75	3.0	0.25	**22.18**	**0.92**
Adult (f) (Sedentary)	0.32	8.5	0.39	5.5	1.25	9.75	2.7	0.25	**17.68**	**0.74**
See ICRP94, Tables 8, B.16A, and B.16B for methods to calculate breathing rates.										

Parent radionuclides with a half-life less than 6 hours are excluded from ingestion pathway analysis because it is unlikely a quantity 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.

Table 8-1. ILs, Crop DRLs, and Transfer Factors

Radionuclide	FDA Listed	IL[a] (µCi/kg_{wet})	Crop DRL[b] (µCi/m^2)	Leafy TF[c] (kg_{soil}/ kg_{dry})	Fruit TF[c] (kg_{soil}/ kg_{dry})	Non-Leafy TF[c] (kg_{soil}/ kg_{dry})	Grain TF[c] (kg_{soil}/ kg_{dry})
Am-241	Y	5.41E-05	5.40E-04	2.70E-04	6.20E-06	6.70E-04	2.20E-05
Ba-140	Y	1.86E-01	1.92E+00	5.00E-03	1.30E-03	5.00E-03	1.00E-03
Ce-141	Y	1.95E-01	1.97E+00	6.00E-03	1.00E-03	1.30E-02	3.10E-03
Ce-144	Y	1.35E-02	1.35E-01	6.00E-03	1.00E-03	1.30E-02	3.10E-03
Cf-252		1.03E-03	1.03E-02	4.70E-04	1.00E-02	3.50E-04	2.20E-05
Cm-242	Y	5.14E-04	5.14E-03	1.40E-03	1.50E-05	8.50E-04	2.30E-05
Cm-244	Y	5.41E-05	5.40E-04	1.40E-03	1.50E-05	8.50E-04	2.30E-05
Co-60		3.55E-02	3.55E-01	1.70E-01	7.00E-03	1.10E-01	8.50E-03
Cs-134	Y	2.51E-02	2.51E-01	6.00E-02	1.30E-03	4.20E-02	2.90E-02
Cs-136		1.78E+00	1.83E+01	6.00E-02	1.30E-03	4.20E-02	2.90E-02
Cs-137	Y	3.68E-02	3.67E-01	6.00E-02	1.30E-03	4.20E-02	2.90E-02
Cs-134 + Cs-137[d]	Y	3.24E-02	3.24E-01	6.00E-02	1.30E-03	4.20E-02	2.90E-02
Gd-153		7.59E-01	7.59E+00	2.00E-02	2.00E-02	2.00E-02	2.00E-02
I-129	Y	1.51E-03	3.03E-03	4.00E-02	1.30E-03	4.00E-02	4.00E-02
I-131	Y	4.59E-03	9.59E-03	4.00E-02	1.30E-03	4.00E-02	4.00E-02
I-133	Y	1.89E-01	5.64E-01	4.00E-02	1.30E-03	4.00E-02	4.00E-02
I-135		4.96E+01	3.52E+02	4.00E-02	1.30E-03	4.00E-02	4.00E-02
Ir-192		3.53E-01	3.55E+00	5.50E-02	1.50E-02	1.50E-02	1.50E-02
La-140		1.03E+01	1.27E+02	5.70E-03	1.00E-03	1.60E-03	2.00E-05
Mo-99		2.35E+01	2.64E+02	5.10E-01	6.00E-02	3.20E-01	8.00E-01
Nb-95	Y	3.24E-01	3.27E+00	1.70E-02	2.50E-02	8.00E-03	1.40E-02
Nb-95m		1.32E+01	1.46E+02	1.70E-02	2.50E-02	8.00E-03	1.40E-02
Np-237	Y	1.08E-04	1.08E-03	2.70E-02	1.00E-02	2.20E-02	2.90E-03
Np-239	Y	7.57E-01	8.76E+00	2.70E-02	1.00E-02	2.20E-02	2.90E-03
Pa-233		1.13E+00	1.15E+01	4.70E-04	2.50E-04	3.50E-04	2.20E-05
Pm-147		4.33E-01	4.33E+00	2.00E-02	2.00E-02	4.20E-02	1.40E-02
Pu-238	Y	6.76E-05	6.76E-04	8.30E-05	4.50E-05	6.50E-05	9.50E-06
Pu-239	Y	5.95E-05	5.94E-04	8.30E-05	4.50E-05	6.50E-05	9.50E-06
Pu-241	Y	3.24E-03	3.24E-02	8.30E-05	4.50E-05	6.50E-05	9.50E-06
Pu-238 + Pu-239 + Am-241[d]	Y	5.41E-05	5.40E-04	2.70E-04	4.50E-05	6.70E-04	2.20E-05
Ra-226		5.48E-05	5.48E-04	9.10E-02	1.70E-02	1.70E-02	1.70E-02

Radionuclide	FDA Listed	IL[a] (µCi/kg$_{wet}$)	Crop DRL[b] (µCi/m^2)	Leafy TF[c] (kg$_{soil}$/ kg$_{dry}$)	Fruit TF[c] (kg$_{soil}$/ kg$_{dry}$)	Non-Leafy TF[c] (kg$_{soil}$/ kg$_{dry}$)	Grain TF[c] (kg$_{soil}$/ kg$_{dry}$)
Ru-103	Y[e]	1.84E-01	1.85E+00	9.00E-02	2.00E-02	2.00E-02	3.00E-03
Ru-106	Y[e]	1.22E-02	1.22E-01	9.00E-02	2.00E-02	2.00E-02	3.00E-03
Sb-127		4.54E+00	4.97E+01	9.40E-05	5.40E-02	1.30E-04	1.80E-03
Se-75		1.64E-01	1.64E+00	2.50E-01	5.00E-02	5.00E-02	2.50E-01
Sr-89	Y	3.78E-02	3.79E-01	7.60E-01	2.70E-02	7.20E-01	1.10E-01
Sr-90	Y	4.32E-03	4.31E-02	7.60E-01	2.70E-02	7.20E-01	1.10E-01
Sr-91		1.39E+02	3.29E+03	7.60E-01	2.70E-02	7.20E-01	1.10E-01
Tc-99m		6.72E+03	1.43E+05	2.10E+02	1.50E+00	2.40E-01	7.30E-01
Te-127		4.63E+02	1.13E+04	3.00E-01	3.00E-01	8.00E-04	1.00E-01
Te-129m		2.83E-01	2.86E+00	3.00E-01	3.00E-01	8.00E-04	1.00E-01
Te-131m		1.18E+01	1.55E+02	3.00E-01	3.00E-01	8.00E-04	1.00E-01
Te-132	Y	1.19E-01	1.32E+00	3.00E-01	3.00E-01	8.00E-04	1.00E-01
Tm-170		1.64E-01	1.65E+00	6.00E-03	1.00E-03	1.30E-02	3.10E-03
U-237		5.27E+00	5.55E+01	2.00E-02	1.50E-02	1.50E-02	6.20E-03
Y-90		3.64E+00	4.14E+01	2.00E-03	2.00E-03	2.00E-03	5.00E-04
Y-91	Y	3.24E-02	3.26E-01	2.00E-03	2.00E-03	2.00E-03	5.00E-04
Yb-169		1.39E+00	1.41E+01	8.00E-03	2.20E-03	2.00E-03	7.70E-03
Zr-95	Y	1.08E-01	1.09E+00	4.00E-03	1.10E-03	4.00E-03	1.00E-03

Notes:

[a] If the nuclide is "FDA Listed" this value is a DIL. If the nuclide is NOT "FDA Listed" this value is a FIL. DILs are copied from FDA98. FILs 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 the 1-year-old where it is assumed to be 1.0. (See Method 3.1)

[b] Assumes Crops are ready to harvest (e.g., Time to Harvest = 0). See Method 3.2. The displayed Crop DRL uses the largest Transfer Factor of the four crop types included in this table.

[c] Transfer Factors from PNNL20.

[d] The displayed Transfer Factors for FDA grouped radionuclides use the largest Transfer Factor of the individual radionuclides in the group.

[e] ^{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 radionuclide is present.

Table 8-2. ILs, Milk and Meat DRLs, and Transfer Factors

Radionuclide	FDA Listed	IL[a] (µCi/kg_{wet})	Forage TF[b] (kg_{soil}/kg_{dry})	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 DRL[d] (area) (µCi/m^2)	Meat DRL[d] (mass) (µCi/kg_{wet})	Meat DRL[d] (water) (µCi/l)	Meat TF[d] (d/kg_{wet})
Am-241	Y	5.41E-05	1.50E-03	3.71E+00	2.68E+00	2.23E+00	4.20E-07	3.00E-03	2.16E-03	2.16E-03	5.00E-04
Ba-140	Y	1.86E-01	2.00E+00	3.65E+01	2.63E+01	2.19E+01	1.60E-04	1.07E+02	7.69E+01	7.69E+01	1.40E-04
Ce-141	Y	1.95E-01	3.70E-01	1.76E+02	1.27E+02	1.06E+02	3.30E-05	4.09E+01	2.95E+01	2.95E+01	2.00E-04
Ce-144	Y	1.35E-02	3.70E-01	1.19E+01	8.55E+00	7.12E+00	3.30E-05	1.97E+00	1.42E+00	1.42E+00	2.00E-04
Cf-252		1.03E-03	1.50E-03	3.96E+01	2.86E+01	2.38E+01	7.50E-07	7.24E-01	5.22E-01	5.22E-01	4.00E-05
Cm-242	Y	5.14E-04	1.00E-03	1.55E-01	1.12E-01	9.33E-02	9.60E-05	3.87E-01	2.79E-01	2.79E-01	4.00E-05
Cm-244	Y	5.41E-05	1.00E-03	1.63E-02	1.17E-02	9.76E-03	9.60E-05	3.76E-02	2.71E-02	2.71E-02	4.00E-05
Co-60		3.55E-02	4.50E-02	9.32E+00	6.72E+00	5.60E+00	1.10E-04	2.31E+00	1.66E+00	1.66E+00	4.30E-04
Cs-134	Y	2.51E-02	2.50E-01	1.58E-01	1.14E-01	9.48E-02	4.60E-03	3.23E-02	2.33E-02	2.33E-02	2.20E-02
Cs-136		1.78E+00	2.50E-01	1.21E+01	8.73E+00	7.27E+00	4.60E-03	6.28E+00	4.53E+00	4.53E+00	2.20E-02
Cs-137	Y	3.68E-02	2.50E-01	2.31E-01	1.66E-01	1.39E-01	4.60E-03	4.64E-02	3.35E-02	3.35E-02	2.20E-02
Cs-134 + Cs-137[e]	Y	3.24E-02	2.50E-01	2.03E-01	1.47E-01	1.22E-01	4.60E-03	4.10E-02	2.95E-02	2.95E-02	2.20E-02
Gd-153		7.59E-01	3.70E-01	7.33E+02	5.28E+02	4.40E+02	3.00E-05	1.11E+03	8.02E+02	8.02E+02	2.00E-05
I-129	Y	1.51E-03	3.70E-03	4.06E-03	5.83E-03	4.86E-03	5.40E-03	3.15E-03	4.52E-03	4.52E-03	6.70E-03
I-131	Y	4.59E-03	3.70E-03	1.40E-02	2.01E-02	1.68E-02	5.40E-03	5.15E-02	7.40E-02	7.40E-02	6.70E-03
I-133	Y	1.89E-01	3.70E-03	1.69E+00	2.42E+00	2.02E+00	5.40E-03	2.33E+06	3.35E+06	3.35E+06	6.70E-03
I-135		4.96E+01	3.70E-03	5.94E+03	8.53E+03	7.11E+03	5.40E-03	2.86E+23	4.11E+23	4.11E+23	6.70E-03
Ir-192		3.53E-01	4.50E-02	5.17E+03	3.72E+03	3.10E+03	2.00E-06	7.85E+00	5.65E+00	5.65E+00	1.50E-03
La-140		1.03E+01	2.00E-02	2.77E+04	2.00E+04	1.66E+04	2.00E-05	6.95E+06	5.01E+06	5.01E+06	1.30E-04
Mo-99		2.35E+01	5.40E+00	8.97E+02	6.47E+02	5.40E+02	1.10E-03	8.90E+04	6.42E+04	6.42E+04	1.00E-03
Nb-95	Y	3.24E-01	2.00E-02	2.35E+04	1.69E+04	1.41E+04	4.10E-07	5.09E+04	3.67E+04	3.67E+04	2.60E-07

Radionuclide	FDA Listed	IL[a] (µCi/kg$_{wet}$)	Forage TF[b] (kg$_{soil}$/kg$_{dry}$)	Milk DRL[c] (area) (µCi/m²)	Milk DRL[c] (mass) (µCi/kg$_{wet}$)	Milk DRL[c] (water) (µCi/l)	Milk TF[c] (d/l)	Meat DRL[d] (area) (µCi/m²)	Meat DRL[d] (mass) (µCi/kg$_{wet}$)	Meat DRL[d] (water) (µCi/l)	Meat TF[d] (d/kg$_{wet}$)
Nb-95m		1.32E+01	2.00E-02	1.24E+06	8.96E+05	7.46E+05	4.10E-07	5.97E+07	4.30E+07	4.30E+07	2.60E-07
Np-237	Y	1.08E-04	6.10E-02	6.24E-01	4.50E-01	3.75E-01	5.00E-06	3.00E-03	2.16E-03	2.16E-03	1.00E-03
Np-239	Y	7.57E-01	6.10E-02	6.79E+03	4.89E+03	4.08E+03	5.00E-06	6.50E+03	4.69E+03	4.69E+03	1.00E-03
Pa-233		1.13E+00	1.50E-03	6.81E+03	4.91E+03	4.09E+03	5.00E-06	1.30E+03	9.37E+02	9.37E+02	4.00E-05
Pm-147		4.33E-01	3.70E-01	4.17E+02	3.01E+02	2.51E+02	3.00E-05	6.10E+02	4.40E+02	4.40E+02	2.00E-05
Pu-238	Y	6.76E-05	5.50E-04	1.95E-01	1.41E-01	1.17E-01	1.00E-05	1.71E+00	1.23E+00	1.23E+00	1.10E-06
Pu-239	Y	5.95E-05	5.50E-04	1.72E-01	1.24E-01	1.03E-01	1.00E-05	1.50E+00	1.08E+00	1.08E+00	1.10E-06
Pu-241	Y	3.24E-03	5.50E-04	9.36E+00	6.75E+00	5.62E+00	1.00E-05	8.20E+01	5.91E+01	5.91E+01	1.10E-06
Pu-238 + Pu-239 + Am-241[e]	Y	5.41E-05	1.50E-03	1.56E-01	1.12E-01	9.37E-02	1.00E-05	3.00E-03	2.16E-03	2.16E-03	5.00E-04
Ra-226		5.48E-05	7.10E-02	4.16E-03	3.00E-03	2.50E-03	3.80E-04	8.95E-04	6.45E-04	6.45E-04	1.70E-03
Ru-103	Y[f]	1.84E-01	2.00E-03	5.79E+02	4.18E+02	3.48E+02	9.40E-06	2.18E+00	1.57E+00	1.57E+00	3.30E-03
Ru-106	Y[f]	1.22E-02	2.00E-03	3.74E+01	2.70E+01	2.25E+01	9.40E-06	1.06E-01	7.64E-02	7.64E-02	3.30E-03
Sb-127		4.54E+00	2.00E+00	4.51E+03	3.26E+03	2.71E+03	3.80E-05	3.51E+03	2.53E+03	2.53E+03	1.20E-03
Se-75		1.64E-01	3.50E-01	1.19E+00	8.58E-01	7.15E-01	4.00E-03	3.39E-01	2.44E-01	2.44E-01	1.50E-02
Sr-89	Y	3.78E-02	1.30E+00	8.57E-01	6.18E-01	5.15E-01	1.30E-03	1.05E+00	7.61E-01	7.61E-01	1.30E-03
Sr-90	Y	4.32E-03	1.30E+00	9.60E-02	6.92E-02	5.77E-02	1.30E-03	9.24E-02	6.66E-02	6.66E-02	1.30E-03
Sr-91		1.39E+02	1.30E+00	4.12E+04	2.97E+04	2.48E+04	1.30E-03	1.26E+18	9.12E+17	9.12E+17	1.30E-03
Tc-99m		6.72E+03	7.60E+01	8.56E+07	6.32E+07	5.27E+07	1.40E-04	4.81E+29	3.55E+29	3.55E+29	1.00E-04
Te-127		4.63E+02	1.00E+00	5.67E+05	4.09E+05	3.41E+05	3.40E-04	2.14E+18	1.55E+18	1.55E+18	7.00E-03
Te-129m		2.83E-01	1.00E+00	2.48E+01	1.79E+01	1.49E+01	3.40E-04	1.68E+00	1.21E+00	1.21E+00	7.00E-03
Te-131m		1.18E+01	1.00E+00	2.30E+03	1.66E+03	1.38E+03	3.40E-04	2.32E+06	1.67E+06	1.67E+06	7.00E-03
Te-132	Y	1.19E-01	1.00E+00	1.40E+01	1.01E+01	8.39E+00	3.40E-04	3.20E+01	2.31E+01	2.31E+01	7.00E-03
Tm-170		1.64E-01	3.70E-01	1.45E+02	1.04E+02	8.71E+01	3.30E-05	2.53E+02	1.83E+02	1.83E+02	2.00E-05

Radionuclide	FDA Listed	IL[a] (µCi/kg$_{wet}$)	Forage TF[b] (kg$_{soil}$/ kg$_{dry}$)	Milk DRL[c] (area) (µCi/m²)	Milk DRL[c] (mass) (µCi/kg$_{wet}$)	Milk DRL[c] (water) (µCi/l)	Milk TF[c] (d/l)	Meat DRL[d] (area) (µCi/m²)	Meat DRL[d] (mass) (µCi/kg$_{wet}$)	Meat DRL[d] (water) (µCi/l)	Meat TF[d] (d/kg$_{wet}$)
U-237		5.27E+00	4.60E-02	9.86E+01	7.10E+01	5.92E+01	1.80E-03	2.78E+03	2.00E+03	2.00E+03	3.90E-04
Y-90		3.64E+00	5.00E-03	7.75E+03	5.59E+03	4.66E+03	2.00E-05	1.59E+04	1.15E+04	1.15E+04	1.00E-03
Y-91	Y	3.24E-02	5.00E-03	4.76E+01	3.43E+01	2.86E+01	2.00E-05	1.13E+00	8.17E-01	8.17E-01	1.00E-03
Yb-169		1.39E+00	3.70E-01	1.26E+03	9.08E+02	7.57E+02	3.30E-05	2.95E+03	2.13E+03	2.13E+03	2.00E-05
Zr-95	Y	1.08E-01	1.00E-02	8.81E+02	6.35E+02	5.29E+02	3.60E-06	3.09E+03	2.23E+03	2.23E+03	1.20E-06

Notes:

[a] If the nuclide is "FDA Listed" this value is a DIL. If the nuclide is NOT "FDA Listed" this value is a FIL. DILs are copied from FDA98. FILs 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 the 1-year-old where it is assumed to be 1.0. (See Method 3.1)

[b] Forage Transfer Factors from IAEA10 for available elements. Transfer Factors for elements not covered by IAEA10 were inferred using the methodology described in PNNL03.

[c] Values for Cow's Milk ready to harvest (e.g., Time to Grazing and Time to Harvest = 0). Transfer Factors from PNNL20. See Method 3.3.

[d] Values for Beef ready to harvest (e.g., Time to Grazing and Time to Harvest =0). Transfer Factors from PNNL20. See Method 3.4.

[e] The displayed Transfer Factors for FDA grouped radionuclides use the largest Transfer Factor of the individual radionuclides in the group.

[f] ^{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 radionuclide is present.

Table 8-3. EPA Water DRLs

Radionuclide	Water DRL (μCi/l)[a]	
	100 mrem PAG	500 mrem PAG
Am-241	1.04E-04	1.11E-03
Ba-140[b]	7.15E-03	4.58E-02
Ce-141	4.78E-02	3.17E-01
Ce-144[b]	5.80E-03	4.27E-02
Cf-252	7.79E-05	2.49E-03
Cm-242	6.63E-04	1.93E-02
Cm-244	1.32E-04	1.83E-03
Co-60	7.15E-03	6.59E-02
Cs-134	4.34E-03	1.17E-02
Cs-136	2.23E-02	7.35E-02
Cs-137[b]	6.15E-03	1.66E-02
Gd-153	1.31E-01	8.08E-01
I-129	5.43E-04	2.13E-03
I-131	1.31E-03	1.03E-02
I-133	5.87E-03	5.27E-02
I-135[b]	2.88E-02	2.41E-01
Ir-192	2.89E-02	1.65E-01
La-140	1.99E-02	1.12E-01
Mo-99[b]	6.84E-02	3.60E-01
Nb-95	7.68E-02	3.83E-01
Nb-95m	6.08E-02	3.98E-01
Np-237[b]	1.93E-04	2.09E-03
Np-239	4.36E-02	2.83E-01
Pa-233	3.99E-02	2.57E-01
Pm-147	1.07E-01	8.64E-01
Pu-238	9.74E-05	9.89E-04
Pu-239[b]	9.25E-05	8.98E-04
Pu-241[b]	6.87E-03	4.75E-02
Ra-226[b]	5.42E-05	8.05E-04
Ru-103[b]	5.43E-02	3.06E-01
Ru-106[b]	4.62E-03	3.22E-02

Radionuclide	Water DRL (µCi/l)[a]	
	100 mrem PAG	500 mrem PAG
Sb-127[b]	2.11E-02	1.24E-01
Se-75	1.63E-02	8.64E-02
Sr-89	1.08E-02	8.77E-02
Sr-90[b]	1.00E-03	7.42E-03
Sr-91[b]	6.57E-02	3.43E-01
Tc-99m	1.89E+00	1.01E+01
Te-127	2.21E-01	1.33E+00
Te-129m[b]	8.78E-03	7.47E-02
Te-131m[b]	1.73E-02	1.14E-01
Te-132[b]	7.54E-03	5.49E-02
Tm-170	2.42E-02	1.71E-01
U-237	4.65E-02	2.96E-01
Y-90	1.24E-02	8.38E-02
Y-91	1.40E-02	9.51E-02
Yb-169	5.48E-02	3.17E-01
Zr-95[b]	1.95E-02	9.96E-02

Notes:

[a] Listed Water DRL values are only appropriate when the mixture of interest contains only 1 radionuclide (and associated daughters). By agreement with EPA, FRMAC currently only considers the standard 6 ICRP age groups for Water DRL calculations.

[b] Water DRL includes dose contribution (if any) from daughter(s) at equilibrium.

Table 9-1. Dry-to-Wet Mass [a]

Plant Type	Mass Conversion Factor kg_{dry}/kg_{wet}
Leafy vegetables	0.2
Non-leafy 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
Non-leafy vegetables	4
Fruit	5.56
Grain	1.1
Animal Feed	
Forage	4.55
Stored hay	4.55
Stored grain	1.1

Table 10. Daily Food Intake Rates

This table lists the average DFIR for populations of various ages in the United States. Intake rates were calculated using the methodology described in Table D-3 of FDA98.

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 [a]	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 (kg/d)	**1.1**	**1.4**	**1.8**	**2.1**	**2.4**	**2.6**
Total Annual Intake (kg/year)	**420**	**510**	**660**	**780**	**870**	**940**

Sources: EPA84, FDA98 (Rounded to 2 significant figures.)

[a] These values SHOULD NOT be used for determining Water DRLs, see EPA17 for appropriate water intake rates. (Those values will be in Method 3.8 of this Manual when that method is finalized.)

Table 11. Ingestion Pathway Default Assumptions

The variables 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.

Variable	Description	Default Value [a]
Animal Feed Daily Intake Rate [b] (AFDIR)	Milk Cow	50 kg/d
	Beef Cow	50 kg/d
	Goat	6 kg/d
Animal Soil Daily Intake Rate (ASDIR)	Milk Cow	0.5 kg/d [c]
	Beef Cow	0.5 kg/d [c]
	Goat	0.06 kg/d [d]
Animal Water Daily Intake Rate (AWDIR)	Milk Cow	60 l/d
	Beef Cow	50 l/d
	Goat	8 l/d
Consumption Time	Time contaminated food is consumed.	365 d
Crop Retention Factor (CRF)	Forage	0.5 [e]
	Forage, Iodine radionuclides	1.0
	Crop	0.2
	Crop, Iodine radionuclides	1.0
	Crops not growing above the surface at the time of deposition	0.0
Crop Weathering Decay Constant	Corresponds to a 15-day half-life.	4.62E-02 d^{-1} [f]
Crop Yield (Y)	Crop	2.0 kg/m^2
	Forage	0.7 kg/m^2
Daily Soil Intake Rate (DSIR)	Adult	5.0E-05 kg/d [g]
	Child	1.0E-04 kg/d [g]
Density of Milk (ρ_{milk})		1.04 kg/L [h]
Density of Soil (ρ_{soil})		1600 kg/m^3 [h]
Fraction of Diet Contaminated (FDC)	I-131, I-133, Te-132, and Np-239 for the infant (3 month and 1 year old)	1.0 [i]
	All other Radionuclide/Age Group combinations	0.3 [i]
Fraction of Diet Contaminated (Forage, Fodder, or Water)	Cow Feed (FDC_{forage} or FDC_{fodder}) Cow Water (FDC_{water})	1.0
Fraction of Food Subgroup Contaminated ($FFC_{subgroup}$)		1.0 [h]
Mature Root Depth (d_r)	Leafy	0.3 m [j]
	Non-Leafy	0.3 m [j]
	Grain	0.6 m [j]
	Fruit	0.3 m [j]
	Forage	0.6 m [j]
Mixing Depth (d_m)	Paved	1.0E-04 m [k]
	Unplowed (First Growing Season)	1.0E-03 m [k]

Variable	Description	Default Value [a]
	After Plowing (plow depth)	0.15 m [h]
Time to Market (t_m)	Crop	1 d
	Milk	2 d
	Meat	20 d

Notes:

[a] All values from NRC77 unless otherwise indicated.

[b] Forage + Fodder

[c] ANL01. Note: Adjustments to $AFDIR_{forage}$ should also be made to ASDIR to reflect the change in exposure to radionuclides on the ground

[d] Goat value estimated based on ratio of Feed to Soil for Cows (100:1).

[e] Ng77 (Appendix B, page 113)

[f] NCRP07 (Page 165)

[g] EPA11 (Table ES-1)

[h] FRMAC Assumption

[i] FDA98 (Appendix E, page 2)

[j] USDA97. To be conservative, Mature Root Depth values shown are the minimum value for the ranges provided for each crop type.

[k] EPA89

Table 12. Alternate Lung Clearance Types for Selected Radionuclides

For most emergency response scenarios, FRMAC defaults to the ICRP recommended Lung Clearance Type (LCT) as specified in ICRP Publication 72 (ICRP96). However, in the case of scenarios where a specific physical form is known for the radionuclides shown below, the recommendation is to use the listed LCT.

Radionuclide	LCT
Pu	Pu-239: Slow[a]
Sr	$SrTiO_3$: Slow[b]
U	High Fired Ceramic[c]: Slow[d]

[a] Ryan82

[b] ICRP Publication 68, Dose Coefficients for Intakes of Radionuclides by Workers, Table F.1 (ICRP94b)

[c] Powder sintered at temperatures greater than 800C

[d] SAIC

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APPENDIX D. WORKSHEETS

This section is reserved for potential inclusion of Worksheets in the future.

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APPENDIX E. UNIT CONVERSIONS

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+12 rem/Ci
Dose Rate Conversion:	1 (mrem/year)/(µCi/m^2)	=	0.114 (rem/h)/(Ci/m^2)

TIME

		s	min	h	d	year
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 h	=	3600	60	1	4.17E-02	8760
1 d	=	8.64E+04	1.44E+03	24	1	2.74E-03
1 year	=	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/h
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/h	=	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

Air Density = (0.001293 g/cm^3 at STP)

1 ft^3 = 0.0807 lb

1 m^3 = 1.29 kg

Avogadro's number

6.02E+23 per g-mole

Molar Volume

22.4 L/g-mole

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APPENDIX F. SUPPLEMENTAL INFORMATION

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SUPPLEMENT 1 – DECAY AND IN-GROWTH CALCULATIONS

In order to model complex decay chains more completely, the Bateman equations (H. Bateman, *"Solution of a System of Differential Equations Occurring in the Theory of Radioactive Transformations,"* Proc. Cambridge Phil. Soc. IS, 423 (1910)) are used to determine the amount of a radionuclide present at the Evaluation Time (t_n) based on the decay and in-growth of all radionuclides present in the mixture. A general overview of the calculations is presented below.

To perform this calculation, it is necessary to evaluate the production and decay of each radionuclide in the chain to determine the total amount of each radionuclide present at the Evaluation Time (t_n). For example, in a 3-nuclide chain:

The activity of the parent radionuclide at t_n is:

$$A_{p,t_n} = A_{p,0} * e^{-\lambda_p t_n} \quad \text{(Eq. 1)}$$

The activity of its first-generation daughter, including Branching Ratio (BrR_{d1}), at t_n is:

$$A_{d_1,t_n} = A_{p,0} * \left(\lambda_{d_1} * BrR_{d_1}\right) * \left(\frac{e^{-\lambda_p t_n} - e^{-\lambda_{d_1} t_n}}{\lambda_{d_1} - \lambda_p}\right) \quad \text{(Eq. 2)}$$

The activity of its second-generation daughter, including Branching Ratio (BrR_{d2}), at t_n is:

$$A_{d_2,t_n} = A_{p,0} * \left(\lambda_{d_1} * BrR_{d_1} * \lambda_{d_2} * BrR_{d_2}\right) * \left[\frac{e^{-\lambda_p t_n}}{(\lambda_{d_1} - \lambda_p)(\lambda_{d_2} - \lambda_p)} + \frac{e^{-\lambda_{d_1} t_n}}{(\lambda_p - \lambda_{d_1})(\lambda_{d_2} - \lambda_{d_1})} + \frac{e^{-\lambda_{d_2} t_n}}{(\lambda_p - \lambda_{d_2})(\lambda_{d_1} - \lambda_{d_2})}\right]$$

(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:

$$A_{d_2,t_n} = \left\{ \begin{matrix} A_{p,0} * \left(\lambda_{d_1} * BrR_{d_1} * \lambda_{d_2} * BrR_{d_2}\right) \\ * \begin{bmatrix} \frac{e^{-\lambda_p t_n}}{(\lambda_{d_1}-\lambda_p)(\lambda_{d_2}-\lambda_p)} \\ + \frac{e^{-\lambda_{d_1} t_n}}{(\lambda_p-\lambda_{d_1})(\lambda_{d_2}-\lambda_{d_1})} \\ + \frac{e^{-\lambda_{d_2} t_n}}{(\lambda_p-\lambda_{d_2})(\lambda_{d_1}-\lambda_{d_2})} \end{bmatrix} \end{matrix} \right\}$$

$$+ \left[A_{d_1,0} * \left(\lambda_{d_2} * BrR_{d_2}\right) * \left(\frac{e^{-\lambda_{d_1} t_n} - e^{-\lambda_{d_2} t_n}}{\lambda_{d_2}-\lambda_{d_1}}\right)\right] + A_{d_2,0} * e^{-\lambda_{d_2} t_n} \quad \text{(Eq. 6)}$$

In the general case, the activity of the "nth" 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:

$$C_1 = \frac{\lambda_{d_1}\lambda_{d_2}\ldots\lambda_{d_n}}{(\lambda_{d_1} - \lambda_p)(\lambda_{d_2} - \lambda_p)\ldots(\lambda_{d_n} - \lambda_p)}$$

$$C_2 = \frac{\lambda_{d_1}\lambda_{d_2}\ldots\lambda_{d_n}}{(\lambda_p - \lambda_{d_1})(\lambda_{d_2} - \lambda_{d_1})\ldots(\lambda_{d_n} - \lambda_{d_1})}$$

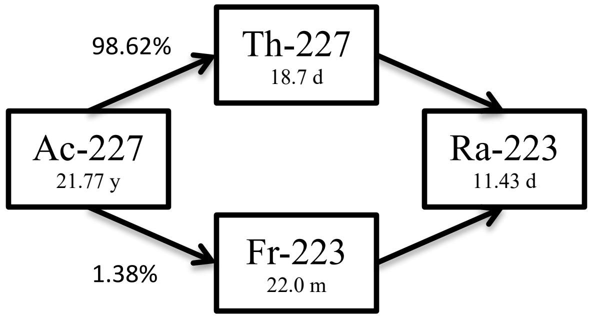
$$\vdots$$

$$C_n = \frac{\lambda_{d_1}\lambda_{d_2}\ldots\lambda_{d_n}}{(\lambda_p-\lambda_{d_n})(\lambda_{d_1}-\lambda_{d_n})\ldots(\lambda_{d_{n-1}}-\lambda_{d_n})} \quad \text{(Eq. 7)}$$

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.

F.1.1. 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}

$\lambda_{Th} =$ 3.71E-02 d^{-1} $BrR_{Ac,Th} = 0.9862$

$\lambda_{Fr} =$ 45.4 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:

$$A_{\text{Ra,100days,Th}} = 1\text{Ci} * (3.71\text{E-02 d}^{-1} * 0.9862 * 6.06\text{E-02 d}^{-1} * 1) * \left[\frac{e^{-8.72\text{E-05 d}^{-1} * 100 \text{ d}}}{(3.71\text{E-02 d}^{-1} - 8.72\text{E-05 d}^{-1})(6.06\text{E-02 d}^{-1} - 8.72\text{E-05 d}^{-1})} + \frac{e^{-3.71\text{E-02d}^{-1} * 100 \text{ d}}}{(8.72\text{E-05 d}^{-1} - 3.71\text{E-02 d}^{-1})(6.06\text{E-02 d}^{-1} - 3.71\text{E-02 d}^{-1})} + \frac{e^{-6.06\text{E-02 d}^{-1} * 100 \text{ d}}}{(8.72\text{E-05 d}^{-1} - 6.06\text{E-02 d}^{-1})(3.71\text{E-02 d}^{-1} - 6.06\text{E-02 d}^{-1})} \right]$$

$$= 0.923 \text{ Ci}$$

For the Fr-223 branch, from equation 4 above:

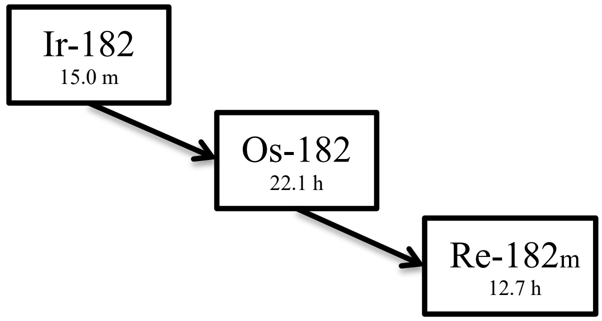
$$A_{\mathrm{Ra,100days,Fr}} = 1\mathrm{Ci} * (45.4\ \mathrm{d}^{-1} * 0.0138 * 6.06\mathrm{E}\text{-}02\ \mathrm{d}^{-1} * 1) * \left[\begin{array}{c} \dfrac{e^{-8.72\mathrm{E}\text{-}05\ \mathrm{d}^{-1} * 100\ \mathrm{d}}}{(45.4\ \mathrm{d}^{-1} - 8.72\mathrm{E}\text{-}05\ \mathrm{d}^{-1})(6.06\mathrm{E}\text{-}02\ \mathrm{d}^{-1} - 8.72\mathrm{E}\text{-}05\ \mathrm{d}^{-1})} \\ + \dfrac{e^{-3.71\mathrm{E}\text{-}02\ \mathrm{d}^{-1} * 100\ \mathrm{d}}}{(8.72\mathrm{E}\text{-}05\ \mathrm{d}^{-1} - 45.4\ \mathrm{d}^{-1})(6.06\mathrm{E}\text{-}02\ \mathrm{d}^{-1} - 45.4\ \mathrm{d}^{-1})} \\ + \dfrac{e^{-6.06\mathrm{E}-02\mathrm{d}^{-1} * 100\mathrm{d}}}{(8.72\mathrm{E}\text{-}05\ \mathrm{d}^{-1} - 6.06\mathrm{E}\text{-}02\ \mathrm{d}^{-1})(45.4\ \mathrm{d}^{-1} - 6.06\mathrm{E}\text{-}02\ \mathrm{d}^{-1})} \end{array} \right]$$

$$= 0.0137\ \mathrm{Ci}$$

The total Ra-223 activity after 100 days is then the sum of these two quantities, 0.937 Ci.

F.1.2. 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	$\lambda_{Ir} = 2.77\ h^{-1}$
Os-182	1.04E-02 Ci	$\lambda_{Os} = 3.14E\text{-}02\ h^{-1}$
Re-182m	3.97E-04 Ci	$\lambda_{Re} = 5.46E\text{-}02\ h^{-1}$

From equation 6 above:

$$A_{\mathrm{Re,6h}} = \left\{ \begin{array}{l} 6.25\text{E-}02\ \mathrm{Ci} * (3.14\text{E-}02\ \mathrm{h}^{-1} * 1 * 5.46\text{E-}02\ \mathrm{h}^{-1} * 1) \\ * \left[\begin{array}{l} \dfrac{e^{-2.77\ \mathrm{h}^{-1} * 6\mathrm{h}}}{(3.14\text{E-}02\ \mathrm{h}^{-1} - 2.77\ \mathrm{h}^{-1})(5.46\text{E-}02\ \mathrm{h}^{-1} - 2.77\ \mathrm{h}^{-1})} \\ + \dfrac{e^{-3.14\text{E-}02\ \mathrm{h}^{-1} * 6\ \mathrm{h}}}{(2.77\ \mathrm{h}^{-1} - 3.14\text{E-}02\ \mathrm{h}^{-1})(5.46\text{E-}02\ \mathrm{h}^{-1} - 3.14\text{E-}02\ \mathrm{h}^{-1})} \\ + \dfrac{e^{-6.06\text{E}-02\mathrm{d}^{-1} * 6\mathrm{h}}}{(2.77\ \mathrm{h}^{-1} - 5.46\text{E-}02\ \mathrm{h}^{-1})(3.14\text{E-}02\ \mathrm{h}^{-1} - 5.46\text{E-}02\ \mathrm{h}^{-1})} \end{array} \right] \end{array} \right\} + \left[\begin{array}{l} 1.04\text{E-}02\ \mathrm{Ci} * (5.46\text{E-}02\ \mathrm{h}^{-1} * 1) * \\ \left(\dfrac{e^{-3.14\text{E-}02\ \mathrm{h}^{-1} * 6\ \mathrm{h}} - e^{-5.46\text{E-}02\ \mathrm{h}^{-1} * 6\ \mathrm{h}}}{5.46\text{E-}02\ \mathrm{h}^{-1} - 3.14\text{E-}02\ \mathrm{h}^{-1}} \right) \end{array} \right]$$

$$+3.97\text{E-}04\ \mathrm{Ci} * e^{-5.46\text{E-}02\ \mathrm{h}^{-1} * 6\ \mathrm{h}}$$

$$= 3.09\text{E-}03\ \mathrm{Ci}$$

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SUPPLEMENT 2 – CALCULATION OF RESUSPENSION AND WEATHERING PARAMETERS

The Resuspension and Weathering Parameters are similar in that they both involve radioactive decay and a physical removal process. These two effects would seem to be complementary, but in fact are competing and must be addressed separately over the integration period. Therefore, standard mathematical methods for combining equations are not appropriate and exact solutions are only achievable through numerical integration. This can be approximated by hand using a series technique, such as a Taylor expansion. Full treatment of this process is outside the scope of this manual.

The methods described below represent an approximate solution for parent radionuclides and should only be used if a computer code, such as Turbo FRMAC©, is not available to complete these calculations.

This supplement addresses the calculation of the following quantities:

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

K_t = Resuspension Factor, The fraction of radioactive material transferred from the surface to the atmosphere at a given time (*t*) after initial deposition, m^{-1}.

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

WF = Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind), unitless;

NOTE: Weathering is used in this manual both as a contributor to the Weathering Parameter and as an independent factor. This Supplement treats Weathering as a contributor to the WP. If a calculation involves weathering as an independent factor the section on Weathering may be performed as a stand-alone calculation.

F.2. 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 it can be shown to more accurately predict the resuspension in the area under investigation.

$$KP_{i,TP} = \int_{t_1}^{t_2} \left(K_t * Dp_{i,t}\right) dt \qquad \text{(Eq. 1)}$$

$$\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} = \int_{\text{s}}^{\text{s}} \left(\frac{1}{\text{m}} * \frac{\mu\text{Ci}}{\text{m}^2}\right)$$

where:

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

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

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

K_t = Resuspension Factor, the fraction of radioactive material transferred from the surface to the breathing zone at a given time (*t*) after initial deposition, m^{-1}; and

$Dp_{i,t}$ = Deposition, the areal activity of radionuclide *i* at time *t*, µCi/m^2.

NOTE: This value is calculated using the Bateman equations as demonstrated in Appendix F – Supplement 1.

F.2.1. Resuspension

Resuspension is the fraction of radioactive material transferred from the surface to the breathing zone at a given time (*t* in seconds) after initial deposition. The units of resuspension are m^{-1}, representing the air concentration (µCi/m^3) divided by the areal activity (µCi/m^2) in a given area.

Resuspension as a function of time is represented by Equation 2:

$$K_t = (1.0\text{E-}05 * e^{-8.1\text{E-}07 * t}) + (7.0\text{E-}09 * e^{-2.31\text{E-}08 * t}) + 1.0\text{E-}09 \qquad \text{(Eq. 2)}$$

where:

K_t = Resuspension Factor, the fraction of radioactive material transferred from the surface to the breathing zone at a given time (*t*) after initial deposition, m^{-1}; and

t = Time, the time elapsed from initial deposition, s.

The resuspension model used here is the standard FRMAC approach found in the Maxwell-Anspaugh paper "An Improved Model for Prediction of Resuspension" (Max11), but may not be appropriate for the environmental conditions existing in the area under investigation. An alternate resuspension model may be substituted, with approval from local decision makers, if it can be shown to more accurately predict the resuspension in the area under investigation.

F.2.2. Combining Resuspension with Radioactive Decay and In-growth to produce the Resuspension Parameter

For a **parent radionuclide**, multiplying K_t by the radioactive decay yields:

$$KP_{i,TP} = \int_{t_1}^{t_2} \left[\begin{pmatrix} 1.0\text{E-}05 * e^{-8.1\text{E-}07*t} \\ +7.0\text{E-}09 * e^{-2.31\text{E-}08*t} \\ +1.0\text{E-}09 \end{pmatrix} * \left(Dp_{i,t_0} * e^{-\lambda_i t}\right) \right] dt \qquad \text{(Eq. 3a)}$$

where:

$Dp_{i,t0}$ = Initial Deposition, the areal activity of radionuclide *i* at the time of deposition t_0, µCi/m^2;

λ_i = Decay constant for radionuclide *i*, s^{-1};

This simplifies to:

$$KP_{i,TP} = Dp_{i,t_0} \int_{t_1}^{t_2} \left[\begin{pmatrix} 1.0\text{E-}05 * e^{(-t*(\lambda_i+8.1\text{E-}07))} \\ +7.0\text{E-}09 * e^{(-t*(\lambda_i+2.31\text{E-}08))} \\ +1.0\text{E-}09 * e^{(-t*(\lambda_i))} \end{pmatrix} \right] dt \qquad \text{(Eq. 3b)}$$

Integrating over the time phase under consideration yields the following:

$$KP_{i,TP} = Dp_{i,t_0} * \left[\begin{array}{c} \frac{1.0\text{E-}05*\left(e^{(-t_2*(\lambda_i+8.1\text{E-}07))} - e^{(-t_1*(\lambda_i+8.1\text{E-}07))}\right)}{-(\lambda_i+8.1\text{E-}07)} \\ + \frac{7.0\text{E-}09*\left(e^{(-t_2*(\lambda_i+2.31\text{E-}08))} - e^{(-t_1*(\lambda_i+2.31\text{E-}08))}\right)}{-(\lambda_i+2.31\text{E-}08)} \\ + \frac{1.0\text{E-}09*\left(e^{(-t_2*(\lambda_i))} - e^{(-t_1*(\lambda_i))}\right)}{-(\lambda_i)} \end{array} \right]$$

(Eq. 3c)

$$\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^3} = \frac{\mu\text{Ci}}{\text{m}^2} * \left[\begin{array}{l} \frac{\text{m}^{-1} * \text{unitless}}{\text{s}^{-1}} \\ + \frac{\text{m}^{-1} * \text{unitless}}{\text{s}^{-1}} \\ + \frac{\text{m}^{-1} * \text{unitless}}{\text{s}^{-1}} \end{array} \right]$$

Calculations for daughters may be performed in the same manner by replacing ($Dp_{i,t0} * e^{-\lambda t}$) in Equation (3a) above with the Bateman equation that is appropriate for the "generation" of daughter under consideration (Found in Appendix F – Supplement 1).

F.3. Weathering Parameter

The Weathering Parameter (WP) adjusts for radioactive decay and in-growth and the time-dependent weathering factor (WF) over the time phase under consideration.

$$WP_{i,TP} = \int_{t_1}^{t_2} \left(WF_t * Dp_{i,t} \right) dt \qquad \text{(Eq. 4)}$$

$$\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^2} = \int_{\text{s}}^{\text{s}} \left(\text{unitless} * \frac{\mu\text{Ci}}{\text{m}^2} \right)$$

where:

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

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

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

WF_t = Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind) from t_0 (deposition) to t_n (Evaluation Time), unitless; (An02); and

$Dp_{i,t}$ = Deposition, the areal activity of radionuclide *i* at time *t*, μCi/m^2.

NOTE: This value is calculated using the Bateman equations as demonstrated in Appendix F – Supplement 1.

F.3.1. Weathering Factor

The Weathering Factor (WF) adjusts for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind). The

FRMAC's default WF model was developed using data from the Nevada Test Site and the Chernobyl nuclear power plant accident (An02).

NOTE: This WF model is the default approach, but may not be appropriate for the environmental conditions existing in the area under investigation. An alternate WF model may be substituted, with approval from local authorities, if it can be shown to more accurately predict the weathering in the area under investigation.

$$WF_t = 0.4 * e^{-1.46\text{E}-0.8t} + 0.6 * e^{-4.44\text{E}-10t} \quad \text{(Eq. 5)}$$

$$\text{uniteless} = \text{unitelss} * \left(\text{e}^{-\left(\text{s}^{-1} * \text{s}\right)}\right) + \text{unitelss} * \left(\text{e}^{-\left(\text{s}^{-1} * \text{s}\right)}\right)$$

where:

WF = Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind), unitless; and

t = Time, the time elapsed from initial deposition, s.

NOTE: Ignoring Weathering: If desired, the WF can be ignored when calculating the external dose from groundshine. To ignore weathering, set the WF value to 1 (constant over time). This will cause the WP to be simply a radioactive decay and in-growth adjustment for each radionuclide over the time phase under consideration.

F.3.2. Combining the Weathering Factor and Radioactive Decay and In-growth to produce the Weathering Parameter

If weathering is addressed, the math in this part of the calculation is a little more complicated so the intermediate steps have been included.

For a **<u>parent radionuclide</u>**, multiplying the WF by the radioactive decay yields:

$$WP_{i,TP} = \int_{t_1}^{t_2} \left[\begin{matrix} \left(0.4 * e^{-1.46\text{E-}08t} + 0.6 * e^{-4.44\text{E-}10t}\right) \\ * \left(Dp_{i,t_0} * e^{-\lambda_i t}\right) \end{matrix} \right] dt \quad \text{(Eq. 6a)}$$

where:

$Dp_{i,t0}$ = Initial Deposition, the areal activity of radionuclide *i* at the time of deposition t_0, µCi/m^2;

λ_i = Decay constant for radionuclide *i*, s^{-1};

This simplifies to:

$$WP_{i,TP} = Dp_{i,t_0} * \int_{t_1}^{t_2} \begin{bmatrix} 0.4 * e^{\left(-t*(\lambda_i + 1.46\text{E-}08)\right)} \\ + 0.6 * e^{\left(-t*(\lambda_i + 4.44\text{E-}10)\right)} \end{bmatrix} dt \quad \text{(Eq. 6b)}$$

Integrating over the time phase under consideration yields the following:

$$WP_{i,TP} = Dp_{i,t_0} * \begin{bmatrix} \frac{0.4*\left(e^{\left(-t_2*(\lambda_i+1.46\text{E-}08)\right)} - e^{\left(-t_1*(\lambda_i+1.46\text{E-}08)\right)}\right)}{-(\lambda_i+1.46\text{E-}08)} \\ + \frac{0.6*\left(e^{\left(-t_2*(\lambda_i+4.44\text{E-}10)\right)} - e^{\left(-t_1*(\lambda_i+4.44\text{E-}10)\right)}\right)}{-(\lambda_i+4.44\text{E-}10)} \end{bmatrix} \quad \text{(Eq. 6c)}$$

$$\frac{\mu\text{Ci}\cdot\text{s}}{\text{m}^2} = \frac{\mu\text{Ci}}{\text{m}^2} * \begin{bmatrix} \frac{\text{unitless}*\text{unitless}}{\text{s}^{-1}} \\ + \frac{\text{unitless}*\text{unitless}}{\text{s}^{-1}} \end{bmatrix}$$

Calculations for daughters may be performed in the same manner by substituting the appropriate Bateman equation (Found in Appendix F – Supplement 1) for ($Dp_{i,t0}*e^{-\lambda t}$) in the equations above.

SUPPLEMENT 3 – 1992 EPA PAG MANUAL CROSSWALK

The 1992 EPA PAG Manual provided tabulated data that was useful to many users. The revised PAG Manual does not contain the data, but refers the user to the FRMAC Assessment Manual. This manual attempts to provide similar data based on updated methodologies.

Tables 5-1 through 5-5 and Tables 7-1 through 7-4 in the 1992 EPA PAG Manual are based on the ICRP 23/26/30 dosimetry models. This manual is based on the ICRP 60+ dosimetry models that are currently endorsed by the EPA.

FRMAC uses a default Evaluation Time for DRL calculations of 12 hours after the start of the release, allowing atmospheric dispersion models to simulate 12 hours of downwind transport. This was chosen because 12 hours is generally sufficient for complete deposition of a single release to occur so that deposition contours can be plotted on data products. In other scenarios (e.g., a protracted Power Plant accident) this may not be appropriate and other assumptions will be required.

Tables in this manual are based on the FRMAC default Evaluation Time of 12 hours (except where noted).

Values calculated in the 1992 EPA PAG Manual were based on an Evaluation Time equal to the time of release. Because of this, significant differences may exist between this manual and the 1992 EPA PAG Manual for radionuclides with short half-lives.

The Tables below provide a crosswalk from the 1992 PAG Manual to the FRMAC Assessment Manual.

NOTE: The calculated values for dose per unit activity over a Time Phase were called Dose Conversion Factors (DCF) in the 1992 PAG Manual and are called Dose Parameters (DP) in the FRMAC Assessment Manual.

General		
EPA 1992	**EPA 2017**	**FRMAC Assessment Manual**
Table 2-1: PAGs for Early Phase	Table 2-1	Table 2-1
Table 2-2: Worker Guidance	Table 2-2	Table 2-2
Table 4-1: PAGs for Intermediate Phase	Table 3-1	Table 2-1

Early Phase		
EPA 1992	**EPA 2017**	**FRMAC Assessment Manual**
Table 5-1: Dose Conversion Factors and DRLs	NA	Table 4-2b “DCF Equivalents” [a] and DRLs
Table 5-2: DCF & DRL corresponding to 5 rem Thyroid (Adult) – ICRP30	NA	Table 5-1 (Child) Table 5-2 (Adult) Thyroid DPs and DRLs.
Table 5-3: DCFs & DRL for External Exposure – Immersion	NA	DCF = Table 4-1 Pl_ExDP DRL = PAG/Pl_ExDP
Table 5-4: DCFs & DRL for Plume Inhalation	NA	DCF = Table 4-1 Pl_InhDP DRL = PAG/Pl_InhDP
Table 5-5: DCFs & DRL for Groundshine	NA	0-96 h, Table 4-2a 12-108 h, Table 4-3a DCF = Dp_ExDP DRL = PAG/Dp_ExDP
[a] The “DCF Equivalent” value is the Dose Parameter per unit of the radionuclide for all four Primary Dose Pathways. This includes the dose from the plume and a 0-96 hour exposure to deposited material and is analogous to the 3-Pathway DCF in Table 5-1 of the 92 PAG Manual. Values are presented in both deposition units (mrem·m^2/µCi) and integrated air units (mrem·m^3/µCi·s) in Table 4-2b.		

Intermediate Phase		
EPA 1992	**EPA 2017**	**FRMAC Assessment Manual**
Table 7-1: Gamma Exposure Rate and Effective Dose Equivalent (Weathering Included)	NA	Initial Exposure Rate = Table 1, Dp_ExDF Year one = Table 4-4a, Dp_ExDP Year two = Table 4-5a, Dp_ExDP 50 Year = Table 4-6a, Dp_ExDP
Table 7-2: Gamma Exposure Rate and Effective Dose Equivalent (Weathering Not Included)	NA	The default FRMAC assumption is to include weathering. Turbo FRMAC can “turn off” weathering to duplicate this calculation.
Table 7-3: Example Calculation based on Measured Concentration	NA	Use methodology described in 92 PAG Table 7-3 using values specified for conversion from Table 7-1.
Table 7-4: DCFs for Resuspension Inhalation	NA	Year one = Table 4-4a, Dp_InhDP Year two = Table 4-5a, Dp_InhDP

SUPPLEMENT 4 – RADIONUCLIDES WITH MULTIPLE CHEMICAL/ PHYSICAL FORMS

As a default approach FRMAC considers all radionuclides to be present in the particulate physical form. However, if incident-specific information indicates that one or more radionuclides may exist in different chemical/physical forms, they should be modeled accordingly. Inhalation and ingestion dose coefficients have been developed for a limited set of radionuclides that can be present in one or more forms (e.g., gas, vapor) in addition to the particulate form.

When performing radiological assessment including any of these nuclides, the 100% particulate assumption may not be appropriate. The Assessment Scientist should remain aware of the radionuclides that may exist in multiple chemical/physical forms and apply the correct dose coefficients based upon predetermined defaults and event-specific knowledge.

F.4. Inhalation

Radionuclides that may exist in gas or vapor chemical/physical forms, in addition to a particulate form, and have corresponding inhalation dose coefficients include:

Carbon	Carbon Monoxide (CO) Carbone Dioxide (CO_2)
Hydrogen	Tritiated Water Vapor (HTO) Elemental Tritium (HT) Organically Bound Tritium
Iodine	Iodine Vapor Methyl Iodide (CH_3I)
Mercury	Mercury Vapor
Nickel	Nickel Vapor
Ruthenium	Ruthenium Vapor
Sulfur	Sulfur Dioxide ($S0_2$) Carbon Disulfide (CS_2)
Tellurium	Tellurium Vapor

F.5. Ingestion

Some radionuclides have been assigned specific ingestion dose coefficients based on their chemical/physical forms, including:

Hydrogen	Organically Bound Tritium Tritiated Water Vapor (HTO)
Mercury	Inorganic Methyl Organic
Polonium	Inorganic Organic

F.6. Default Assumptions for Nuclear Power Plant Releases

- Iodine released from a nuclear power plant under accident conditions is an important example of a radionuclide that exists in multiple chemical/physical forms. When modeling a NPP release, to be consistent with NRC methodology (NUREG-1940), the FRMAC default approach is to partition the total iodine released as follows:

Form	Partition	V_d m/s
Methyl Iodide/Non-reactive Gas (CH_3I)	45%	0
Iodine Vapor/Reactive Gas (I_2)	30%	6.4E-03
Particulate	25%	6.5E-03

For resuspension dose calculations, all deposited Iodine Vapor/Reactive Gas is assumed to be converted to 1-micron particulate.

- Tritium released from a nuclear power plant under accident conditions should be modeled as existing in the Tritiated Water Vapor (HTO) form with a deposition velocity (V_d) of 0.0 m/s to be consistent with the NRC.

APPENDIX G. REFERENCES

Reference	Title
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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.
EPA11	*Exposure Factors Handbook*, EPA/600/R-090/052F, U.S. Environmental Protection Agency, Washington, DC, September 2011.
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APPENDIX H. CHANGE HISTORY

The May 2023 FRMAC Assessment Manual contains the following changes from the previous (July 2020) version:

1. New Preface added.
2. GLOBAL: Cross-references and hyperlinks updated.
3. Table of Contents (main and sub): hyperlinks added to all sections for easier navigation of document.
4. Appendices: new Headings added.

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