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**FEDERAL RADIOLOGICAL
MONITORING AND ASSESSMENT CENTER**

FRMAC ASSESSMENT MANUAL

VOLUME 1

OVERVIEW AND METHODS

The Federal Manual for Assessing Environmental Data During a Radiological Emergency

December 2012

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FRMAC Assessment Manual

Overview and Methods

Volume 1

December 2012

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

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PREFACE

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

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

The primary purposes of this volume are:

- To define the technical methods for performing radiological assessment.
- To serve as the scientific basis for the Turbo FRMAC© software.

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

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

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

Users are urged to update their manual as appropriate.

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

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

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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 the Change History document with the date of this Volume for a list of changes made from the previous version.

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

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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
CDC	Centers for Disease Control and Prevention
CED	Committed Effective Dose
DCFPAK	Dose Coefficient Package
DHS	US Department of Homeland Security
DIL	Derived Intervention Level
DOE	US Department of Energy
DRL	Derived Response Level
EPA	US Environmental Protection Agency
FDA	US Food and Drug Administration
FRMAC	Federal Radiological Monitoring and Assessment Center
ICRP	International Commission on Radiological Protection
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

OVERVIEW

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Introduction

The Federal Radiological Monitoring and Assessment Center (FRMAC) Assessment Manual is the tool used to organize and guide activities of the FRMAC Assessment Division. 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.

This manual:

1) Is intended for use by trained FRMAC Assessment Scientists. It is the basis for training FRMAC Assessment Scientists in standard FRMAC technical methods, and defines the standard technical methods used when responding to radiological incidents.
2) Represents the technical consensus of multiple federal agencies with expertise in and authority over aspects of radiological emergency response.
3) Defines Methods to make many different radiological assessment calculations based on default assumptions agreed upon by the interagency FRMAC Assessment Working Group as being most applicable to a wide variety of conditions. These default assumptions may or may not be appropriate for a specific incident.
4) Frequently uses the word "would" to define the result of the calculation, and it is important to be aware that this result is based on the established default assumptions. Should circumstances of the specific incident be different than the default assumptions, the predicted results may not reflect actual conditions. It is recommended that assessors obtain real-world data as soon as possible to validate the predictions made by the Methods in this Manual.
5) Is only intended to address the early and intermediate phases of a radiological incident. It does not address 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 Assessment Working Group 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. 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), ALL of the 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 International Commission on Radiological Protection (ICRP) 60+ dosimetry model based on agreement with the EPA. ICRP 60+ refers to ICRP 60 (ICRP90) and the collection of ICRP documents relating to the ICRP 60 dosimetry model published subsequently. ICRP 60+ terminology is used throughout the manual.

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.

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

Section 1 – Public Protection;
Section 2 – Emergency Worker Protection;
Section 3 – Ingestion Pathway Analysis; and,
Section 4 – Supplemental Methods.

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

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

Volume 2 provides analyses for pre-assessed scenarios. These default scenarios include:

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

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

Overview of Assessment

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

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

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

Assessment Objectives

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

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

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

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

Manual Objectives

The objectives of the FRMAC Assessment Manual are:

- Provide technical basis for assessments

  The manual describes each assessment method in detail, provides references to scientific publications and guidance documents, and specifies the assumptions used.

- Provide technical basis for the Turbo FRMAC© Software Package

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

- Document the assessment process

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

- Function as an orientation and training guide for Assessment Division members

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

- Provide Federal family consensus

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

Utilization

Using this Manual

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

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

PARs and PAGs are defined in the EPA's Protective Action Guides and Planning Guidance for Radiological Incidents (EPA PAG Manual) (EPA13).

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

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

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

Using Data Products

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

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

- The **PAG Zone Maps** indicate where particular PAGs might be exceeded. Initially, the PAG Zone Maps are based only on atmospheric dispersion modeling predictions. The FRMAC utilizes the DOE's National Atmospheric Release Advisory Center (NARAC) to predict the downwind dispersion of radiological material. The maps are updated as monitoring and sampling measurements become available.

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

In addition, other data products may be developed to meet specific needs as the incident progresses.

Data products are created as “drafts” or “preliminary” during the Assessment process and may precede approved products by a significant period of time. Draft or preliminary products are not available for release outside of the FRMAC because their quality cannot be assured. Representatives of other FRMAC Divisions, Federal Agencies, the Advisory Team, or local governmental authorities may have access to the draft or preliminary products within the FRMAC. This information may be used to relay progress of monitoring and sampling or developing trends to counterparts.

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

Differences between FRMAC approach and other published guidance

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

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

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

SECTION 1. PUBLIC PROTECTION METHODS

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Introduction to Public Protection Methods

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

DRLs are levels of radioactivity in an environmental medium (i.e., the ground) that would be expected to produce a dose equal to the corresponding PAG (EPA13). DRLs are values which can be measured (e.g., $\mu Ci/m^2$ or mrem/hr) 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)
    - External exposure from plume submersion
    - Inhalation of plume-borne material
- Ground Pathways (deposited material)
    - External exposure from groundshine
    - Inhalation of resuspended material

Methods in this section may be performed in two ways.

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

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 these two options should be performed. When there is uncertainty about the circumstances, the Four-Pathway option 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 and Decision Makers endorse their use.

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

1) The dose projections from this section may include contributions from either two or four exposure pathways:
   a. Two-Pathway (2Path) Assessment includes the ground pathways:
      i. external exposure (groundshine) from material deposited by the release, and
      ii. inhalation of resuspended material deposited by the release.
   b. Four-Pathway (4Path) Assessment includes plume and ground pathways:
      i. the pathways from Two-Pathway Assessment above, plus
      ii. external exposure (plume submersion) during plume passage, and
      iii. inhalation of radioactive material during plume passage.
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.
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.)
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:
    a. outside in the contaminated area continuously during the time phase under consideration without any protective measures (e.g., shielding or respiratory protection);
    b. an adult;
    c. inhaling 1-micron Activity Median Aerodynamic Diameter (AMAD) particles in the lung clearance class which provides the maximum dose.

    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.
9) The Bateman Equations (Ba1910) are used to model the decay and in-growth of all radionuclides. See Appendix F, Supplement 1 for details.
10) FRMAC's public protection methods generally assume that the organ of interest is the whole body (Total Effective Dose). However, other organs may be evaluated against PAGs by utilizing the organ-specific Dose Coefficients and PAGs. (See Method 1.1 Example 1, Section E1.8.)

Default Inputs

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

1) Data – This information may come from predictive analysis (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/hr for inhalation of resuspended material and Light-Exercise Breathing Rate of 1.5 m^3/hr for in-plume inhalation based on the ICRP 60+ lung model);
   - Inhalation dose coefficient (defaults from ICRP 60+ dosimetry model);
   - External dose coefficient (defaults from ICRP 60+ dosimetry model);
   - Dose limits (e.g., PAGs – defaults from EPA/DHS guidance); and
   - Exposure to Dose conversion factor (default of 1.0 mrem/mR).

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

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

   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.)

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 (4Path_DRL$_{\tilde{A}}$ or 2Path_DRL$_{\tilde{A}}$) or areal activity (4Path_DRL$_{Dp}$ or 2Path_DRL$_{Dp}$).

The 4Path_DRL$_{\tilde{A}}$ and 2Path_DRL$_{\tilde{A}}$:

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

The 4Path_DRL$_{Dp}$ and 2Path_DRL$_{Dp}$:

> Represent 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 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) (EPA13) 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 4Path_DRL$_{\tilde{A}}$:

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

from plume-borne materials and from material deposited on the ground and relates the combined dose to the PAG.
3) Is based on the ratio of activities of each radionuclide in a release, not the individual activity values of those radionuclides.

The 4Path_DRL$_{Dp}$:

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

The 2Path_DRL$_{\tilde{A}}$:

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

The 2Path_DRL$_{Dp}$:

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

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

NOTE: Because different elements and chemical 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 and Decision Makers endorse their use.

Outputs

Final

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

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

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

$2Path\_DRL_{\tilde{A}}$ = Two-Pathway Air Derived Response Level, the integrated air activity ($\tilde{A}$) of radionuclide *i* at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration, (μCi•s/m³).

$2Path\_DRL_{Dp}$ = Two-Pathway Deposition Derived Response Level, the areal activity, at time t_n, of radionuclide *i* at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration, (μCi/m²).

Intermediate

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

2Path_MTDP = Two-Pathway Mixture Total Dose Parameter for all radionuclides (mrem)
4Path_MTDP = Four-Pathway Mixture Total Dose Parameter for all radionuclides (mrem)
Dp_ExDP = Deposition External Dose Parameter for each radionuclide (mrem)
Dp_InhDP = Deposition Inhalation Dose Parameter for each radionuclide (mrem)
Dp_TDP = Deposition Total Dose Parameter for each radionuclide (mrem)
Pl_ExDP = Plume External Dose Parameter for each radionuclide (mrem)
Pl_InhDP = Plume Inhalation Dose Parameter for each radionuclide (mrem)
Pl_TDP = Plume Total Dose Parameter for each radionuclide (mrem)

Calculation

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

1) Four-Pathway Air Derived Response Level

Equation 1.1-1 shows the final form of the $4Path\_DRL_{\tilde{A}}$ calculation:

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

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

where:

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

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

2) Four-Pathway Deposition Derived Response Level

Equation 1.1-2 shows the final form of the 4Path_DRL$_{Dp}$ calculation:

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

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

where:

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

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

3) Two-Pathway Air Derived Response Level

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

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

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

where:

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

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

4) Two-Pathway Deposition Derived Response Level

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

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

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

where:

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

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

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

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

The critical factors in determining the DRLs are the Plume Total Dose Parameter (Pl_TDP) and Deposition Total Dose Parameter (Dp_TDP) for each radionuclide in a release.

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

- the Plume Inhalation Dose Parameter (Pl_InhDP) and
- the Plume External Dose Parameter (Pl_ExDP).

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

- the Deposition Inhalation Dose Parameter (Dp_InhDP) and
- the Deposition External Dose Parameter (Dp_ExDP).

1.1.1 Calculating the Plume Total Dose Parameter

The Pl_TDP is calculated using Equation 1.1-5.

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

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

where:

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

The following sections show how to calculate the components of the Pl_TDP.

1.1.1.1 Calculating the Plume Inhalation Dose Parameter

(Plume Inhalation Pathway)

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

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

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

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;
- $\tilde{A}_i$ = 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/hr).

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

1.1.1.2 Calculating the Plume External Dose Parameter (Submersion Exposure Pathway)

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

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

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

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•m³/µCi•s; and

$\tilde{A}_i$ = Integrated air activity of radionuclide *i* in a release, µCi•s/m³.

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

1.1.2 Calculating the Deposition Total Dose Parameter

The Dp_TDP is calculating using Equation 1.1-8.

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

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

where:

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

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

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

The following sections show how to calculate the components of the Dp_TDP.

1.1.2.1 Calculating the Deposition Inhalation Dose Parameter

(Resuspension Inhalation Pathway)

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

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

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

where:

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

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

$KP_{i,\,TP}$ = 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), µC•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/hr).

1.1.2.2 Calculating the Deposition External Dose Parameter

(Groundshine Exposure Pathway)

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

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

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

where:

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

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

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

1.2 Calculating the Mixture Total Dose Parameters

1.2.1 Calculating the Four-Pathway Mixture Total Dose Parameter

The Four-Pathway Mixture Total Dose Parameter (4Path_MTDP) includes the dose contributions from the plume-borne and ground-deposited radionuclide mixture, and is calculated by adding the Pl_TDPs and Dp_TDPs for each radionuclide in the mixture.

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

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

where:

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

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

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

1.2.2 Calculating the Two-Pathway Mixture Total Dose Parameter

The Two-Pathway Mixture Total Dose Parameter (2Path_MTDP) includes the dose contributions from the ground-deposited radionuclide mixture, and is calculated by summing the Dp_TDPs for each radionuclide in the mixture.

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

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

where:

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

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

1.3 Comparing the MTDP to the PAG to Calculate DRLs

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

1.3.1 Four-Pathway Air Derived Response Level (4Path_DRL$_{\tilde{A}}$)

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

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

where:

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

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

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

1.3.2 Four-Pathway Deposition Derived Response Level (4Path_DRL$_{Dp}$)

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

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

where:

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

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

1.3.3 Two-Pathway Air Derived Response Level (2Path_DRL$_{\tilde{A}}$)

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

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

where:

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

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

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

1.3.4 Two-Pathway Deposition Derived Response Level (2Path_DRL$_{Dp}$)

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

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

where:

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

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

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EXAMPLE 1

Problem: Calculate the Total Effective Dose Four-Pathway 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.

Table 1.1-E1

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

The default Early Phase (Total Dose) Time Phase includes all four Dose Pathways. To determine the 4Path_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)
Dp_TDP = Deposition Total Dose Parameter for each radionuclide (mrem)
Pl_ExDP = Plume External Dose Parameter for each radionuclide (mrem•m^3/µCi•s)
Pl_InhDP = Plume Inhalation Dose Parameter for each radionuclide (mrem•m^3/µCi•s)
Pl_TDP = Plume Total Dose Parameter for each radionuclide (mrem•m^3/µCi•s)

The Pl_TDP is then added to the Dp_TDP for each radionuclide to calculate the Four-Pathway Mixture Total Dose Parameter (4Path_MTDP).

NOTE: Values calculated using Turbo FRMAC© may differ from the values shown in this example because of truncation or rounding.

E1.1 Calculating Pl_InhDP (Equation 1.1-6)

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

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

Table 1.1.E2

Radionuclide	InhDC [a] (mrem/μCi)	Integrated Air Activity (μCi•s/m^3)	Breathing Rate (Light Exercise) [b] (m^3/s)	Pl_InhDP (mrem)
Co-60	1.14E+02	6.67E+02	4.17E-04	3.17E+01
Gd-148	9.55E+04	3.33E+02	4.17E-04	1.33E+04
Sr-90	5.81E+02	1.00E+03	4.17E-04	2.42E+02
Y-90	5.55E+00	1.00E+03	4.17E-04	2.31

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

[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 1.1-7)

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.

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

Table 1.1-E3

Radionuclide	Pl_ExDC [a] (mrem•m^3/μCi•s)	Integrated Air Activity (μCi•s/m^3)	Pl_ExDP (mrem)
Co-60	4.40E-04	2.0E+03	2.93E-01
Gd-148	0	1.0E+03	0
Sr-90	3.64E-07	3.0E+03	3.64E-04
Y-90	2.93E-06	3.0E+03	2.93E-03

[a] Values from DCFPAK 2.0 (ICRP 60+).

E1.3 Calculating Dp_InhDP (Equation 1.1-9)

This calculation requires the Inhalation Dose Coefficient (InhDC), the Activity-Averaged Breathing Rate (BR_{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.

$$KP_{\text{Co-60}} = 2\frac{\mu\text{Ci}}{\text{m}^2} * \left[\frac{1.0\text{E-05} * \left(e^{(-3.46\text{E+05}*(4.17\text{E-09}+8.1\text{E-07}))} - e^{(-0*(4.17\text{E-09}+8.1\text{E-07}))}\right)}{-(4.17\text{E-09}+8.1\text{E-07})} + \frac{7.0\text{E-09} * \left(e^{(-3.46\text{E+05}*(4.17\text{E-09}+2.31\text{E-08}))} - e^{(-0*(4.17\text{E-09}+2.31\text{E-08}))}\right)}{-(4.17\text{E-09}+2.31\text{E-08})} + \frac{1.0\text{E-09} * \left(e^{(-3.46\text{E+05}*(4.17\text{E-09}))} - e^{(-0*(4.17\text{E-09}))}\right)}{-(4.17\text{E-09})} \right] \frac{\text{s}}{\text{m}}$$

$$= 6.03 \frac{\mu\text{Ci}\bullet\text{s}}{\text{m}^3}$$

Table 1.1-E4

Radionuclide	Deposition (μCi/m^2)	λ_i (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 [a]
Gd-148	1	2.36E-10	0	3.46E+05	3.02 [a]
Sr-90	3	7.54E-10	0	3.46E+05	9.05 [a]
Y-90	3	3.01E-06	0	3.46E+05	9.05 [b]

[a] Values approximated using equations in Appendix F, Supplement 2.
[b] Value from Turbo FRMAC 2011©. 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.

$$Dp\_InhDP_{\text{Co-60}} = 1.14\text{E+02}\frac{\text{mrem}}{\mu\text{Ci}} * 6.03\frac{\mu\text{Ci}\bullet\text{s}}{\text{m}^3} * 2.56\text{E-04}\frac{\text{m}^3}{\text{s}} = 1.76\text{E-01}\,\text{mrem}$$

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	1.14E+02	6.03	2.56E-04	1.76E-01
Gd-148	9.55E+04	3.02	2.56E-04	7.38E+01
Sr-90	5.81E+02	9.05	2.56E-04	1.35
Y-90	5.55E+00	9.05 [c]	2.56E-04	1.29E-02

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

E1.4 Calculating Dp_ExDP (Equation 1.1-10)

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

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

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

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

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

Table 1.1-E6

Radionuclide	Deposition (µCi/m²)	λ_i (s^{-1})	t_1 (s)	t_2 (s)	WP_i – EP(TD) (µCi•s/m²)
Co-60	2	4.17E-09	0	3.46E+05	6.90E+05 [a]
Gd-148	1	2.36E-10	0	3.46E+05	3.45E+05 [a]
Sr-90	3	7.54E-10	0	3.46E+05	1.04E+06 [a]
Y-90	3	3.01E-06	0	3.46E+05	1.04E+06 [b]

[a] Values approximated using equations in Appendix F, Supplement 2.
[b] Value from Turbo FRMAC 2011©. 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.

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

Table 1.1-E7

Radionuclide	Dp_ExDC [a] (mrem•m²/s•µCi)	GRF (unitless)	WP_i – EP(TD) (µCi•s/m²)	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 2.0 (ICRP 60+).
[b] Value from Turbo FRMAC 2011©.

E1.5 Calculating Pl_TDP and Dp_TDP (Eq 1.1-5 &1.1-8)

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

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

$$Dp\_TDP_{^{60}Co} = 1.76\text{E-01 mrem} + 4.81\text{ mrem} = 4.99\text{ mrem}$$

Table 1.1-E8

Radionuclide	Pl_InhDP (mrem)	Pl_ExDP (mrem)	Pl_TDP (mrem)	Dp_InhDP EP(TD) (mrem)	Dp_ExDP EP(TD) (mrem)	Dp_TDP EP(TD) (mrem)
Co-60	3.17E+01	2.93E-01	**3.20E+01**	1.76E-01	4.81	**4.99**
Gd-148	1.33E+04	0.00E+00	**1.33E+04**	7.38E+01	0	**7.38E+01**
Sr-90	2.42E+02	3.64E-04	**2.42E+02**	1.35	5.15E-03	**1.35**
Y-90	2.31E+00	2.93E-03	**2.32**	1.29E-02	3.47E-01	**3.60E-01**

E1.6 Calculating 4Path_MTDP (Equation 1.1-11)

The Four-Pathway Mixture Total Dose Parameter (4Path_MTDP) includes the dose contributions from the plume-borne and ground-deposited radionuclide mixture, and is calculated by adding the Pl_TDPs and Dp_TDPs for each radionuclide in the mixture.

Table 1.1-E9

Radionuclide	Pl_TDP (mrem)	Dp_TDP EP(TD) (mrem)
Co-60	3.20E+01	4.99
Gd-148	1.33E+04	7.38E+01
Sr-90	2.42E+02	1.35
Y-90	2.32	3.60E-01
4Path_MTDP (mrem)		**1.36E+04**

E1.7 Calculating the Four-Pathway Derived Response Levels

E1.7.1 Calculating 4Path_DRL$_{\tilde{A}}$ (Equation 1.1-1)

Example 4Path_DRL$_{\tilde{A}}$ calculation for Co-60 and 4Path_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 = 1000 mrem
4Path_MTDP = 1.36E+04 mrem

$$4Path\_DRL_{\tilde{A}_{^{60}Co}} = \frac{1000\,\text{mrem} * 6.67\text{E+02}\,\frac{\mu\text{Ci•s}}{\text{m}^3}}{1.36\text{E+04 mrem}} = 4.89\text{E+01}\,\frac{\mu\text{Ci•s}}{\text{m}^3}$$

This means that a Co-60 Integrated Air Activity of 48.9 μCi•s/m^3 in the plume would indicate that the entire mixture has the potential to cause a Four-Pathway Total Effective Dose (Internal + External) over the Early Phase equal to the PAG of 1000 mrem.

Table 1.1-E10

Radionuclide	Integrated Air Activity (µCi•s/m³)	EP(TD) 4Path_DRL$_{\tilde{A}}$ [a] (µCi•s/m³)
Co-60	6.67E+02	**4.89E+01**
Gd-148	3.33E+02	**2.45E+01**
Sr-90	1.0E+03	**7.34E+01**
Y-90	1.0E+03	**7.34E+01**

[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 4Path_DRL$_{Dp}$ (Equation 1.1-2)

Example 4Path_DRL$_{Dp}$ calculation for Co-60 and 4Path_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
4Path_MTDP = 1.36+04 mrem

$$4Path\_DRL_{Dp_{^{60}Co}} = \frac{1000\,\text{mrem} * \left(2\frac{\mu\text{Ci}}{\text{m}^2} * e^{-4.17\text{E-}09*(12*3600)}\right) * 0.9997}{1.36\text{E+04 mrem}} = 1.47\text{E-01}\ \frac{\mu\text{Ci}}{\text{m}^2}$$

This means that a Co-60 Areal Activity of 0.147 µCi/m^2 12 hours after deposition would indicate that the entire mixture has the potential to cause a Four-Pathway Total Effective Dose (Internal + External) over the Early Phase equal to the PAG of 1000 mrem.

Table 1.1-E11

Radionuclide	Dp$_{i,t0}$ (µCi/m²)	WF$_{12\ hrs}$ [a] (unitless)	EP(TD) 4Path_DRL$_{Dp}$ (µCi/m²)
Co-60	2	0.9997	**1.47E-01**
Gd-148	1	0.9997	**7.33E-02**
Sr-90	3	0.9997	**2.20E-01**
Y-90	3	0.9997	**2.20E-01**

[a] $WF_{12\text{ hours}} = 0.4 * e^{-1.46\text{E-}08*(12*3600)} + 0.6 * e^{-4.44\text{E-}10*(12*3600)} = 0.9997$

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

E1.8 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 Two-Pathway Deposition DRL for the First-Year Time Phase (12-8772 hours) for the Following Mixture for an Evaluation Time (t_n) of 12 hours.

Table 1.1-E12

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

To determine the $2Path\_DRL_{Dp}$, 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)
Dp_TDP = Deposition Total Dose Parameter for each radionuclide (mrem)

The Dp_TDP for each radionuclide are then added to calculate the Two-Pathway Mixture Total Dose Parameter (2Path_MTDP).

NOTE: Values calculated using Turbo FRMAC© may differ from the values shown in this example because of truncation or rounding.

E2.1 Calculating Dp_InhDP (Equation 1.1-9)

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.

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

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

Table 1.1-E13

Radionuclide	Deposition (μCi/m^2)	λ_i (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 [a]
Gd-148	1	2.36E-10	4.32E+04	3.16E+07	1.21E+01 [a]
Sr-90	3	7.54E-10	4.32E+04	3.16E+07	3.63E+01 [a]
Y-90	3	3.01E-06	4.32E+04	3.16E+07	3.62E+01 [b]

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

E2.1.2 Calculating the Dp_InhDP

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

$$Dp\_InhDP_{\text{Co-60}} = 1.14\text{E+02}\,\frac{\text{mrem}}{\mu\text{Ci}} * 2.41\text{E+01}\,\frac{\mu\text{Ci}\bullet\text{s}}{\text{m}^3} * 2.56\text{E-04}\,\frac{\text{m}^3}{\text{s}} = 7.02\text{E-01}\,\text{mrem}$$

Table 1.1-E14

Radionuclide	InhDC [a] (mrem/μCi)	KP_i – First Year (μCi•s/m³)	Breathing Rate (Activity-averaged) [b] (m³/s)	Dp_InhDP First Year (mrem)
Co-60	1.14E+02	2.41E+01	2.56E-04	7.02E-01
Gd-148	9.55E+04	1.21E+01	2.56E-04	2.96E+02
Sr-90	5.81E+02	3.63E+01	2.56E-04	5.40
Y-90	5.55E+00	3.62E+01 [c]	2.56E-04	5.14E-02

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

E2.2 Calculating Dp_ExDP (Equation 1.1-10)

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

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

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

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

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

Table 1.1-E15

Radionuclide	Deposition (μCi/m^2)	λ_i (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 [a]
Gd-148	1	2.36E-10	4.32E+04	3.16E+07	2.88E+07 [a]
Sr-90	3	7.54E-10	4.32E+04	3.16E+07	8.57E+07 [a]
Y-90	3	3.01E-06	4.32E+04	3.16E+07	8.57E+07 [b]

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

E2.2.2 Calculating the Dp_ExDP

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

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

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 2.0 (ICRP 60+).
[b] Value from Turbo FRMAC 2011©.

E2.3 Calculating Dp_TDP (Eq. 1.1-8)

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

$$Dp\_TDP_{^{60}Co} = 7.02\text{E-01 mrem} + 3.78\text{E+02 mrem} = 3.79\text{E+02 mrem}$$

Table 1.1-E17

Radionuclide	Dp_InhDP First Year (mrem)	Dp_ExDP First Year (mrem)	Dp_TDP First Year (mrem)
Co-60	7.02E-01	3.78E+02	**3.79E+02**
Gd-148	2.96E+02	0	**2.96E+02**
Sr-90	5.40	4.26E-01	**5.82**
Y-90	5.14E-02	2.86E+01	**2.87E+01**

E2.4 Calculating 2Path_MTDP (Equation 1.1-12)

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

Table 1.1-E18

Radionuclide	Dp_TDP First Year (mrem)
Co-60	3.79E+02
Gd-148	2.96E+02
Sr-90	5.82
Y-90	2.87E+01
2Path_MTDP =	**7.10E+02**

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

Example 2Path_DRL$_{Dp}$ calculation for Co-60 and 2Path_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
2Path_MTDP = 7.10E+02 mrem

$$2Path\_DRL_{Dp_{60_{Co}}} = \frac{2000\,\text{mrem} * \left(2\,\frac{\mu\text{Ci}}{\text{m}^2} * e^{-4.17\text{E-}09*(12*3600)}\right) * 0.9997}{7.10\text{E+}02\ \text{mrem}} = 5.64\ \frac{\mu\text{Ci}}{\text{m}^2}$$

This means that a Co-60 Areal Activity of 5.64 µCi/m^2 12 hours after deposition would indicate that the entire mixture has the potential to cause a Two-Pathway Total Effective Dose (Internal + External) over the First Year equal to the PAG of 2000 mrem.

Table 1.1-E19

Radionuclide	$Dp_{i,t0}$ (µCi/m^2)	WF_{tn} (unitless)	1st Year 2Path_DRL$_{Dp}$ (µCi/m^2)
Co-60	2	0.9997	**5.64**
Gd-148	1	0.9997	**2.82**
Sr-90	3	0.9997	**8.45**
Y-90	3	0.9997	**8.45**

[a] $WF_{12\text{ hours}} = 0.4 * e^{-1.46\text{E-}08*(12*3600)} + 0.6 * e^{-4.44\text{E-}10*(12*3600)} = 0.9997$

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

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 both Four-Pathway (4Path) and Two-Pathway (2Path) assessments of a radionuclide mixture.

The Dose Rate DRLs ($4Path\_DRL_{DR}$ and $2Path\_DRL_{DR}$):

> Represent the external dose rate (mrem/hr, 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 ($4Path\_DRL_{XR}$ and $2Path\_DRL_{XR}$):

> Represent the external exposure rate (mR/hr, 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) (EPA13), the Department of Homeland Security (DHS) (DHS08) or local Decision Makers. A projected or measured value greater than the DRL indicates the potential to exceed the PAG.

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

3) Calculated using the appropriate Mixture Total Dose Parameter (4Path or 2Path) value from Method 1.1.

Discussion

The $4Path\_DRL_{DR}$ and $4Path\_DRL_{XR}$:

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

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

The $2Path\_DRL_{DR}$ and $2Path\_DRL_{XR}$:

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

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

Assumptions

The following assumptions apply in addition to the Default Assumptions:

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

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

Inputs

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

Four-Pathway Mixture Total Dose Parameter (4Path_MTDP) – Calculated using Method 1.1, Section 1.2.1.

or

Two-Pathway Mixture Total Dose Parameter (2Path_MTDP) – Calculated using Method 1.1, Section 1.2.2.

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

Outputs

Final

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

$4Path\_DRL_{DR}$ = Four-Pathway 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 (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration (*TP*), mrem/hr.

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

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

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

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

Intermediate

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

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

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

Calculation

The Dose Rate DRL relates a dose rate measurement from a survey instrument 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 progeny in equilibrium. Therefore the user is urged to use a computer code, such as Turbo FRMAC©, to complete these calculations.

1.2.1.1 Calculating the Four-Pathway Dose Rate DRL

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

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

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

where:

$4Path\_DRL_{DR,\,tn,\,TP}$ = Four-Pathway 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 (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration (*TP*), mrem/hr;

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

Dp_MExDF_{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/hr; and

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

1.2.1.2 Calculating the Two-Pathway Dose Rate DRL

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

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

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

where:

$2Path\_DRL_{DR,\,tn,\,TP}$ = Two-Pathway 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 (considering only ground dose pathways) would equal the PAG over the time phase under consideration (*TP*), mrem/hr;

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

Dp_MExDF_{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/hr; and

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

1.2.1.3 Calculating the Deposition Mixture External Dose Factor

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

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

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

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/hr;

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•hr.

1.2.1.4 Comparing the Dp_MExDF to the PAG to Calculate DRLs

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

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

or

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

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

where:

$4Path\_DRL_{DR,\,tn,\,TP}$ = Four-Pathway 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 (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration (*TP*), mrem/hr;

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

Dp_MExDF_{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/hr;

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

$2Path\_DRL_{DR,\,tn,\,TP}$ = Two-Pathway 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 (considering only ground dose pathways) would equal the PAG over the time phase under consideration (*TP*), mrem/hr; and

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

Method 1.2.2 Exposure Rate Derived Response Levels ($4Path\_DRL_{XR}$ and $2Path\_DRL_{XR}$)

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

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

or

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

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

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Example 1

Problem: Calculate the Total Effective Dose Four-Pathway Dose Rate DRL for the Early Phase (Total Dose) Time Phase (0-96 hours) for the Following Mixture for an Evaluation Time (t_n) of 12 hours.

Table 1.2-E1

Radionuclide	Deposition (µCi/m²)	$t_{1/2}$ (s)
Co-60	2	1.66E+08
Gd-148	1	2.93E+09
Sr-90	3	9.19E+08
Y-90	3	2.30E+05

To determine the $4Path\_DRL_{DR}$, the intermediate term for the Deposition Mixture External Dose Factor (Dp_MExDF) must first be calculated.

E1.1 Calculating Dp_MExDF (Equation 1.2-3)

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-E2

Radionuclide	$Dp_{i,0}$ (µCi/m²)	$WF_{12\ hrs}$ [a] (unitless)	Dp_ExDC [b] (mrem•m²) per (µCi•hr)	GRF (unitless)	WF x GRF x $Dp_{i,tn}$ x Dp_ExDC (mrem/hr)
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] $WF_{12\ hours} = 0.4 * e^{-1.46E\text{-}08*(12*3600)} + 0.6 * e^{-4.44E\text{-}10*(12*3600)} = 0.9997$

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

[b] Values from DCFPAK 2.0 (ICRP 60+).

E1.2 Calculating 4Path_DRL$_{DR}$ (Equation 1.2-1)

4Path_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
4Path_MTDP: 1.36E+04 mrem (from Method 1.1, Example 1, Table 1.1-E9)

$$4Path\_DRL_{DR} = \frac{1000\,\text{mrem} * 5.39\text{E-}02\,\frac{\text{mrem}}{\text{hr}}}{1.36\text{E+}04\ \text{mrem}} = 3.95\text{E-}03\,\frac{\text{mrem}}{\text{hr}}$$

This means that a dose rate of 3.95E-03 mrem/hr 12 hours after deposition indicates that the entire mixture has the potential to cause a Four-Pathway Total Effective Dose (Internal + External) over the Early Phase equal to the PAG of 1000 mrem.

E1.3 Calculating the 4Path_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 4Path_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 Two-Pathway 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.

Table 1.2-E3

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

To determine the $2Path\_DRL_{DR}$, 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	$Dp_{i,0}$ ($\mu Ci/m^2$)	$WF_{12\ hrs}$ [a] (unitless)	Dp_ExDC [b] (mrem•m²) per (µCi•hr)	GRF (unitless)	WF x GRF x $Dp_{i,tn}$ x Dp_ExDC (mrem/hr)
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] $$WF_{12\text{ hours}} = 0.4 * e^{-1.46E-08*(12*3600)} + 0.6 * e^{-4.44E-10*(12*3600)} = 0.9997$$

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

[b] Values from DCFPAK 2.0 (ICRP 60+).

E2.2 Calculating 2Path_DRL$_{DR}$ (Equation 1.2-2)

2Path_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
2Path_MTDP: 7.21E+02 mrem (from Method 1.1, Example 2, Table 1.1-E18)

$$2Path\_DRL_{DR} = \frac{2000\,\text{mrem} * 5.38\text{E-}02\,\frac{\text{mrem}}{\text{hr}}}{7.10\text{E+}02\ \text{mrem}} = 1.52\text{E-}01\,\frac{\text{mrem}}{\text{hr}}$$

This means that a dose rate of 0.152 mrem/hr 12 hours after deposition indicates that the entire mixture has the potential to cause a Two-Pathway Total Effective Dose (Internal + External) over the First Year equal to the PAG of 2000 mrem.

E2.3 Calculating the 2Path_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 2Path_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 ($4Path\_DRL_{\alpha,\tilde{A}}$ or $2Path\_DRL_{\alpha,\tilde{A}}$) or areal activity ($4Path\_DRL_{\alpha,Dp}$ or $2Path\_DRL_{\alpha,Dp}$).

The $4Path\_DRL_{\alpha,\tilde{A}}$:

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

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

The $4Path\_DRL_{\alpha,Dp,tn}$:

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 (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.

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

The $2Path\_DRL_{\alpha,\tilde{A}}$:

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

2) Is calculated using the Two-Pathway Air Derived Response Level calculated in Method 1.1, Section 1.3.3.

The $2Path\_DRL_{\alpha,Dp,tn}$:

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 (considering only ground dose pathways) would equal the PAG over the time phase under consideration.

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

All DRLs developed in this Method are:

1) Derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA13), 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 α cpm/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 FRMAC Monitoring and Sampling Division is responsible for converting between the units presented in this method ($\mu Ci_\alpha \bullet s/m^3$ or $\mu Ci/m^2$) and the units generated in the field (i.e., cpm/filter or cpm/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:
   - Four-Pathway Air Derived Response Level, (See Method 1.1),
   - Four-Pathway Deposition Derived Response Level, (See Method 1.1),
   - Two-Pathway Air Derived Response Level, (See Method 1.1), or
   - Two-Pathway Deposition Derived Response Level, (See Method 1.1).

   NOTE: The same type must be used for the 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 and Decision Makers endorse their use.

Outputs

Final

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

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

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

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

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

Intermediate

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

None.

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

Calculation

The $4Path\_DRL_{\alpha,\tilde{A}}$ 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.

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

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

where:

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

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

Calculation

The $4Path\_DRL_{\alpha,Dp}$ 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.

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

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

where:

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

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

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

Method 1.3.3 Two-Pathway Air Alpha Derived Response Level ($2Path\_DRL_{\alpha,\tilde{A}}$)

Calculation

The $2Path\_DRL_{\alpha,\tilde{A}}$ 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.

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

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

where:

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

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

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

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

Calculation

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

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

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

where:

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

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

Table 1.3-E1

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

This calculation requires the Four-Pathway Air Derived Response Level ($4Path\_DRL_{\tilde{A}}$) 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/m^3)	Alpha Yield	Early Phase (Total Dose) $4Path\_DRL_{\tilde{A}}$ (µCi•s/m^3)
Co-60	6.67E+02	0	4.89E+01
Gd-148	3.33E+02	1	2.45E+01
Sr-90	1.0E+03	0	7.34E+01
Y-90	1.0E+03	0	7.34E+01

Applying these values in equation 1.3-1 yields:

$$4Path\_DRL_{\alpha,\tilde{A}} = \left(2.45E+01 \frac{\mu Ci \bullet s}{m^3} * 1 \frac{\mu Ci_\alpha}{\mu Ci} \right)$$

$$= 2.45E+01 \frac{\mu Ci_\alpha \bullet s}{m^3}$$

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 an total Alpha Integrated Air Activity of 24.5 µCi•s/m^3 would indicate that the entire mixture has the potential to cause a Four-Pathway Total Effective Dose (Internal + External) over the Early Phase equal to the PAG of 1000 mrem.

EXAMPLE 2

Problem: Calculate the Total Effective Dose Two-Pathway 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.

Table 1.3-E3

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

This calculation requires the Two-Pathway Deposition Derived Response Level ($2Path\_DRL_{Dp}$) 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 ($\mu Ci/m^2$)	Alpha Yield	1^{st}-Year $2Path\_DRL_{Dp}$ ($\mu Ci/m^2$)
Co-60	2	0	5.64
Gd-148	1	1	2.82
Sr-90	3	0	8.45
Y-90	3	0	8.45

Applying these values in equation 1.3-3 yields:

$$2Path\_DRL_{\alpha,Dp} = \left(2.82 \frac{\mu Ci}{m^2} * 1 \frac{\mu Ci_\alpha}{\mu Ci} \right)$$

$$= 2.82 \frac{\mu Ci_\alpha}{m^2}$$

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

This means that a total Alpha Areal Activity of 2.82 $\mu Ci/m^2$ 12 hours after deposition would indicate that the entire mixture has the potential to cause a Two-Pathway Total Effective Dose (Internal + External) over the First Year equal to the PAG of 2000 mrem.

METHOD 1.4 BETA DERIVED RESPONSE LEVEL

Application

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

The 4Path_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 (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.

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

The 4Path_DRL$_{\beta,Dp,tn}$:

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 (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.

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

The 2Path_DRL$_{\beta,\tilde{A}}$:

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 (considering only ground dose pathways) would equal the PAG over the time phase under consideration.

2) Is calculated using the Four-Pathway Air Activity Derived Response Level calculated in Method 1.1, Section 1.3.3.

The 2Path_DRL$_{\beta,Dp,tn}$:

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 (considering only ground dose pathways) would equal the PAG over the time phase under consideration.

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

All DRLs developed in this Method are:

1) Derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA13), 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 β^- cpm/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 FRMAC Monitoring and Sampling Division is responsible for converting between the units presented in this method ($\mu Ci_\beta \bullet s/m^3$ or $\mu Ci/m^2$) and the units generated in the field (i.e., cpm/filter or cpm/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:
    - Four-Pathway Air Derived Response Level, (See Method 1.1),
    - Four-Pathway Deposition Derived Response Level, (See Method 1.1),
    - Two-Pathway Air Derived Response Level, (See Method 1.1), or
    - Two-Pathway Deposition Derived Response Level, (See Method 1.1).

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

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

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

Outputs

Final

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

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

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

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

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

Intermediate

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

None

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

Calculation

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

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

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

where:

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

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

Calculation

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

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

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

where:

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

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

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

Method 1.4.3 Two-Pathway Air Beta Derived Response Level ($2Path\_DRL_{\beta,\tilde{A}}$)

Calculation

The $2Path\_DRL_{\beta,\tilde{A}}$ 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.

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

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

where:

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

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

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

Method 1.4.4 Two-Pathway Deposition Beta Derived Response Level ($2Path\_DRL_{\beta,Dp}$)

Calculation

The $2Path\_DRL_{\beta,Dp}$ 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.

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

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

where:

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

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

Table 1.4-E1

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

This calculation requires the Four-Pathway Air Derived Response Level ($4Path\_DRL_{\tilde{A}}$) 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/m^3)	Beta Yield	Early Phase (Total Dose) $4Path\_DRL_{\tilde{A}}$ (µCi•s/m^3)
Co-60	6.67E+02	1	4.89E+01
Gd-148	3.33E+02	0	2.45E+01
Sr-90	1.0E+03	1	7.34E+01
Y-90	1.0E+03	1	7.34E+01

Applying these values in equation 1.4-1 yields:

$$4Path\_DRL_{\beta,\tilde{A}} = \left(4.89E+01\frac{\mu Ci \bullet s}{m^3} * 1\frac{\mu Ci_\beta}{\mu Ci}\right) + \left(7.34E+01\frac{\mu Ci \bullet s}{m^3} * 1\frac{\mu Ci_\beta}{\mu Ci}\right) + \left(7.34E+01\frac{\mu Ci \bullet s}{m^3} * 1\frac{\mu Ci_\beta}{\mu Ci}\right) = 1.96E+02\frac{\mu Ci_\beta \bullet s}{m^3}$$

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 196 µCi•s/m^3 would indicate that the entire mixture has the potential to cause a Four-Pathway Total Effective Dose (Internal + External) over the Early Phase equal to the PAG of 1000 mrem.

Example 2

Problem: Calculate the Total Effective Dose Two-Pathway 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.

Table 1.4-E3

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

This calculation requires the Two-Pathway Deposition Derived Response Level (2Path_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	Integrated Air Activity (μCi•s/m^3)	Beta Yield	1st-Year 2Path_DRL$_{Dp}$ (μCi•s/m^3)
Co-60	2.0E+03	1	5.64
Gd-148	1.0E+03	0	2.82
Sr-90	3.0E+03	1	8.45
Y-90	3.0E+03	1	8.45

Applying these values in equation 1.4-3 yields:

$$
\begin{aligned}
2Path\_DRL_{\beta,Dp} &= \left(5.64\frac{\mu\text{Ci}}{\text{m}^2} * 1\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}}\right) \\
&+ \left(8.45\frac{\mu\text{Ci}}{\text{m}^2} * 1\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}}\right) + \left(8.45\frac{\mu\text{Ci}}{\text{m}^2} * 1\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}}\right) \\
&= 2.25\text{E+01}\frac{\mu\text{Ci}_\beta}{\text{m}^2}
\end{aligned}
$$

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

This means that a total Beta Areal Activity of 22.5 μCi/m^2 12 hours after deposition would indicate that the entire mixture has the potential to cause a Two-Pathway Total Effective Dose (Internal + External) over the First Year equal to the PAG of 2000 mrem.

METHOD 1.5 PROJECTED PUBLIC DOSE

Application

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

The 4Path_PPD:

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

The 2Path_PPD:

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

Both types of PPDs are:

1) Compared to Protective Action Guides (PAGs) for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA13), the Department of Homeland Security (DHS) (DHS08) or local Decision Makers.

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

Discussion

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

1) Summing the Pl_TDPs and Dp_TDPs for each radionuclide in the mixture.

or

2) Comparing a measured dose rate (mrem/hr) to the calculated $4Path\_DRL_{DR}$ for a mixture. Because the $4Path\_DRL_{DR}$ is determined using a PAG, the ratio of the measured value to the appropriate DRL can be used to calculate a projected dose relative to the PAG.

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

1) Summing the Dp_TDPs for each radionuclide in the mixture.

or

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

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

Assumptions

There are no additional assumptions beyond the default assumptions.

Inputs

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

1) Plume Total Dose Parameter (Pl_TDP) and Deposition Total Dose Parameter (Dp_TDP) for each radionuclide, calculated using Method 1.1.

or

2) Four-Pathway or Two-Pathway Dose Rate DRLs ($4Path\_DRL_{DR}$ or $2Path\_DRL_{DR}$) for the mixture, calculated using Method 1.2.

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

Outputs

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

Final

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

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

Intermediate

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

None

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

Calculation

1.5.1.1 Calculating the Four-Pathway Projected Public Dose

The Four-Pathway Projected Public Dose (4Path_PPD) includes the dose contributions from the plume-borne and ground-deposited radionuclide mixture, and is calculated by adding the Pl_TDPs and Dp_TDPs for each radionuclide in the mixture.

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

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

where:

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

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

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

1.5.1.2 Calculating the Two-Pathway Projected Public Dose

The Two-Pathway Projected Public Dose (2Path_PPD) includes the dose contributions from the ground-deposited radionuclide mixture, and is calculated by summing the Dp_TDPs for each radionuclide in the mixture.

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

mrem = mrem

where:

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

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

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

Calculation

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

1.5.2.1 Calculating the Four-Pathway Projected Public Dose

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

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

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

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

where:

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

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

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

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

1.5.2.2 Calculating the Two-Pathway Projected Public Dose

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

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

where:

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

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

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

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

Example 1

Problem: Calculate the Four-Pathway Projected Public Total Effective Dose for the Early Phase (Total Dose) Time Phase (0-96 hours) for the Following Mixture.

Table 1.5-E1

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

E1.1 Calculating 4Path_PPD (Equation 1.5-1)

This calculation requires the Plume Total Dose Parameter (Pl_TDP) and the Deposition Total Dose Parameter (Dp_TDP) for each radionuclide in the mixture. Table 1.5-E2 shows the values calculated in Method 1.1 (Table 1.1-E9) for the Early Phase.

Table 1.5-E2

Radionuclide	Pl_TDP EP(TD) (mrem)	Dp_TDP EP(TD) (mrem)
Co-60	**3.20E+01**	**4.99**
Gd-148	**1.33E+04**	**7.38E+01**
Sr-90	**2.42E+02**	**1.35**
Y-90	**2.32**	**3.60E-01**

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

$$4Path\_PPD_{TP} = \begin{bmatrix} (3.20\text{E+01 mrem}) + (4.99\text{ mrem}) \\ +(1.33\text{E+04 mrem}) + (7.38\text{E+01 mrem}) \\ +(2.42\text{E+02 mrem}) + (1.35\text{ mrem}) \\ +(2.32\text{ mrem}) + (3.60\text{E-01 mrem}) \end{bmatrix}$$

$$= 1.36\text{E+04 mrem}$$

This means that the entire mixture has the potential to cause a Four-Pathway Total Effective Dose (Internal + External) over the Early Phase equal to 1.36E+04 mrem.

E1.2 Calculating a 4Path_PPD for an Individual Organ

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

EXAMPLE 2

Problem: Calculate the Two-Pathway 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. Assume the dose rate measurement was 5 mrem/hr at 12 hours.

Table 1.5-E3

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

E2.1 Calculating 2Path_PPD$_{TP}$ (Equation 1.5-3b)

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

Organ of Interest: Whole Body
PAG: 2000 mrem
$2Path\_DRL_{DR}$: 1.52E-01 mrem/hr (from Method 1.2, Example 2, Section E2.2)

Applying these values to Equation 1.5-3b yields:

$$2Path\_PPD_{TP} = \frac{5\ \frac{\text{mrem}}{\text{hr}} * 2000\ \text{mrem}}{1.52\text{E-01}\ \frac{\text{mrem}}{\text{hr}}} = 6.58\text{E+04 mrem}$$

This means that the entire mixture has the potential to cause a Two-Pathway Total Effective Dose (Internal + External) over the First Year equal to 6.58E+04 mrem.

E2.2 Calculating a 2Path_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 2Path_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/hr, measured at 1 m above the ground) at a given time (t_n), at which the external dose from *all radionuclides* in a fallout deposition mixture may equal the appropriate Protective Action Guide (PAG) over the time phase under consideration.

2) Is derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA13) 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):

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

   where:

   t = Time after detonation, hr;
   $ExDR_t$ = External dose rate at time t, mrem/hr;
   $ExDR_r$ = Reference external dose rate at 1 hour after nuclear detonation, mrem/hr;
   x = Power Function Exponent, the value that represents the decay of fallout radioactivity at a given location. Default value = 1.2, see Section 1.7.4 for instructions on calculating this value if requested.

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

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

Inputs

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

Power Function Exponent (x) – Default of 1.2.

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

Outputs

Final

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

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

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

Intermediate

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

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

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

Method 1.7.1 Nuclear Fallout Dose

Calculation

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

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

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

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

where:

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

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

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

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

Integrating this equation produces:

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

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

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

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

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:

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

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

where:

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

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

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

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

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

Integrating this equation produces:

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

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

Solving this equation for $ExDR_r$ yields:

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

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

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

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

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

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

where:

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

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

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

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

Or, for the default value of x = 1.2:

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

Method 1.7.3 Nuclear Fallout Stay Time:

Calculation

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

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

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

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

Solving for t_2:

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

Taking the natural log of both sides:

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

Solving for t_2:

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

Therefore:

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

To obtain the stay time, subtract t_1 from t_2.

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

Calculation

The decay of fission products after a nuclear detonation can be approximated by the power function, t^{-x}. FRMAC uses a default value of 1.2 for the exponent (x) (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/hr;
$ExDR_b$ = External dose rate measured at time t_b, mrem/hr;
$ExDR_r$ = Reference external dose rate at 1 hour after detonation, mrem/hr;

By the rule of the power function:

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

Therefore:

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

and,

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

Taking the natural log of both sides:

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

Solving for -x:

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

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:

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

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:

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

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

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

when x=1, this is changed to:

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

EXAMPLE 1

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

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

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

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

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

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

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

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

$$= 0.88 \frac{\text{rem}}{\text{hr}}$$

This means that a Dose Rate measurement of 880 mrem/hr 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/hr, 12 hours after detonation, and
2) 3.6 rem/hr, 16 hours after detonation.

The external dose is calculated using equation 1.7-3:

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

x = 1.21 from Example 1,

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

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

Then:

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

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

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

EXAMPLE 3

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

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

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

x = 1.21 from Example 1,

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

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

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

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

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 emergency worker turn-back limits (TBL) and Stay Times (ST) that are applied by the Health and Safety Division. The methods consider the dose received from external exposure and inhalation of resuspended material. The EPA established dose limits for workers performing emergency services (EPA13). Table 2-1 summarizes the EPA emergency worker dose guidance in terms of the projected Total Effective Dose (TED). When possible, TBLs and STs should be based on measured and projected work area conditions. Limits should be established for each worker and revised after shift-specific monitoring data is available, if necessary.

Default Assumptions

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

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

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

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

Default Inputs

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

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

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

METHOD 2.1 BASIC WORKER PROTECTION

Application

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

The results of this calculation will be used to develop turn-back and stay time guidance for emergency workers based on comparison to the PAGs for radiological emergency planning established by the EPA (EPA13), DHS (DHS08) or others established for the specific incident by Decision Makers.

Discussion

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

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

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

Assumptions

The following are exceptions to the default assumptions:

1) The dose projections from this method only include contributions from groundshine; inhalation is not addressed.

2) The composition of the mixture does not change significantly, either through radioactive decay or weathering, over the time phase (worker shift) in question.

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

Inputs

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

Constants – Dose Limits for Workers Performing Emergency Services.

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

Outputs

Final

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

TBL_{DR} = Worker Dose Rate Turn-Back Limit (mrem/hr)
TBL_{XR} = Worker Exposure Rate Turn-Back Limit (mR/hr)
ST = Stay Time (hr)

Intermediate

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

None

Calculation

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

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

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

where:

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

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

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

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

where:

ST = Stay Time, how long the worker will be allowed to work in the contaminated area, hr;
ExDR = External dose rate, mrem/hr; and
Dose Limit = Dose that the worker is allowed to receive for the shift, mrem.

NOTE: Either of these equations may be modified to apply to exposure rates rather than dose rates by applying the Exposure to Dose Conversion Factor ($XDCF_{A\ or\ C}$) of 0.7 mrem/mR (acute) or 1.0 mrem/mR (chronic) to calculate a TBL or ST when readings in mR/hr are needed. (See Example in Method 2.2 for application.)

EXAMPLE 1

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

Dose Limit: 25000 mrem
Shift Length: 8 hours

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

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

EXAMPLE 2

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

Dose Limit: 5000 mrem
Dose Rate: 500 mrem/hr

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

Workers may stay in the field for 10 hours.

METHOD 2.2 WORKER PROTECTION DOSES AND INTEGRATED TURN BACK LIMITS

Application

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

The TBL:

- Represents the integrated external dose (or exposure) that would produce a total dose (external and internal) over a worker's shift equal to the appropriate Protective Action Guide (PAG).
- Is derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA13) or the Department of Homeland Security (DHS) (DHS08) or other dose limits established for worker protection. A projected or measured value greater than the TBL indicates the potential to exceed the PAG.
- Is calculated from the Deposition Inhalation Dose Parameter (Dp_InhDP) and the Deposition External Dose Parameter (Dp_ExDP) values calculated in Method 1.1.

Discussion

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

Assumptions

The following is an exception to the default assumptions:

1) The use of respiratory protection is addressed by this method.

Inputs

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

1) Other Factors – Assigned protection factor (APF) for respirator use, Potassium Iodide protection factor (KIPF).
2) Deposition Inhalation and External Dose Parameters (Dp_InhDP and Dp_ExDP) for each radionuclide in the mixture, based on the start and end times and dose limit for the worker's shift (calculated using Method 1.1).

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

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

Outputs

Final

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

TBL_D = Worker Turn-Back Limit for Integrated External Dose (mrem)
TBL_X = Worker Turn-Back Limit for Integrated External Exposure (mR)

Intermediate

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

$ExTDCF_{TP}$ = External to Total Dose Conversion Factor, the ratio of the total dose (external + inhalation) to the external dose for a deposition of radioactive material over the time phase under consideration (*TP*), $mrem_{inh+external}/mrem_{external}$.
NOTE: This value is used to convert a measurement from a self-reading dosimeter into a dose that includes the effects of inhalation of resuspended material.

Calculation

1) Calculating the Worker Turn-Back Limit

The calculation of the Turn-Back Limit for Integrated External Dose (TBL_D) is based on the Dose Limit chosen by the decision makers for the incident and the ratio of total (inhalation + external) dose to external dose.

NOTE: The default assumption is that this calculation will be performed to evaluate Whole-Body (Effective) dose. This method can also be used to evaluate TBLs for other organs by calculating the ExTDCF for that organ.

$$TBL\_D_{TP} = \frac{Dose\ Limit}{ExTDCF_{TP}} \qquad \text{(Eq. 2.2-1)}$$

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

where:

- TBL_D_{TP} = Turn-Back Limit for Integrated External Dose, the integrated external dose, as recorded by the self-reading dosimeter, received from a radionuclide mixture deposited on the ground over the time phase under consideration (*TP*) that would result in the worker receiving their dose limit, $\text{mrem}_{\text{external}}$;
- *Dose Limit* = Worker (or receptor) dose limit, mrem; and
- $ExTDCF_{TP}$ = External to Total Dose Conversion Factor, the ratio of the total dose (external + inhalation) to the external dose for a deposition of radioactive material over the time phase under consideration (*TP*), $\text{mrem}_{\text{inh+external}}/\text{mrem}_{\text{external}}$.

When the worker's self-reading dosimeter reaches the calculated integrated external dose, this indicates that the worker has potentially received the dose limit (external plus inhalation dose) from the radionuclides deposited on the ground.

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

$$TBL\_X_{TP} = \frac{TBL\_D_{TP}}{XDCF_{A \text{ or } C}} \qquad \text{(Eq. 2.2-2)}$$

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

where:

- TBL_X_{TP} = Turn-Back Limit for Integrated External Exposure, the integrated external exposure, as recorded by the self-reading dosimeter, received from a radionuclide mixture deposited on the ground over the time phase under consideration (*TP*) that would result in the worker receiving their dose limit, $\text{mR}_{\text{external}}$;
- TBL_D_{TP} = Turn-Back Limit for Integrated External Dose, the integrated external dose, as recorded by the self-reading dosimeter, received from a radionuclide mixture deposited on the ground over the time phase under consideration (*TP*) that would result in the worker receiving their dose limit, $\text{mrem}_{\text{external}}$;

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

$XDCF_C$ = Exposure to Dose Conversion Factor (chronic), the constant used to convert external exposure (mR) to deep tissue (1 cm) dose (mrem), 1.0.

These limits should be used as the Dose (or Exposure) Limit in the calculation of stay time shown in Method 2.1.

2) Calculating the External to Total Dose Conversion Factor

NOTE: See Method 1.1, Section 1.1.2 for the Derivation of Dp_InhDP and Dp_ExDP.

The External to Total Dose Conversion Factor ($ExTDCF_{TP}$) for the time phase of interest can be calculated by adding the contributions to total dose from external exposure and respiration of resuspended material and dividing the total by the external contribution as shown in Equations 2.2-3(a-c).

$$ExTDCF_{TP} = \frac{\sum_i \left(\frac{Dp\_InhDP_{i,TP}}{KIPF * APF} \right) + \sum_i \left(Dp\_ExDP_{i,TP} \right)}{\sum_i \left(Dp\_ExDP_{i,TP} \right)} \qquad \text{(Eq. 2.2-3a)}$$

which can be expanded to:

$$ExTDCF_{TP} = \frac{\sum_i \left(\frac{Dp\_InhDP_{i,TP}}{KIPF * APF} \right)}{\sum_i \left(Dp\_ExDP_{i,TP} \right)} + \frac{\sum_i \left(Dp\_ExDP_{i,TP} \right)}{\sum_i \left(Dp\_ExDP_{i,TP} \right)} \qquad \text{(Eq.2.2-3b)}$$

which simplifies to:

$$ExTDCF_{TP} = \frac{\sum_i \left(\frac{Dp\_InhDP_{i,TP}}{KIPF * APF} \right)}{\sum_i \left(Dp\_ExDP_{i,TP} \right)} + 1 \qquad \text{(Eq. 2.2-3c)}$$

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

where:

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

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

> **NOTE:** For Worker Protection Calculations, *Dp_InhDP* should be calculated using the Light Exercise Breathing Rate for an Adult Male (BR_{LE}) (4.17E-04 m^3/s) rather than the Activity Averaged Breathing Rate (BR_{AA}).

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

KIPF = Potassium Iodide Protection Factor (Default of 1 for all non-iodine isotopes or when no KI is administered), unitless; and

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

> **NOTE:** Consult Health and Safety personnel for appropriate values for *APF* and/or *KIPF*. Typical *APF* values are:
> Half-face Air-purifying Respirator: 10
> Full-face Air-purifying Respirator: 50
> Pressure-Demand SCBA: 10,000

3) Comparison of the ExTDCF to the workers' Dose Limit.

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

$$TBL\_D_{TP} = \frac{Dose\ Limit}{ExTDCF_{TP}} \quad \text{(Eq. 2.2-4)}$$

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

where:

TBL_D_{TP} = Turn-Back Limit for Integrated External Dose, the integrated external dose as recorded by the self-reading dosimeter, received from a radionuclide mixture deposited on the ground over the time phase under consideration (*TP*) that would result in the worker receiving their dose limit, $\text{mrem}_{\text{external}}$;

Dose Limit = Worker (or receptor) dose limit, mrem; and

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

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

4) Calculation of Worker Dose

To calculate a worker's dose at any point during the shift, multiply the current reading on the worker's dosimeter by the ExTDCF.

$$Dose = \text{SRD Readout} * ExTDCF_{TP} \qquad \text{(Eq. 2.2-5)}$$

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

where:

- *Dose* = Worker (or receptor) dose, mrem;
- SRD Readout = Current reading on Self-Reading Dosimeter, mrem; and
- $ExTDCF_{TP}$ = External to Total Dose Conversion Factor, the ratio of the total dose (external + inhalation) to the external dose for a deposition of radioactive material over the time phase 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.

$$Dose = \text{SRD Readout} * XDCF_{A \text{ or } C} * ExTDCF_{TP} \qquad \text{(Eq. 2.2-6)}$$

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

where:

- $XDCF_A$ = Exposure to Dose Conversion Factor (acute), the constant used to convert external exposure (mR) to midline (bone marrow) dose (mrem), 0.7 mrem/mR.
- $XDCF_C$ = Exposure to Dose Conversion Factor (chronic), the constant used to convert external exposure (mR) to deep tissue (1 cm) dose (mrem), 1.0 mrem/mR.

EXAMPLE 1

Problem: Calculate the worker Turn-Back Limit for an 8-hour shift <u>with and without</u> 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/m^2)	$t_{1/2}$ (s)
Co-60	2	1.66E+08
Gd-148	1	2.93E+09
Sr-90	3	9.19E+08
Y-90	3	2.30E+05

E1.1 Calculating the ExTDCF (Equation 2.2-3c)

This calculation requires values for Dp_InhDP and Dp_ExDP. See Method 1.1 for development of these quantities.

Table 2.2-E2

Radionuclide	Dp_i (μCi/m^2)	Dp_ExDP[a] (mrem)	Dp_InhDP[a] (mrem)
Co-60	2	4.02E-01	2.70E-02
Gd-148	1	0	1.13E+01
Sr-90	3	4.30E-04	2.07E-01
Y-90	3	2.88E-02	1.98E-03
	∑	**4.31E-01**	**1.15E+01**

[a] Values from Turbo FRMAC 2011© – Breathing rate for "Light Exercise".

With a respirator:

$$ExTDCF_{TP} = \frac{\frac{1.15\text{E+01}}{1*50}}{4.31\text{E-01}} + 1 = 1.54\ \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}$$

Without a respirator:

$$ExTDCF_{TP} = \frac{\frac{1.15\text{E+01}}{1*1}}{4.31\text{E-01}} + 1 = 2.78\text{E+01}\ \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}$$

E1.2 Calculating the TBL_D and TBL_X (Equation 2.2-1, 2.2-2)

The Turn-Back Limits for Integrated External Dose and Exposure for this radionuclide mixture with a Dose limit of 5000 mrem would be:

With a respirator:

$$TBL\_D_{TP} = \frac{5000\ \text{mrem}_{inh+external}}{1.54\ \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}} \simeq 3260\ \text{mrem}_{external}$$

$$TBL\_X_{TP} = \frac{3260\ \text{mrem}_{external}}{1.0\ \text{mrem}/\text{mR}} \simeq 3260\ \text{mR}_{external}$$

This means that when a worker’s dosimeter indicates an external dose of **3260** mrem (exposure of 3260 mR), the worker has potentially received 5000 mrem of total (external + inhalation) dose and should exit the work area.

Without a respirator:

$$TBL\_D_{TP} = \frac{5000\ \text{mrem}_{inh+external}}{27.8\ \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}} \simeq 180\ \text{mrem}_{external}$$

$$TBL\_X_{TP} = \frac{180\ \text{mrem}_{external}}{1.0\ \text{mrem}/\text{mR}} = 180\ \text{mR}_{external}$$

This means that when a worker’s dosimeter indicates an external dose of **180** mrem (exposure of 180 mR), the worker has potentially received 5000 mrem of total (external + inhalation) dose and should exit the work area.

METHOD 2.3 WORKER PROTECTION - STAY TIME CALCULATION

This method is reserved for future development.

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METHOD 2.4 WORKER PROTECTION - SKIN DOSE

This method is reserved for future development.

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SECTION 3. INGESTION PATHWAY METHODS

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INTRODUCTION TO INGESTION PATHWAY METHODS

These methods are used to assess measured or projected environmental measurements for comparison to the FDA DILs for radioactive contamination in food (FDA98).

The FDA has established DILs for contamination in food for a list of radionuclides and has specified a method to calculate DILs for all other radionuclides. The DILs are based on PAGs of 0.5 rem Committed Effective Dose (E) and 5 rem to any specific organ (H_T), whichever is more limiting. FDA Ingestion PAGs are presented in Appendix C, Table 2-2, and DILs for selected radionuclides (including the full FDA list) are presented in Appendix C, Table 8.

Dose calculations assume radionuclide concentrations are for foods as prepared for consumption and ingestion is assumed to take place for a period of one year (or less for radionuclides with half-lives < 54 days – See Method 4.1).

These methods may include the use of Transfer Factors (TFs) to estimate the concentration of radionuclides in food products. Transfer factors are the ratio of the concentration of a radionuclide in food products to the concentration in the source medium such as soil, plant forage, or water (PNNL03).

The equations presented in these methods use the following assumptions about Transfer Factors:

1) Transfer Factors assume a long-term exposure during which equilibrium is reached.
2) Transfer Factors used in these methods for terrestrial plants are based on dry weight.
3) Transfer Factors used in these methods for animal products and aquatic plants are based on wet weight.

These methods consider both mature (ready for harvest) and immature food products. Calculations for mature products assume that the product will enter the food supply immediately and therefore do not include the effects of weathering and radioactive decay. Calculations for immature products include the effects of weathering and radioactive decay until the crops are ready for harvest and consumption. Both types of calculations address decay during transport from the field to the table.

For the ingestion pathway, daughter radionuclides in transient (or secular) equilibrium are excluded from independent analysis because their contribution to dose is included in the dose coefficient of the ultimate parent. Daughter radionuclides with a half-life greater than 6 hours **are analyzed separately from the parent radionuclide** because it may be possible to prepare food for consumption before significant decay occurs.

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METHOD 3.1 DERIVED INTERVENTION LEVELS

Application

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

The DIL:

1) Represents the concentration ($\mu Ci/kg_{wet}$) 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) Is derived from the PAG for radiological emergency planning established by the Food and Drug Agency (FDA) (FDA98). A projected or measured value greater than the DIL indicates the potential to exceed the PAG.

3) Applies to the activity concentration in the food "as prepared for consumption" or "wet."

4) Is applied during the first year after an incident and based on the most sensitive population (age group) and target organ to provide a large margin of safety to the public (FDA98).

5) Is used to create data products and define activity concentration levels to assist decision makers in determining where it may be advisable to implement protective actions (e.g., sheltering livestock, embargos, special product handling).

Discussion

DILs were recommended by the FDA in 1998 as the radionuclide activity concentration in food at which point protective actions should be considered. Food with activity concentrations below the DIL is permitted to move in commerce without restriction. However, local decision makers have the flexibility to apply alternate limits in special circumstances.

The FDA established DILs for 9 principle isotopes in 5 groups, 15 secondary isotopes, and provided a method to calculate DILs. The nuclides with FDA-provided DILs are shown in Table 3.1-1 below and in Appendix C, Table 8.

FRMAC does not have the authority to calculate or use different DILs for radionuclides for which the FDA has provided recommended values unless alternate values are requested by the Advisory Team or local decision makers. FRMAC can calculate DILs for the radionuclides for which the FDA does not provide recommended values, but these values are not automatically approved by the FDA and must receive approval from the Advisory Team or local decision makers before they are used.

Assumptions

The FRMAC radiological assessment calculations use the default assumptions established by the FDA. The following default assumptions are used in this method:

1) DILs apply to individual radionuclides (or FDA-specified groups of radionuclides); there is no sum-of-fraction rule (except for ^{103}Ru and ^{106}Ru).

2) DILs apply only to the parent radionuclide in a chain. DO NOT calculate a DIL for a daughter radionuclide independently unless it exists in the mixture as a separate parent (i.e., in excess of its equilibrium concentration).

3) DILs are based on average annual dietary intake (kg_{wet}/yr) of all dietary components (e.g., produce, grains, meat, etc.), including tap water used for drinking.

4) Annual intake is adjusted for short-lived ($t_{1/2}$ < 54 days) radionuclides to account for radioactive decay.

5) Annual intake varies by age group (3 month, 1 yr, 5 yr, 10 yr, 15 yr, and adult).

6) DILs are applicable to foods "as prepared for consumption" or "wet". To compare with analytical results it may be necessary to convert to "dry weight," see Method 4.2.

7) ICRP 26 Ingestion Dose Conversion Factors should not be used to calculate DILs because they only consider the adult receptor (ICRP77).

8) The default Ingestion PAGs are:
   - 500 mrem to the whole body or
   - 5000 mrem to an individual organ, whichever is more limiting.

9) Inadvertent ingestion of soil is not included in these methods. If ingestion of soil is a significant dose pathway (i.e., >10% of the total dose), it should be addressed separately. (See Method 3.7).

10) Default calculations for non-FDA-listed radionuclides use the International Commission on Radiological Protection (ICRP) 60+ dosimetry model.

Inputs

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

1) Data – Composition of the deposited radionuclide mixture (radionuclides and concentration). This information may come from predictive analysis (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 and Decision Makers endorse their use.

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

Outputs

Final

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

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

Intermediate

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

None

Method 3.1.1 DILs for FDA-Listed Radionuclides

Table 3.1-1 provides the DILs for the FDA-listed radionuclides. These values must be used when evaluating the radionuclides (and groups of radionuclides) in the table unless an alternate DIL is requested by the Advisory Team or local decision makers. Follow the calculation steps in Method 3.1.2 for all other radionuclides.

Table 3.1-1 FDA-Listed Ingestion DILs (FDA 1998)

Radionuclide Group	FDA DIL[a] (Bq/kg_{wet})	FDA DIL[a] ($\mu Ci/kg_{wet}$)
Principal Nuclides		
^{90}Sr	160	4.3E-03
^{131}I	170	4.6E-03
$^{134}Cs + ^{137}Cs$	1200	3.2E-02
^{134}Cs	930	2.5E-02
^{137}Cs	1360	3.7E-02
$^{238}Pu + ^{239}Pu + ^{241}Am$	2	5.4E-05
^{238}Pu	2.5	6.8E-05
^{239}Pu	2.2	6.0E-05
^{241}Am	2	5.4E-05
$^{103}Ru + ^{106}Ru$	(^{103}Ru/6800) + (^{106}Ru/450) <1	(^{103}Ru/0.18) + (^{106}Ru/1.2E-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 DILs for Non-FDA-Listed Radionuclides

Calculation

This method uses the FDA approach for all calculations.

DIL calculations can be complex, given the number of age group/organ combinations that need to be calculated to determine the most restrictive value for each radionuclide. Therefore the user is urged to use a computer code, such as Turbo FRMAC©, to complete these calculations. All calculated values must be approved by an FDA representative on the Advisory Team prior to publication.

Equation 3.1-1 shows the DIL calculation.

$$DIL_{organ,\,age,\,i} = \frac{PAG_{organ}}{FDC_{age,i} * DFIR_{age} * EDI_i * IngDC_{organ,\,age,i}} \quad \text{(Eq. 3.1-1)}$$

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

where:

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

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;

EDI_i = Effective Days of Intake, the number of days required for the radionuclide to decay to <1% of its initial activity (maximum of 365), d; and

$$EDI_i = \frac{-\ln(0.01)}{\lambda_i} \quad \text{where } \lambda_i = \frac{\ln 2}{t_{1/2_i}} \quad \text{(Eq. 3.1-2)}$$

NOTE: If the radionuclide half-life is greater than 54 days, the EDI_i = 365 days.

$IngDC_{organ,age,i}$ = Ingestion Dose Coefficient, the ingestion pathway dose coefficient for the target organ for a specific age group for radionuclide *i*, mrem/µCi.

This calculation will determine a DIL for one age group and one organ. To determine the most restrictive value for a given radionuclide:

- Calculate the DIL for the whole body and for the organ with the highest IngDC for each age group.
- Apply the DIL for the age group and organ with the most conservative (lowest) activity concentration level (µCi/kg_{wet}).

EXAMPLE 1

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

^{136}Cs is not an FDA-listed radionuclide; therefore the DIL must be calculated according to Method 3.1.2. Determining a final DIL requires calculating the DIL for each age group for each organ and choosing the most conservative value.

$$DIL_{organ,age,i} = \frac{PAG_{organ}}{FDC_{age,i} * DFIR_{age} * EDI_i * IngDC_{organ,age,i}} \qquad \text{(Eq. 3.1-1)}$$

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

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

$$EDI_i = \frac{4.6}{5.29\text{E-02}} = 87 \text{ d} \quad \text{where } \lambda_i = \frac{0.693}{13.1} = 5.29\text{E-02} \qquad \text{(Eq. 3.1-2)}$$

Table 3.1-E1 shows the values, calculated using Equation 3.1-1, for each age group for the Whole Body and for the organ with the highest IngDC.

Table 3.1-E1

Age Group	Organ	IngDC (mrem/µCi)	FDC	DFIR (kg_{wet}/d)	EDI (d)	PAG (mrem)	DIL (µCi/kg_{wet})
Infant (3 month)	**Whole Body**	**53.7**	**0.3**	**1.14**	**87**	**500**	**0.31**
	LLI [a]	85.1	0.3			5000	1.97
1 year	Whole Body	35.6	0.3	1.38	87	500	0.39
	LLI	58.1	0.3			5000	2.39
5 year	Whole Body	22.6	0.3	1.81	87	500	0.47
	LLI	34.2	0.3			5000	3.09
10 year	Whole Body	16.2	0.3	2.14	87	500	0.55
	LLI	22	0.3			5000	4.07
15 year	Whole Body	12.7	0.3	2.38	87	500	0.63
	Pancreas	14.6	0.3			5000	5.51
Adult	Whole Body	11.4	0.3	2.59	87	500	0.65
	LLI	13.7	0.3			5000	5.40
						Most Restrictive DIL	**0.31**

[a] Lower Large Intestine

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

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METHOD 3.2 CROP/PRODUCE INGESTION DERIVED RESPONSE LEVELS

Application

This method has been developed to calculate Ingestion Derived Response Levels for radioactive material deposited on crop/produce.

The Crop/Produce Ingestion Derived Response Level (Crop_DRL):

1) Represents the areal activity (μCi/m^2), of radionuclide *i* that would cause the crop/produce growing in that area to equal the Derived Intervention Level (DIL) for that radionuclide.

2) Is indirectly derived (through the DIL) from the PAG for radiological emergency planning established by the Food and Drug Agency (FDA) (FDA98). A projected or measured value greater than the Crop_DRL indicates the potential to exceed the PAG.

3) Is applied during the first year after an incident and based on the most sensitive population (age group) and target organ to provide a large margin of safety to the public (FDA98).

4) Is used to create data products and define contamination levels to assist decision makers in determining where it may be advisable to conduct sampling to evaluate the potential for implementing protective actions (e.g., sheltering livestock, embargos, special product handling).

5) Is calculated using the DIL calculated in Method 3.1

Discussion

The Crop_DRL predicts the amount of radioactivity deposited on a crop (μCi/m^2) that would cause the crop to equal the DIL. Crop sampling efforts should concentrate on the area where the contamination is equal to or greater than the Crop_DRL to determine if the DIL has been exceeded in those areas. Protective actions should be considered in areas where the DIL is exceeded. FDA guidance permits food with radioactivity concentrations below the DIL to move in commerce without restriction. However, the FDA and local decision makers have flexibility in whether to apply restrictions in special circumstances.

FRMAC does not have the authority to calculate or use different DILs for radionuclides for which the FDA has provided recommended values unless alternate values are requested by the Advisory Team or local decision makers. FRMAC can calculate DILs for the radionuclides for which the FDA does not provide recommended values, but these values are not automatically approved by the FDA and must receive approval from the Advisory Team or local decision makers before they are used.

Assumptions

The FRMAC radiological assessment calculations use the default assumptions established by the FRMAC Assessment Working Group. The following default assumptions are used in this method:

Crop DRLs:

1) Apply to individual radionuclides; there is no sum-of-fraction rule (except for the FDA-listed ^{103}Ru and ^{106}Ru).
2) Are based on the most restrictive DIL for each radionuclide based on age group and target organ. See Method 3.1 for DIL calculation assumptions.
3) Apply to the plant as a whole and do not predict contamination of only the edible portions (e.g., apples on the tree.)
4) Assume a crop yield of 2 kg_{wet}/m^2 for fresh produce.
5) Assume a soil density of 1600 kg_{soil}/m^3.
6) Assume a mixing depth of 1.0E-03 m for the first growing season (EPA89) and 0.15 after plowing.
7) Assume a half-life of 15 days for material weathering off plant material
8) Assume a Time to Market of 1 day for fresh produce.
9) Assume, for immature crops, that the crop will remain growing in the contaminated soil for a period of time sufficient to reach equilibrium.
10) Are calculated for food as prepared for consumption. To compare with analytical results it may be necessary to convert to "dry weight," see Method 4.2.
11) Use Crop Retention Factors for fresh produce of:
    - 1.0 for radioiodine and
    - 0.2 for all other radionuclides.
12) DRLs for FDA grouped radionuclides (e.g., ^{134}Cs + ^{137}Cs) are adjusted for decay during Growing Time and Time to Market using the decay constant for the longest-lived group member.

Inputs

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

1) Data – Composition of the deposited radionuclide mixture (radionuclides and concentration). This information may come from predictive analysis (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.
4) Appropriate DIL for each radionuclide – Calculated using Method 3.1.

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

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

Outputs

Final

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

$Crop\_DRL_{mat,i}$ = Ingestion Derived Response Level for mature Crop/Produce, the areal activity (µCi/m^2), of radionuclide *i* that would cause the crop/produce growing in that area to equal the applicable Derived Intervention Level (DIL) at the time of contamination, µCi/kg_{wet}.

$Crop\_DRL_{imm,i}$ = Ingestion Derived Response Level for immature Crop/Produce, the areal activity (µCi/m^2), of radionuclide *i* that would cause the crop/produce growing in that area to equal the applicable Derived Intervention Level (DIL) at the time of harvest, µCi/kg_{wet}.

Intermediate

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

None

Method 3.2.1 Crop_DRL for Mature Crop/Produce

This method is used to evaluate fresh produce that will be harvested for immediate consumption. Because of the short time frame involved, the following have not been included in this method:

- Reduction in radioactivity due to weathering.
- Reduction in radioactivity due to biological processes in the crop.

- Increase in radioactivity due to root uptake from contaminated soil.
- Increase in radioactivity due to re-deposition of resuspended material.

Calculation

Equation 3.2-1 shows the $Crop\_DRL_{mat,i}$ calculation.

$$Crop\_DRL_{mat,i} = \frac{DIL_{organ,age,i} * Y}{CRF_i * e^{-\lambda_i t_m}} \qquad \text{(Eq. 3.2-1)}$$

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

where:

$Crop\_DRL_{mat,i}$ = Ingestion Derived Response Level for mature Crop/Produce, the areal activity (µCi/m^2), of radionuclide *i* that would cause the crop/produce growing in that area to equal the applicable Derived Intervention Level (DIL) at the time of contamination, µCi/kg;

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

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

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

λ_i = Decay constant for radionuclide *i*, d^{-1}; and

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d.

Method 3.2.2 Crop_DRL for Immature Crop/Produce

This method is used to predict the level of radioactive material (e.g., µCi/kg) present in food which has reached maturity while growing in a field that was:

- Contaminated by a deposition of radioactive material during the first growing season (i.e., after the crop was planted), or
- Contaminated and then plowed before the crop was planted.

This method accounts for the following processes that change the level of radioactive material present in a crop:

1. Reduction in radioactivity level due to radioactive decay over the growing season,

2. Reduction in radioactivity level due to material weathering off the crop over the growing season,
3. Reduction in radioactivity level due to transport time to market,
4. Reduction in radioactivity level due to biological processes in the crop,
5. Increase in radioactivity level due to root uptake from contaminated soil, and
6. Increase in radioactivity level due to re-deposition of resuspended material.

The method 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, root vegetable, fruit, or grain). (See PNNL-13421 for details on TFs).

Calculation

Equation 3.2-2 shows the $Crop\_DRL_{imm,i}$ calculation.

$$Crop\_DRL_{imm,i} = \frac{DIL_{organ,age,i}}{\left(\frac{CRF * \left(\frac{1\text{-}e^{-\lambda_w t_g}}{\lambda_w * t_g}\right)}{Y} + \frac{TF_{crop,i} * MCF_{D-W,f}}{d_m * \rho_{soil}}\right) * \left(\frac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g}\right) * e^{-\lambda_i t_m}} \quad \text{(Eq. 3.2-2)}$$

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

where:

$Crop\_DRL_{imm,i}$ = Ingestion Derived Response Level for immature Crop/Produce, the areal activity ($\mu Ci/m^2$), of radionuclide *i* that would cause the crop/produce growing in that area to equal the applicable Derived Intervention Level (DIL) at the time of harvest, $\mu Ci/kg_{wet}$.

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

CRF = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop, unitless;
NOTE: For crops planted AFTER deposition, the CRF=0.

λ_w = Decay constant for weathering radioactive material off plants (See Appendix C, Table 11), d^{-1};

t_g = Growing Time, the time the crop spends growing in the contaminated field, d;

$\left(\frac{1\text{-}e^{-\lambda_w t_g}}{\lambda_w * t_g}\right)$ = Integrated average weathering of radioactive material off plants during the time the crop is growing in the field (the integral of the weathering over the Growing Time divided by the Growing Time), unitless;

Y = 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 during the growing season, $\mu Ci/kg_{dry}$ per $\mu Ci/kg_{soil}$;

$MCF_{D\text{-}W,f}$ = Mass Conversion Factor (dry to wet), the ratio of dry mass to wet mass for a food type *f* (See Appendix C, Table 9), kg_{dry}/kg_{wet};

d_m = Mixing Depth (See Appendix C, Table 11), m;

ρ_{soil} = Soil density (See Appendix C, Table 11), kg_{soil}/m^3;

λ_i = Decay constant for radionuclide *i*, d^{-1};

$\left(\frac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g}\right)$ = Integrated average decay of radioactive material during the time the crop is growing in the field (the integral of radioactive decay over the Growing Time divided by the Growing Time), unitless; and

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d.

EXAMPLE 1

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

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

Assuming that the crop is ready for immediate harvest, Equation 3.2-1 can be used to calculate the DRL.

$$Crop\_DRL_{mat,i} = \frac{DIL_{organ,age,i} * Y}{CRF_i * e^{-\lambda_i t_m}} \qquad \text{(Eq. 3.2-1)}$$

$$\frac{\mu Ci}{m^2} = \frac{\frac{\mu Ci}{kg_{wet}} * \frac{kg_{wet}}{m^2}}{unitless * unitless}$$

Assuming:

CRF = 0.2 (fresh produce),
Y = 2.0 kg_{wet}/m^2;
λ_{Co} = 3.6E-04 d^{-1}; and
t_m = 1 d.

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

This means that a Co-60 Areal Activity of 0.2 µCi/m^2 has the potential to cause a dose to the 3 month old whole body equal to the PAG of 500 mrem.

EXAMPLE 2

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

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

Assuming that the lettuce has already been planted and will be harvested in 90 days, Equation 3.2-2 can be used to calculate the DRL.

$$Crop\_DRL_{imm,i} = \frac{DIL_{organ,age,i}}{\left(\frac{CRF * \left(\frac{1\text{-}e^{-\lambda_w t_g}}{\lambda_w * t_g}\right)}{Y} + \frac{TF_{crop,i} * MCF_{D-W,f}}{d_m * \rho_{soil}}\right) * \left(\frac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g}\right) * e^{-\lambda_i t_m}} \quad \text{(Eq. 3.2-2)}$$

Assuming:

CRF = 0.2 (fresh produce)
λ_w = 4.62E-02 d^{-1};
t_g = 90 d;
Y = 2.0 kg$_{wet}$/m^2;
$TF_{lettuce,i}$ = 0.23 µCi/kg$_{dry}$ per µCi/kg$_{soil}$;
$MCF_{D\text{-}W,f}$ = 0.2 kg$_{dry}$/kg$_{wet}$ for leafy vegetables;
d_m = 1.0E-03 m;
ρ_{soil} = 1600 kg$_{soil}$/m^3;
λ_{Co} = 3.6E-04 d^{-1}; and
t_m = 1 d.

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

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

This means that a Co-60 Areal Activity of 0.39 µCi/m^2, when the crop is harvested in 90 days, has the potential to cause a dose to the 3 month old whole body equal to the PAG of 500 mrem.

METHOD 3.3 MILK INGESTION DERIVED RESPONSE LEVEL

Application

This method has been developed to calculate Ingestion Derived Response Levels for radioactive material deposited on animal feed/forage or water for the milk pathway.

The Milk Ingestion Derived Response Level:

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

2) Is indirectly derived (through the DIL) from the PAG for radiological emergency planning established by the Food and Drug Agency (FDA) (FDA98). A projected or measured concentration value greater than the Milk_DRL indicates the potential to exceed the PAG.

3) Is applied during the first year after an incident and based on the most sensitive population (age group) and target organ to provide a large margin of safety to the public (FDA98).

4) Is used to create data products and define contamination levels to assist decision makers in determining where it may be advisable to conduct sampling to evaluate the potential for implementing protective actions (e.g., sheltering livestock, embargos, special product handling).

5) Is calculated using the DIL calculated in Method 3.1.

Discussion

The Milk_DRL predicts the amount of radioactivity deposited either on an animal's grazing area (µCi/m^2) or in an animal's feed (including forage) or water (µCi/kg_{wet} or µCi/l) that would cause the animal's milk to equal the DIL. Sampling efforts should concentrate on the area where the contamination is equal to the Milk_DRL to determine if the DIL has been exceeded in those areas. Protective actions (e.g., use of stored feed) should be considered in areas where the DIL is exceeded. Milk embargo protective actions should be considered after milk samples indicate that the DIL has actually been exceeded. FDA guidance permits food with radioactivity concentrations below the DIL to move in commerce without restriction. However the FDA and local decision makers have flexibility in whether to apply restrictions in special circumstances.

FRMAC does not have the authority to calculate or use different DILs for radionuclides for which the FDA has provided recommended values unless alternate values are requested by the Advisory Team or local decision makers. FRMAC can calculate DILs for the radionuclides for which the FDA does not provide recommended values, but these values are not automatically approved by the FDA and must receive approval from the Advisory Team or local decision makers before they are used.

Because milk is obtained from grazing animals daily this method treats milk as a “mature product” and there is no consideration for weathering or radioactive decay during grazing.

Assumptions

The FRMAC radiological assessment calculations use the default assumptions established by the FRMAC Assessment Working Group. The following default assumptions are used in this method:

Milk DRLs:

1) Apply to individual radionuclides; there is no sum-of-fraction rule (except for the FDA-listed ^{103}Ru and ^{106}Ru).
2) Are based on the most restrictive DIL for each radionuclide based on age group and target organ. See Method 3.1 for DIL calculation assumptions.
3) Assume only one intake pathway is present (i.e., if feed (including forage)/soil is contaminated, drinking water is clean).
4) Assume Animal intake rates of:
    - Cow – 50 kg_{wet}/d for feed (including forage), 60 l/d for water, and 0.5 kg_{soil}/d for soil.
    - Goat – 6 kg_{wet}/d for feed (including forage), 8 l/d for water, and 0.06 kg_{soil}/d for soil.
5) Assume a forage yield of 0.7 kg_{wet}/m^2 for pastureland.
6) Assume a milk density of 1.04 kg_{wet}/l.
7) Assume a soil density of 1600 kg_{soil}/m^3.
8) Assume a mixing depth of 1.0E-03 m for the first growing season (EPA89) and 0.15 m after plowing.
9) Assume a time to market of 2 days.

10) Assume the animal consumes the contaminated material (feed/forage or water) over a period of time sufficient for the animal product intended for human consumption to reach equilibrium.

11) Assume that 100% of the contaminated pathway (feed/forage or water) is contaminated.

12) Use Crop Retention Factors for pastureland of:
    - 1.0 for radioiodine and
    - 0.5 for all other radionuclides.

13) DRLs for FDA grouped radionuclides (e.g., $^{134}Cs+^{137}Cs$) are adjusted for decay during Time to Market using the decay constant for the longest-lived group member.

Inputs

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

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 (including forage), Water, Soil), Transfer Factor for Milk for each radionuclide, density of milk.

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

4) Appropriate DIL for each radionuclide – Calculated using Method 3.1.

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

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

Outputs

Final

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

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

a. $Milk\_DRL_{area}$: The areal activity (µCi/m^2), of radionuclide *i* deposited over a grazing area that would result in the grazing animal's milk equaling the Derived Intervention Level (DIL) for that radionuclide;

b. $Milk\_DRL_{mass}$: The mass concentration ($\mu Ci/kg_{wet}$) of radionuclide *i* in animal feed (including forage) that would result in the animal's milk equaling the Derived Intervention Level (DIL) for that radionuclide; or
c. $Milk\_DRL_{water}$: The water concentration (µCi/l) of radionuclide *i* in an animal's drinking water that would result in the animal's milk equaling the Derived Intervention Level (DIL) for that radionuclide.

Intermediate

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

None

Method 3.3.1 Ingestion DRL for Milk based on areal activity (µCi/m^2) on forage

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

Calculation

Equation 3.3-1 shows this $Milk\_DRL_{area}$ calculation.

$$Milk\_DRL_{area,A,i} = \frac{DIL_{organ,age,i} * \rho_{milk}}{\left[\frac{(CRF * AFDIR)}{Y} + \frac{ASDIR}{\rho_{soil} * d_m}\right] * FDC_F * TF_{Milk,A,i} * e^{-\lambda_i t_m}} \quad \text{(Eq. 3.3-1)}$$

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

where:

$Milk\_DRL_{area,A,i}$ = Milk Ingestion Derived Response Level – Area, the areal activity of radionuclide *i* deposited over a grazing area that would result in the grazing animal's (*A*) milk equaling the DIL for that radionuclide, µCi/m^2;

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

ρ_{milk} = Milk density (See Appendix C, Table 11), kg$_{wet}$/l;

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

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

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

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

ρ_{soil} = Soil density (See Appendix C, Table 11), kg$_{soil}$/m^3;

d_m = Mixing Depth (See Appendix C, Table 11), m;

FDC_F = Fraction of Diet Contaminated (feed), the fraction of the animal's diet that is from contaminated feed (including forage), unitless;
NOTE: See Appendix C, Table 11 for default *FDC* values. If there is convincing local information that the actual *FDC* is considerably different, local authorities may decide to use a different *FDC*.

$TF_{Milk,A,i}$ = Transfer Factor for Milk, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the milk produced by the animal, µCi/l per µCi/d;

λ_i = Decay constant for radionuclide *i*, d^{-1};

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d; and

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

Method 3.3.2 Ingestion DRL for Milk based on radionuclide concentration (µCi/kg$_{wet}$) in feed (including forage) mass

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

Calculation

Equation 3.3-2 shows this $Milk\_DRL_{mass}$ calculation.

$$Milk\_DRL_{mass,A,i} = \frac{DIL_{organ,age,i} * \rho_{milk}}{AFDIR * FDC_F * TF_{Milk,A,i} * e^{-\lambda_i t_m}} \quad \text{(Eq. 3.3-2)}$$

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

where:

$Milk\_DRL_{mass,A,i}$ = Milk Ingestion Derived Response Level – Mass, the mass concentration of radionuclide *i* in animal feed (including forage) that would result in the grazing animal's (*A*) milk equaling the DIL for that radionuclide, µCi/kg_{wet};

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

ρ_{milk} = Milk density (See Appendix C, Table 11), kg_{wet}/l;

AFDIR = Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed (including forage), kg_{wet}/d;

FDC_F = Fraction of Diet Contaminated (feed), the fraction of the animal's diet that is from contaminated feed (including forage), unitless;
NOTE: See Appendix C, Table 11 for default *FDC* values. If there is convincing local information that the actual *FDC* is considerably different, local authorities may decide to use a different *FDC*.

$TF_{Milk,A,i}$ = Transfer Factor for Milk, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the milk produced by the animal, µCi/l per µCi/d;

λ_i = Decay constant for radionuclide *i*, d^{-1};

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d; and

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

NOTE: Soil ingestion is not included in this method because any soil (and any radioactivity) included in the fodder being analyzed would inherently be included in the mass and activity values determined by the measurement process.

Method 3.3.3 Ingestion DRL for Milk based on radionuclide concentration (µCi/l) in water

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

Calculation

Equation 3.3-3 shows this $Milk\_DRL_{water}$ calculation.

$$Milk\_DRL_{water,A,i} = \frac{DIL_{organ,age,i} * \rho_{milk}}{AWDIR * FDC_W * TF_{Milk,A,i} * e^{-\lambda_i t_m}} \qquad \text{(Eq. 3.3-3)}$$

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

where:

$Milk\_DRL_{water,A,i}$ = Milk Ingestion Derived Response Level – Water, the water concentration of radionuclide *i* in an animal's drinking water that would result in the grazing animal's (*A*) milk equaling the DIL for that radionuclide, µCi/l;

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

ρ_{milk} = Milk density (See Appendix C, Table 11), kg_{wet}/l;

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

FDC_W = Fraction of Diet Contaminated (water), the fraction of an animal's diet that is from contaminated water, unitless;
NOTE: See Appendix C, Table 11 for default *FDC* values. If there is convincing local information that the actual *FDC* is considerably different, local authorities may decide to use a different *FDC*.

$TF_{Milk,A,i}$ = Transfer Factor for Milk, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the milk produced by the animal, µCi/l per µCi/d;

λ_i = Decay constant for radionuclide *i*, d^{-1};

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d; and

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

NOTE: Soil ingestion is not included in this method because any soil (and any radioactivity) included in the water being analyzed would inherently be included in the mass and activity values determined by the measurement process.

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EXAMPLE 1

Problem: Calculate the Cow Milk Ingestion DRL for ^{60}Co in units of areal activity (µCi/m^2)

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

Equation 3.3-1 can be used to calculate the DRL.

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

Assuming:

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

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

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

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

EXAMPLE 2

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

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

Equation 3.3-2 can be used to calculate the DRL.

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

Assuming:

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

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

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

Therefore cows that eat feed (including forage) with ^{60}Co contamination greater than 1.38 µCi/kg$_{wet}$ have the potential to produce milk that would equal the DIL. Milk that equals the DIL could produce a dose that equals the PAG when consumed by a 3 month old.

EXAMPLE 3

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

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

Equation 3.3-3 can be used to calculate the DRL.

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

Assuming:

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

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

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

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

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METHOD 3.4 MEAT INGESTION DERIVED RESPONSE LEVEL

Application

This method has been developed to calculate Ingestion Derived Response Levels for radioactive material deposited on animal feed/forage or water for the meat pathway.

The Meat Ingestion Derived Response Level:

1) Represents:
   a. $Meat\_DRL_{area,A,i}$: The areal activity (μCi/m^2), of radionuclide *i* deposited over a grazing area that would result in a grazing animal's (*A*) meat equaling the Derived Intervention Level (DIL) for that radionuclide when the animal is harvested;
   b. $Meat\_DRL_{mass,A,i}$: The mass concentration (μCi/kg_{wet}), of radionuclide *i* in animal feed (including forage) that would result in the animal's (*A*) meat equaling the Derived Intervention Level (DIL) for that radionuclide when the animal is harvested; or
   c. $Meat\_DRL_{water,A,i}$: The water concentration (μCi/l), of radionuclide *i* in an animal's drinking water that would result in the animal's (*A*) meat equaling the Derived Intervention Level (DIL) for that radionuclide when the animal is harvested.

2) Is indirectly derived (through the DIL) from the PAG for radiological emergency planning established by the Food and Drug Agency (FDA) (FDA98). A projected or measured concentration value greater than the Meat_DRL indicates the potential to exceed the PAG.

3) Is applied during the first year after an incident and based on the most sensitive population (age group) and target organ to provide a large margin of safety to the public (FDA98).

4) Is used to create data products and define contamination levels to assist decision makers in determining where it may be advisable to conduct sampling to evaluate the potential for implementing protective actions (e.g., sheltering livestock, embargos, special product handling).

5) Is calculated using the DIL calculated in Method 3.1

Discussion

The Meat_DRL predicts the amount of radioactivity deposited either on an animal's grazing area (μCi/m^2) or in an animal's feed (including forage) or water (μCi/kg_{wet} or μCi/l) that would cause the animal's meat to equal the DIL.

Sampling efforts should concentrate on the area where the contamination is equal to the Meat_DRL to determine if the DIL has been exceeded in those areas. Protective actions (e.g., use of stored feed) should be considered in areas where the DIL is exceeded. Meat embargo protective actions should be considered after meat samples indicate that the DIL has actually been exceeded. FDA guidance permits food with radioactivity concentrations below the DIL to move in commerce without restriction. However the FDA and local decision makers have flexibility in whether to apply restrictions in special circumstances.

FRMAC does not have the authority to calculate or use different DILs for radionuclides for which the FDA has provided recommended values unless alternate values are requested by the Advisory Team or local decision makers. FRMAC can calculate DILs for the radionuclides for which the FDA does not provide recommended values, but these values are not automatically approved by the FDA and must receive approval from the Advisory Team or local Decision Makers before they are used.

Assumptions

The FRMAC radiological assessment calculations use the default assumptions established by the FRMAC Assessment Working Group. The following default assumptions are used in this method:

Meat DRLs:

1) Apply to individual radionuclides; there is no sum-of-fraction rule (except for the FDA-listed ^{103}Ru and ^{106}Ru).
2) Are based on the most restrictive DIL for each radionuclide based on age group and target organ. See Method 3.1 for DIL calculation assumptions.
3) Assume only one intake pathway is present (i.e., if feed (including forage)/soil is contaminated, drinking water is clean).
4) Assume Animal intake rates of:
   - Cow – 50 kg_{wet}/d for feed (including forage), 50 l/d for water, and 0.5 kg_{soil}/d for soil.
   - Goat – 6 kg_{wet}/d for feed (including forage), 8 l/d for water, and 0.06 kg_{soil}/d for soil.
5) Assume a forage yield of 0.7 kg_{wet}/m^2 for pastureland.
6) Assume a soil density of 1600 kg_{soil}/m^3.
7) Assume a mixing depth of 1.0E-03 m for the first growing season (EPA89) and 0.15 m after plowing.
8) Assume a half-life of 15 days for material weathering off plant material.
9) Assume a time to market of 20 days.
10) Assume the animal consumes the contaminated material (feed/forage or water) over a period of time sufficient for the animal product intended for human consumption to reach equilibrium.

11) Assume that 100% of the contaminated pathway (feed/forage or water) is contaminated.

12) Uses Crop Retention Factors for pastureland of:
   - 1.0 for radioiodine and
   - 0.5 for all other radionuclides.

13) DRLs for FDA grouped radionuclides (e.g., $^{134}Cs+^{137}Cs$) are adjusted for decay during Grazing Time and Time to Market using the decay constant for the longest-lived group member.

Inputs

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

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 (including forage), Water, Soil), Transfer Factor for each type of Meat and for each radionuclide.
3) Other Factors – Decay of radionuclides during the time period under consideration, fraction of animals' diet contaminated, soil mixing depth.
4) Appropriate DIL for each radionuclide – Calculated using Method 3.1.

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

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

Outputs

Final

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

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

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

b. $Meat\_DRL_{mass,A,i}$: The mass concentration (µCi/kg_{wet}) of radionuclide *i* in animal feed (including forage) that would result in the animal's (*A*) meat equaling the Derived Intervention Level (DIL) for that radionuclide when the animal is harvested; or
c. $Meat\_DRL_{water,A,i}$: The water concentration (µCi/l) of radionuclide *i* in an animal's drinking water that would result in the animal's (*A*) meat equaling the Derived Intervention Level (DIL) for that radionuclide when the animal is harvested.

Intermediate

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

None

Method 3.4.1 Ingestion DRL for Meat based on areal activity (µCi/m²) on forage

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

Calculation

Equation 3.4-1 shows this $Meat\_DRL_{area}$ calculation.

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

(Eq. 3.4-1)

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

where:

$Meat\_DRL_{area,A,i}$ = Meat Ingestion Derived Response Level – Area, the areal activity of radionuclide *i* that would result in a grazing animal's (*A*) meat equaling the DIL for that radionuclide, µCi/m^2;

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

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

λ_w = Decay constant for weathering radioactive material off plants (See Appendix C, Table 11), d^{-1};

t_g = Grazing Time, the time the animal spends grazing in the contaminated field, d;

$\left(\frac{1\text{-}e^{-\lambda_w t_g}}{\lambda_w * t_g}\right)$ = Integrated average weathering of radioactive material off plants during the time the animal is grazing in the field (the integral of the weathering over the Grazing Time divided by the Grazing Time), unitless;

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

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

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

ρ_{soil} = Soil density (See Appendix C, Table 11), kg$_{soil}$/m^3;

d_m = Mixing Depth (See Appendix C, Table 11), m;

FDC_F = Fraction of Diet Contaminated (feed), the fraction of the animal's diet that is from contaminated feed (including forage), unitless;
NOTE: See Appendix C, Table 11 for default *FDC* values. If there is convincing local information that the actual *FDC* is considerably different, local authorities may decide to use a different *FDC*.

$TF_{Meat,A,i}$ = Transfer Factor for Meat, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the meat of the animal, µCi/kg$_{wet}$ per µCi/d;

λ_i = Decay constant for radionuclide *i*, d^{-1};

$\left(\frac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g}\right)$ = Integrated average decay of radioactive material during the time the animal is grazing in the field (the integral of radioactive decay over the Grazing Time divided by the Grazing Time), unitless;

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d; and

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

Method 3.4.2 Ingestion DRL for Meat based on radionuclide concentration (µCi/kg$_{wet}$) in feed (including forage) mass

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

Calculation

Equation 3.4-2 shows this $Meat\_DRL_{mass}$ calculation.

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

(Eq. 3.4-2)

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

where:

$Meat\_DRL_{mass,A,i}$ = Meat Ingestion Derived Response Level – Mass, the mass concentration of radionuclide *i* in animal feed (including forage) that would result in the animal's (*A*) meat equaling the DIL for that radionuclide when the animal is harvested, µCi/kg$_{wet}$;

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

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

FDC_F = Fraction of Diet Contaminated (feed), the fraction of an animal's diet that is from contaminated feed (including forage), unitless;
NOTE: See Appendix C, Table 11 for default *FDC* values. If there is convincing local information that the actual *FDC* is considerably different, local authorities may decide to use a different *FDC*.

$TF_{Meat,A,i}$ = Transfer Factor for Meat, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the meat of the animal, µCi/kg$_{wet}$ per µCi/d;

λ_w = Decay constant for weathering radioactive material off plants (See Appendix C, Table 11), d^{-1};

t_g = Grazing Time, the time the animal spends grazing in the contaminated field, d;

λ_i = Decay constant for radionuclide *i*, d^{-1};

$\left(\frac{1\text{-}e^{-\lambda_w t_g}}{\lambda_w * t_g}\right)$ = Integrated average weathering of radioactive material off plants during the time the animal is grazing in the field (the integral of the weathering over the Grazing Time divided by the Grazing Time), unitless;

NOTE: If the calculation is being performed for stored feed, this weathering term should not be included (set value to 1).

$\left(\frac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g}\right)$ = Integrated average decay of radioactive material during the time the animal is grazing in the field (the integral of radioactive decay over the Grazing Time divided by the Grazing Time), unitless;

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d; and

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

NOTE: Soil ingestion is not included in this method because any soil (and any radioactivity) included in the fodder being analyzed would inherently be included in the mass and activity values determined by the measurement process.

Method 3.4.3 Ingestion DRL for Meat based on radionuclide concentration (µCi/l) in water

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

NOTE: Because any form of "weathering" that could be applied to this calculation could vary by such a large amount (dependent on water source), and because not including weathering is the conservative approach, no consideration of physical removal of contamination from the drinking water is addressed in this method.

Calculation

Equation 3.4-3 shows this $Meat\_DRL_{water}$ calculation.

$$Meat\_DRL_{water,A,i} = \frac{DIL_{organ,age,i}}{AWDIR * FDC_W * TF_{Meat,A,i} * \left(\frac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g}\right) * e^{-\lambda_i t_m}} \quad \text{(Eq. 3.4-3)}$$

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

where:

$Meat\_DRL_{water,A,i}$ = Meat Ingestion Derived Response Level – Water, the water concentration of radionuclide *i* in an animal's drinking water that would result in the animal's (*A*) meat equaling the DIL for that radionuclide when the animal is harvested, µCi/l;

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

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

FDC_W = Fraction of Diet Contaminated (water), the fraction of an animal's diet that is from contaminated water, unitless;
NOTE: See Appendix C, Table 11 for default *FDC* values. If there is convincing local information that the actual *FDC* is considerably different, local authorities may decide to use a different *FDC*.

$TF_{Meat,A,i}$ = Transfer Factor for Meat, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the meat of the animal, µCi/kg_{wet} per µCi/d;

λ_i = Decay constant for radionuclide *i*, d^{-1};

t_g = Grazing Time, the time the animal spends grazing in the contaminated field, d;

$\left(\frac{1-e^{-\lambda_i t_g}}{\lambda_i * t_g}\right)$ = Integrated average decay of radioactive material during the time the animal is grazing in the field (the integral of radioactive decay over the Grazing Time divided by the Grazing Time), unitless;

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d; and

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

NOTE: Soil ingestion is not included in this method because any soil (and any radioactivity) included in the water being analyzed would inherently be included in the mass and activity values determined by the measurement process.

EXAMPLE 1

Problem: Calculate the Meat (Beef) Ingestion DRL for ^{60}Co in units of areal activity (µCi/m^2)

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

Assuming that the cow will continue to graze on the contaminated field for 90 days after deposition, Equation 3.4-1 can be used to calculate the DRL.

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

Assuming:

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

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

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

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

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

EXAMPLE 2

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

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

Assuming that the cow will continue to graze on the contaminated field for 90 days after deposition, Equation 3.4-2 can be used to calculate the DRL.

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

Assuming:

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

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

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

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

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

EXAMPLE 3

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

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

Assuming that the cow will continue to drink the contaminated water for 90 days after deposition, Equation 3.4-3 can be used to calculate the DRL.

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

Assuming:

$AWDIR_{cow}$ = 50 l/d,
FDC_W = 1.0,
$TF_{Meat,cow,60Co}$ = 1.0E-02 µCi/kg_{wet} per µCi/d,
λ_{Co} = 3.60E-04 d^{-1},
t_g = 90 d, and
t_m = 20 days

The *Meat_DRL*$_{water}$ for ^{60}Co for Beef equals:

$$Meat\_DRL_{water,cow,^{60}Co} = \frac{0.02\,\frac{\mu Ci}{kg_{wet}}}{50\,\frac{l}{d} * 1 * 1.0E\text{-}02\,\frac{\mu Ci / kg_{wet}}{\mu Ci / d} * \frac{1\text{-}e^{-3.6E\text{-}04 d^{-1} * 90d}}{3.6E\text{-}04 d^{-1} * 90d} * e^{-3.6E\text{-}04 * 20}} = 4.1E\text{-}02\,\frac{\mu Ci}{l}$$

Therefore cows that drink water for 90 days with ^{60}Co contamination greater than 4.1E-02 µCi/l at the start of the drinking period have the potential to produce meat (beef) that would equal the DIL. Meat that equals the DIL could produce a dose that equals the PAG when consumed by a 3 month old.

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METHOD 3.5 INGESTION DOSE

Application

This method has been developed to calculate the Ingestion Dose from the consumption of radioactive material, either in food, milk or water.

The Ingestion Dose:

1) Can be applied to the whole body (E) or to a specific organ (H_T)

2) Uses sample results for various food types to calculate the dose that a receptor is projected to receive over a specified time phase (generally 1 year) due to ingestion of the contaminated food.

3) Is used to define dose levels to assist decision makers in determining where it may be advisable to implement protective actions (e.g. sheltering livestock, embargos, special product handling).

Discussion

The Ingestion Dose method calculates the expected dose from consuming foods contaminated by radioactive material and is obtained by combining sample results (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, Shell Fish, Other Meat);
2) Crop/Produce (Leafy, Exposed, Protected, Other Produce, Breads, Cereals, Other Grains);
3) Milk (Fresh Cow's Milk, Other Dairy, Eggs); and
4) Beverages (Tap Water, Water Based Drinks, Soups, Other Beverages).

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 FRMAC radiological assessment calculations use the default assumptions established by the FRMAC Assessment Working Group. The following default assumptions are used in this method:

1) Annual intake for each group and subgroup of foods varies by age group (3 month, 1 yr, 5 yr, 10 yr, 15 yr and adult) (FDA98). If specific intake rates are known, use those instead of defaults.

2) Dose calculations are based on samples of foods as prepared for consumption and assume a consumption period of 1 year. To compare with analytical results it may be necessary to convert to "dry weight," see Method 4.2.

3) Inadvertent ingestion of soil is not included in these methods. Activity contained in any soil present in the food would be accounted for in the sample analysis process. Inadvertent Soil Ingestion is discussed in Method 3.7.

4) Default calculations utilize the International Commission on Radiological Protection (ICRP) 60+ dosimetry model.

Inputs

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

1) Data – Activity concentration (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 from sampling time to consumption time (hold time) and over the duration of consumption (default consumption period is 1 year).

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

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

Outputs

Final

The final output of this method is the Ingestion Dose for a diet including food sources that have been contaminated by a deposition of radioactive material.

E = Committed Effective Dose, the dose to the whole body, from the ingestion of all radionuclides in contaminated food, mrem

H_T = Committed Equivalent Dose, the dose to organ T, from the ingestion of all radionuclides in contaminated food, mrem

Intermediate

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

IngDP = Ingestion Dose Parameter for a specific food type for a specific age group ($mrem \cdot d/kg_{wet}$)

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 for:

a. the time between sample evaluation and consumption (hold time) and
b. the duration of consumption (default of 1 year).

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

Equation 3.5-1 represents the final form of the Ingestion Dose calculation:

$$E_{Ing,age} = \sum_{Subgroup} \left(DFIR_{subgroup,age} * FFC_{subgroup} * IngDP_{E,avg,age} \right) \quad \text{(Eq. 3.5-1)}$$

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

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;

$FFC_{subgroup, i}$ = Fraction of Food Subgroup Contaminated, unitless;
NOTE: See Appendix C, Table 11 for default *FFC* values. If there is convincing local information that the actual *FFC* is considerably different, local authorities may decide to use a different *FFC*.

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

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.

$$IngDP_{E,f,age} = \sum_i \left(C_{f,i} * IngDC_{E,age,i} * e^{-\lambda_i t_h} * \frac{1-e^{-\lambda_i t_c}}{\lambda_i} \right) \qquad \text{(Eq. 3.5-2)}$$

$$\frac{\text{mrem}\bullet\text{d}}{\text{kg}_{\text{wet}}} = \sum_i \left(\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \frac{\text{mrem}}{\mu\text{Ci}} * \text{unitless} * \frac{\text{unitless}}{\text{d}^{-1}} \right)$$

where:

$IngDP_{E,f,age}$ = Ingestion Dose Parameter, the committed effective dose received from ingestion of all radionuclides in a specific food type (*f*) by a specific age group, $\text{mrem}\cdot\text{d/kg}_{wet}$;

$C_{f,i}$ = Food Contamination, the level of contamination of radionuclide *i* in a specific food type (*f*), $\mu\text{Ci/kg}_{wet}$ 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_h = Hold Time, the time elapsed from sample measurement to the beginning of the consumption period, d;

$e^{-\lambda_i t_h}$ = Radioactive Decay adjustment for radionuclide *i* over time t_h, unitless;

t_c = Consumption Time, the length of the consumption period (default 365 days), d;

$\frac{1-e^{-\lambda_i t_c}}{\lambda_i}$ = Integrated decay over the length of consumption period, d.

Method 3.5.2 Calculation of Equivalent Dose to an Organ

The preceding calculations assume that the organ of interest is the whole body. The generic approach can be modified to calculate a dose for a specific organ (e.g., skin, thyroid, etc.).

To calculate the dose to a specific organ, replace the IngDC for the whole body with the IngDC for the specific organ when calculating the IngDP.

EXAMPLE 1

Problem: Calculate the Whole Body Ingestion Dose received by an adult from consuming food contaminated with ^{137}Cs and ^{60}Co for 1 year beginning 100 days after sampling.

Assume food samples were collected for several food types with results as shown below:

Table 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
Water	3.50E-03[a]	5.00E-04[a]

[a] Assumes a density of 1.04 kg/l for milk and 1.0 kg/l for water.

E1.1 Calculating IngDP for each food type using Equation 3.5-2

Table 3.5-E2 shows the values needed to calculate the individual IngDP for each food type.

Table 3.5-E2

Radionuclide	IngDC (mrem/µCi)	λ (days^{-1})	$e^{-\lambda t_h}$	$\frac{1-e^{-\lambda t_c}}{\lambda}$ (days)
^{60}Co	12.7	3.6E-04	0.965	342
^{137}Cs	50.3	6.33E-05	0.993	361

Time from sampling to start of consumption (hold time (t_h)): 100 days
Consumption period (t_c): 365 days

Example IngDP calculation for Beef and IngDP values for the other contaminated food types (Table 3.5-E3):

$$\begin{aligned} IngDP_{E,Beef,Adult} &= 2.5\text{E-03}\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * 12.7\frac{\text{mrem}}{\mu\text{Ci}} * 0.965 * 342\text{ d} \\ &\quad + 4.0\text{E-03}\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * 50.3\frac{\text{mrem}}{\mu\text{Ci}} * 0.993 * 361\text{ d} \\ &= 82.6\frac{\text{mrem}\bullet\text{d}}{\text{kg}_{\text{wet}}} \end{aligned}$$

Table 3.5-E3

Food Type	Sub-group	IngDP ($mrem \cdot d/kg_{wet}$)
Beef	Beef	82.6
Corn	Protected Crop	20.7
Lettuce	Leafy Crop	189
Milk	Cow's Milk	62.3
Oranges	Protected Crop	3.45
Water	Tap Water	23.7

E1.2 Calculating Ingestion Dose using Equation 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 ($mrem \cdot d/kg_{wet}$)	Subgroup Ingestion Dose (mrem)
Beef	Beef	0.098	1	82.6	8.09
Corn/ Oranges	Protected Crop	0.155	1	12.1[b]	1.88
Lettuce	Leafy Crop	0.042	1	189	7.94
Milk	Cow's Milk	0.238	1	62.3	14.8
Water	Tap Water	0.679	1	23.7	16.1
				E (∑)	**48.8**

[a] Assumes a density of 1.04 kg/l for milk and 1.0 kg/l for water.

[b] Average value for all the food types in the subgroup. NOTE: When individual food-type DFIRs are known, they may be used and multiplied by the individual food-type IngDP.

E1.3 Calculating an Ingestion Dose for an individual organ or for a different age group

To calculate a Committed Equivalent Dose (H_T) for a specific organ and/or different age group, use the appropriate IngDC for the organ/age group and calculate as demonstrated above.

METHOD 3.6 PROJECTING CONTAMINATION LEVELS IN FOOD

Application

This method has been developed to project potential contamination levels in food (C_f) based on a measured or projected deposition of radioactive material on the ground.

The contamination levels in food:

1) Can be used to determine potential doses to individuals consuming the food when results from direct sampling of the food are not available.
2) Uses deposition data to project potential contamination levels in crops, milk, and meat.
3) Is used to define dose levels to assist decision makers in determining where it may be advisable to implement protective actions (e.g. sheltering livestock, embargos, special product handling).

Discussion

This method projects the potential contamination levels in food using projected or measured deposition (areal activity) values (μCi/m^2). Calculations will be shown for food crops harvested from contaminated ground and for milk and meat from animals grazing on contaminated forage.

Assumptions

The FRMAC radiological assessment calculations use the default assumptions established by the FRMAC Assessment Working Group. The following default assumptions are used in this method:

1) All deposition values used are for the time of deposition (t=0).
2) A time to market of 1 day for fresh produce, 2 days for milk and 20 days for meat.
3) A crop yield of 2 kg$_{wet}$/m^2 for fresh produce.
4) Crop Retention Factors for fresh produce of:
    - 1.0 for radioiodine and
    - 0.2 for all other radionuclides.
5) Animal intake rates:
    - Cow – 50 kg$_{wet}$/d for feed (including forage), 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 (including forage), 8 l/d for water, and 0.06 kg$_{soil}$/d for soil.

6) A forage yield of 0.7 kg_{wet}/m^2 for pastureland.

7) Crop Retention Factors for pastureland of:
    - 1.0 for radioiodine and
    - 0.5 for all other radionuclides.

8) Assume a soil density of 1600 kg_{soil}/m^3.

9) Assume a mixing depth of 1.0E-03 m for the first growing season (EPA89) and 0.15 m after plowing.

10) The animal consumes the contaminated forage or water over a period of time sufficient for the animal product intended for human consumption to reach equilibrium.

Inputs

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

1) Data – Composition of the deposited radionuclide mixture (radionuclides and concentration). This information may come from predictive analysis (atmospheric dispersion models) or field data (monitoring and/or samples).

2) Constants – Crop Retention Factor, Crop Yield, Animal Daily Intake Rates (Feed (including forage), Water, Soil), Transfer Factor for milk for each radionuclide, Transfer Factor for meat for each radionuclide.

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

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

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

Outputs

Final

The final output of this method is the projected contamination levels in foods that have been affected by a deposition of radioactive material.

C_{crop} = Projected Contamination level in a food Crop (fresh produce), the level of activity per mass in a food type harvested from contaminated ground, $\mu Ci/kg_{wet}$;

C_{milk} = Projected Contamination level in Milk, the level of activity per volume in milk produced from consuming radioactive material, µCi/l; and

C_{meat} = Projected Contamination level in Meat, the level of activity per mass in meat produced from consuming radioactive material, $\mu Ci/kg_{wet}$.

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

NOTE: Weathering Factor is not included in this calculation because the food supply is constantly being added to from available sources, using the initial (unweathered) deposition provides a conservative evaluation of the potential contamination in food types regardless of when they are placed into the supply.

Equation 3.6-1 shows the calculation for determining the amount of contamination that would be expected in a crop based on the deposition (areal activity) on the ground:

$$C_{crop,i} = \frac{Dp_{i,t_0} * CRF}{Y} * e^{-\lambda_i t_m} \qquad \text{(Eq. 3.6-1)}$$

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

where:

$C_{crop,i}$ = Projected Contamination level in a food Crop (fresh produce), the level of activity of radionuclide *i* per mass in a food type harvested from contaminated ground, $\mu Ci/kg_{wet}$;

Dp_{i,t_0} = Initial Deposition, the areal activity of radionuclide *i* at the time of deposition t_0, $\mu Ci/m^2$;

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

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

λ_i = Decay constant for radionuclide *i*, d^{-1};

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d; and

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

Method 3.6.2 Calculation of Contamination in Milk

Equation 3.6-2a shows the calculation for determining the amount of contamination that would be expected in milk based on areal contamination of pastureland and contamination in the drinking water of the animal.

$$C_{milk,i} = \left\{ \begin{array}{l} Dp_{i,t_0} * \left[\dfrac{(CRF * AFDIR)}{Y} + \dfrac{ASDIR}{\rho_{soil} * d_m} \right] * FDC_F \\ + \left[AWDIR * FDC_W * C_W \right] \end{array} \right\} * TF_{Milk,A,i} * e^{-\lambda_i t_m} \quad \text{(Eq. 3.6-2a)}$$

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

where:

$C_{milk,i}$ = Projected Contamination level in Milk, the level of activity of radionuclide *i* per volume in milk produced from animals consuming radioactive material, µCi/l;

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

AFDIR = Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed (including forage), kg_{wet}/d;

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

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

ρ_{soil} = Soil density (See Appendix C, Table 11), kg_{soil}/m^3;

d_m = Mixing Depth (See Appendix C, Table 11), m;

FDC_F = Fraction of Diet Contaminated (feed), the fraction of the animal's diet that is from contaminated feed (including forage), unitless;
NOTE: See Appendix C, Table 11 for default *FDC* values. If there is convincing local information that the actual *FDC* is considerably different, local authorities may decide to use a different *FDC*.

Dp_{i,t_0} = Initial Deposition, the areal activity of radionuclide *i* at the time of deposition t_0, $\mu Ci/m^2$;

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

FDC_W = Fraction of the animals' Diet Contaminated (water), unitless;

NOTE: See Appendix C, Table 11 for default *FDC* values. If there is convincing local information that the actual *FDC* is considerably different, local authorities may decide to use a different *FDC*.

C_W = Contamination level in drinking water, µCi/l;

$TF_{Milk,A,i}$ = Transfer Factor for milk, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the milk produced by the animal, µCi/l per µCi/d;

λ_i = Decay constant for radionuclide *i*, d^{-1};

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d; and

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

If the contamination level in the soil is known ($\mu Ci/kg_{soil}$) the equation can be rewritten as shown in Equation 3.6-2b.

$$C_{milk,i} = \left\{ \begin{array}{l} \dfrac{\left(Dp_i * CRF * AFDIR * FDC_F\right)}{Y} + \left(ASDIR * C_S\right) \\ + \left(AWDIR * FDC_W * C_W\right) \end{array} \right\} * TF_{Milk,A,i} * e^{-\lambda_i t_m}$$

(Eq. 3.6-2b)

$$\frac{\mu Ci}{l} = \left\{ \begin{array}{l} \dfrac{\left(\dfrac{\mu Ci}{m^2} * unitless * \dfrac{kg_{wet}}{d} * unitless\right)}{\dfrac{kg_{wet}}{m^2}} + \left(\dfrac{kg_{soil}}{d} * \dfrac{\mu Ci}{kg_{soil}}\right) \\ + \left(\dfrac{l}{d} * unitless * \dfrac{\mu Ci}{l}\right) \end{array} \right\} * \frac{\mu Ci / l}{\mu Ci / d} * unitless$$

where:

C_S = Contamination level in soil, $\mu Ci/kg_{soil}$;

Method 3.6.3 Calculation of Contamination in Meat

Equation 3.6-3a shows the calculation for determining the amount of contamination that would be expected in meat based on areal contamination of pastureland and contamination in the drinking water of the animal.

$$C_{meat,i} = \left\{ \begin{array}{l} Dp_{i,t_0} * \left[\dfrac{\left(CRF * \left(\dfrac{1\text{-}e^{-\lambda_w t_g}}{\lambda_w * t_g} \right) * AFDIR \right)}{Y} + \dfrac{ASDIR}{\rho_{soil} * d_m} \right] * FDC_F \\ + \left[AWDIR * FDC_W * C_W \right] \end{array} \right\} * TF_{Meat,A,i} * \left(\frac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m}$$

(Eq. 3.6-3a)

$$\frac{\mu Ci}{kg_{wet}} = \left\{ \begin{array}{l} \frac{\mu Ci}{m^2} * \left[\frac{\left(unitless * \frac{unitless}{d^{-1} * d} * \frac{kg_{wet}}{d} \right)}{\frac{kg_{wet}}{m^2}} + \frac{\frac{kg_{soil}}{d}}{\frac{kg_{soil}}{m^3} * m} \right] * unitless \\ + \left[\frac{l}{d} * unitless * \frac{\mu Ci}{l} \right] \end{array} \right\} * \frac{\mu Ci / kg_{wet}}{\mu Ci / d} * \frac{unitless}{d^{-1} * d} * unitless$$

where:

$C_{meat,i}$ = Projected Contamination level in Meat, the level of activity of radionuclide *i* per mass in an animal's meat from consuming radioactive material, $\mu Ci/kg_{wet}$;

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

t_g = Grazing Time, the time the animal spends grazing in the contaminated field, d;

λ_w = Decay constant for weathering radioactive material off plants (See Appendix C, Table 11), d^{-1};

$\left(\frac{1 - e^{-\lambda_w t_g}}{\lambda_w * t_g} \right)$ = Integrated average weathering of radioactive material off plants during the time the animal is grazing in the field (the integral of the weathering over the Grazing Time divided by the Grazing Time), unitless;

$AFDIR$ = Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed (including forage), kg_{wet}/d;

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

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

ρ_{soil} = Soil density (See Appendix C, Table 11), kg_{soil}/m^3;

d_m = Mixing Depth (See Appendix C, Table 11), m;

FDC_F = Fraction of Diet Contaminated (feed), the fraction of the animal's diet that is from contaminated feed (including forage), unitless;
NOTE: See Appendix C, Table 11 for default *FDC* values. If there is convincing local information that the actual *FDC* is considerably different, local authorities may decide to use a different *FDC*.

$Dp_{i,t0}$ = Initial Deposition, the areal activity of radionuclide *i* at the time of deposition t_0, $\mu Ci/m^2$;

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

FDC_W = Fraction of the animals' Diet Contaminated (water), unitless;
NOTE: See Appendix C, Table 11 for default *FDC* values. If there is convincing local information that the actual *FDC* is considerably different, local authorities may decide to use a different *FDC*.

C_W = Contamination level in drinking water, $\mu Ci/l$;

$TF_{Meat,A,i}$ = Transfer Factor for Meat, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the meat of the animal, μCi/kg_{wet} per μCi/d;

λ_i = Decay constant for radionuclide *i*, d^{-1};

$\left(\frac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g}\right)$ = Integrated average decay of radioactive material during the time the animal is grazing in the field (the integral of radioactive decay over the Grazing Time divided by the Grazing Time), unitless;

t_m = Time to Market, the number of days from harvest to consumption (See Appendix C, Table 11), d; and

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

If the contamination level in the soil is known (μCi/kg_{soil}) the equation can be rewritten as shown in Equation 3.6-3b.

$$C_{meat,i} = \left\{ \begin{array}{l} \dfrac{\left(Dp_{i,t_0} * CRF * \left(\dfrac{1\text{-}e^{-\lambda_w t_g}}{\lambda_w * t_g} \right) * AFDIR * FDC_F \right)}{Y} + \left(ASDIR * C_S \right) \\ + \left(AWDIR * FDC_W * C_W \right) \end{array} \right\} * TF_{Meat,A,i} * \left(\frac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m}$$

(Eq. 3.6-3b)

$$\frac{\mu\text{Ci}}{\text{l}} = \left\{ \begin{array}{l} \dfrac{\left(\dfrac{\mu\text{Ci}}{\text{m}^2} * \text{unitless} * \dfrac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \dfrac{\text{kg}_{\text{wet}}}{\text{d}} * \text{unitless} \right)}{\dfrac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \left(\dfrac{\text{kg}_{\text{soil}}}{\text{d}} * \dfrac{\mu\text{Ci}}{\text{kg}_{\text{soil}}} \right) \\ + \left(\dfrac{\text{l}}{\text{d}} * \text{unitless} * \dfrac{\mu\text{Ci}}{\text{l}} \right) \end{array} \right\} * \frac{\mu\text{Ci}/\text{l}}{\mu\text{Ci}/\text{d}} * \frac{\text{unitless}}{\text{d}^{-1} * \text{d}} * \text{unitless}$$

where:

C_S = Contamination level in soil, μCi/kg_{soil};

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EXAMPLE 1

Problem: Calculate the projected contamination levels for a lettuce crop from an area with a deposition of ^{60}Co.

Assuming an initial deposition (areal activity) for ^{60}Co of 4.0E-03 µCi/m^2, Equation 3.6-1 can be used to predict the contamination level in the lettuce crop.

$$C_{crop,i} = \frac{Dp_{i,t_0} * CRF}{Y} * e^{-\lambda_i t_m}$$

Assuming:

CRF = 0.2 (fresh produce),
Y = 2.0 kg$_{wet}$/m^2 (fresh produce),
λ_{Co} = 3.60E-04 d^{-1}, and
t_m = 1 day.

$$C_{lettuce,^{60}Co} = \frac{4.0\text{E-03}\,\frac{\mu\text{Ci}}{\text{m}^2} * 0.2}{2.0\,\frac{\text{kg}_{\text{wet}}}{\text{m}^2}} * e^{\text{-3.6E-04}*1} = 4.0\text{E-04}\,\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

EXAMPLE 2

Problem: Calculate the projected contamination levels for cow's milk from an area with a deposition of ^{60}Co.

Assume an initial deposition (areal activity) for ^{60}Co of 4.0E-03 µCi/m^2 and a water concentration value of 3.0E-05 µCi/l.

Equation 3.6-2 can be used to calculate the contamination level in the cow's milk.

$$C_{milk,i} = \left\{ \begin{array}{l} Dp_{i,t_0} * \left[\dfrac{(CRF * AFDIR)}{Y} + \dfrac{ASDIR}{\rho_{soil} * d_m} \right] * FDC_F \\ + \left[AWDIR * FDC_W * C_W \right] \end{array} \right\} * TF_{Milk,A,i} * e^{-\lambda_i t_m}$$

Assuming:

CRF = 0.5 (pasture),
$AFDIR_{cow}$ = 50 kg_{wet}/d,
Y = 0.7 kg_{wet}/m^2 (pasture),
$ASDIR_{cow}$ = 0.5 kg_{soil}/d,
ρ_{soil} = 1600 kg_{soil}/m^3,
d_m = 1.0E-03 m,
FDC_F = 1.0,
$AWDIR_{cow}$ = 60 l/d,
FDC_W = 1.0,
$TF_{Milk,cow,^{60}Co}$ = 3.0E-04 µCi/l per µCi/d,
λ_{Co} = 3.60E-04 d^{-1}, and
t_m = 2 days.

$$C_{milk,^{60}Co} = \left\{ \begin{array}{l} \left[\dfrac{\left(0.5 * 50 \dfrac{kg_{wet}}{d}\right)}{0.7 \dfrac{kg_{wet}}{m^2}} + \dfrac{0.5 \dfrac{kg_{soil}}{d}}{1600 \dfrac{kg_{soil}}{m^3} * 1.0E\text{-}03m} \right] * 1 * 4.0E\text{-}03 \dfrac{\mu Ci}{m^2} \\ + \left[60 \dfrac{l}{d} * 1 * 3.0E\text{-}05 \dfrac{\mu Ci}{l} \right] \end{array} \right\} * 3.0E\text{-}04 \dfrac{\mu Ci / l}{\mu Ci / d} * e^{-3.6E\text{-}04*2}$$

$$= 4.4E\text{-}05 \frac{\mu Ci}{l}$$

EXAMPLE 3

Problem: Calculate the projected contamination levels for beef from an area with a deposition of ^{60}Co.

Assume an initial deposition (areal activity) for ^{60}Co of 4.0E-03 µCi/m^2 and a water concentration value of 3.0E-05 µCi/l.

Assuming that the cow will continue to graze on the contaminated field for 90 days after deposition, Equation 3.6-3 can be used to calculate the contamination level in the cow's meat.

$$C_{meat,i} = \left\{ \begin{array}{l} Dp_{i,t_0} * \left[\dfrac{\left(CRF * \left(\dfrac{1\text{-}e^{-\lambda_w t_g}}{\lambda_w * t_g} \right) * AFDIR \right)}{Y} + \dfrac{ASDIR}{\rho_{soil} * d_m} \right] * FDC_F \\ + \left[AWDIR * FDC_W * C_W \right] \end{array} \right\} * TF_{Meat,A,i} * \left(\dfrac{1\text{-}e^{-\lambda_i t_g}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m}$$

Assuming:

CRF = 0.5 (pasture),
λ_w = 4.62E-02 d^{-1},
t_g = 90 d,
$AFDIR_{cow}$ = 50 kg$_{wet}$/d,
Y = 0.7 kg$_{wet}$/m^2 (pasture),
$ASDIR_{cow}$ = 0.5 kg$_{soil}$/d,
ρ_{soil} = 1600 kg$_{soil}$/m^3,
d_m = 1.0E-03 m,
FDC_F = 1.0,
$AWDIR_{cow}$ = 60 l/d,
FDC_W = 1.0,
$TF_{Meat,cow,^{60}Co}$ = 1.0E-02 µCi/kg$_{wet}$ per µCi/d,
λ_{Co} = 3.60E-04 d^{-1}, and
t_m = 20 days.

$$C_{beef,{}^{60}Co} = \left\{ \left[\frac{\left(0.5 * \frac{1\text{-}e^{-4.62\text{E-}02\text{d}^{-1} * 90\text{d}}}{4.62\text{E-}02\text{d}^{-1} * 90\text{d}} * 50 \frac{\text{kg}_{\text{wet}}}{\text{d}} \right)}{0.7 \frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \frac{0.5 \frac{\text{kg}_{\text{soil}}}{\text{d}}}{1600 \frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 1.0\text{E-}03\text{m}} \right] * 1 * 4.0\text{E-}03 \frac{\mu\text{Ci}}{\text{m}^2} + \left[60 \frac{\text{l}}{\text{d}} * 1 * 3.0\text{E-}05 \frac{\mu\text{Ci}}{\text{l}} \right] \right\}$$

$$* 1.0\text{E-}02 \frac{\mu\text{Ci}/\text{l}}{\mu\text{Ci}/\text{d}} * \frac{1\text{-}e^{-3.6\text{E-}04\text{d}^{-1} * 90\text{d}}}{3.6\text{E-}04\text{d}^{-1} * 90\text{d}} * e^{-3.6\text{E-}04 * 20}$$

$$= 3.6\text{E-}04 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

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 FRMAC radiological assessment calculations use the default assumptions established by the FRMAC Assessment Working Group. The following default assumptions are used in this method:

1) Default soil intake rates are 5.0E-05 kg_{soil}/day for adults and 1.0E-04 kg_{soil}/day for children (EPA11). This method uses the conservative value of 1.0E-04 kg_{soil}/day for all calculations. If specific intake rates are known, use those instead of defaults.
2) Soil density of 1600 kg_{soil}/m^3.
3) Mixing depth of 1.0E-03 m for the surface layer of contaminated soil and 1.0E-04 m for the layer of dust over pavement (EPA89). This method uses the conservative value of 1.0E-04 m for all calculations.

4) Default calculations utilize the International Commission on Radiological Protection (ICRP) 60+ dosimetry model.

Inputs

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

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 and Decision Makers endorse their use.

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

Outputs

Final

The final output of this method is the Ingestion Dose for soils that have been contaminated by a deposition of radioactive material.

E_{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:

$$E_{soil,age} = \frac{DSIR}{\rho_{soil} * d_m} * \sum_i \left(e^{-\lambda_i t_1} * WF_{t_1} * IngDC_{E,age,i} * WP_{i,TP} \right) \qquad \text{(Eq. 3.7-1)}$$

$$\text{mrem} = \frac{\frac{\text{kg}_{\text{soil}}}{\text{d}}}{\frac{\text{kg}_{\text{soil}}}{\text{m}^3} * \text{m}} * \sum_i \left(\text{unitless} * \text{unitless} * \frac{\text{mrem}}{\mu\text{Ci}} * \frac{\mu\text{Ci} \bullet \text{d}}{\text{m}^2} \right)$$

where:

- $E_{soil,age}$ = Committed Effective Dose from inadvertent soil ingestion, the dose to the whole body, received by a specific age group from ingestion of all radionuclides in contaminated soil, mrem;
- $DSIR$ = Daily Soil Intake Rate, 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;
- $e^{-\lambda_i t_1}$ = Radioactive Decay adjustment for radionuclide *i* from t_0 (deposition) to t_1 (start of the time phase), unitless;
- WF_{t_1} = Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind) from t_0 (deposition) to t_1 (start of the time phase), unitless;
  NOTE: See Appendix F, Supplement 2 for details on calculating WF.
- $IngDC_{E,age,i}$ = Ingestion Dose Coefficient, the ingestion pathway dose coefficient for the whole body (*E*) for a specific age group for radionuclide *i*, 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*), uCi•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} = 6.33E-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:

$DSIR$ = 1.0E-04 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 uCi•d/m^2
WP_{Cs} = 1.26 uCi•d/m^2

$$E_{50,soil,Adult} = \frac{1.0\text{E-}04 \ \frac{\text{kg}_{\text{soil}}}{\text{d}}}{1600 \ \frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 1.0\text{E-}04 \text{ m}} * \left(\begin{array}{l} 0.965 * 0.950 * 12.7 \frac{\text{mrem}}{\mu\text{Ci}} * 0.725 \frac{\mu\text{Ci•d}}{\text{m}^2} \\ +0.994 * 0.950 * 50.3 \frac{\text{mrem}}{\mu\text{Ci}} * 1.26 \frac{\mu\text{Ci•d}}{\text{m}^2} \end{array} \right)$$

$$= 4.27\text{E-}02 \text{ mrem}$$

To calculate a Committed Equivalent Dose (H_T) for a specific organ and/or different age group, use the appropriate IngDC for the organ/age group and calculate as demonstrated above.

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SECTION 4. SUPPLEMENTAL METHODS

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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.

$$K_i = \frac{\chi_i}{Dp_i} \qquad \text{(Eq. 4.1-1)}$$

$$m^{-1} = \frac{\mu Ci / m^3}{\mu Ci / m^2}$$

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 DILs.

Discussion

DILs are based on the level of radioactive material in food "as prepared for consumption." The default assumption for this method is that food products are intended to be eaten in a fresh or "wet" condition.

Because many methods of sample analysis require drying the sample material it may be necessary to apply a dry-to-wet conversion factor to the sample results before a direct comparison may be made to the appropriate DIL. Assessment Scientists must determine when it is appropriate to apply the dry-to-wet conversion factor to sample results for comparison to the DIL.

Assumptions

The FRMAC radiological assessment calculations use the default assumptions established by the FDA.

The following default assumptions are used in this method:

- Food products are intended to be eaten in a fresh or "wet" condition. This does not apply to fodder that is to be fed to livestock in a dry form.

Inputs

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

1) Data: Sampling Results from food products/fodder in terms of dry mass ($\mu Ci/kg_{dry}$).
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 and Decision Makers endorse their use.

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

Outputs

Final

The final output of this method is a sample analysis result in "wet mass" that may be directly compared to a DIL.

$C_{sample,i,wet}$ = Sample Contamination, the level of contamination of radionuclide *i* in an analytical sample in terms of wet mass, $\mu Ci/kg_{wet}$.

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
$MCF_{D\text{-}W,subgroup}$ = Mass Conversion Factor (dry to wet) – the ratio of dry mass to wet mass for a food subgroup (See Appendix C, Table 9), kg_{dry}/kg_{wet}.

Note: If the sample results are reported in wet mass, or when the sample is for livestock fodder that will be fed to the animals in a dry form, this calculation is not necessary.

EXAMPLE 1

Problem: Calculate the wet mass Contamination level from sample results

A dried sample of an apple crop is found to contain 6.0E-02 µCi/kg of ^{137}Cs. The crop of apples is intended to be consumed as fresh produce (i.e., not dried or dehydrated).

The DIL for ^{137}Cs is 3.7E-02 µCi/kg; does the sample exceed the DIL?

Because this apple crop's "as prepared for consumption" form will be wet mass, Equation 4.2-1 should be used to calculate the wet mass Concentration.

$$C_{sample,i,wet} = C_{sample,i,dry} * MCF_{D-W,subgroup}$$

Given:

$MCF_{D\text{-}W}$, $_{\text{apples}}$= 0.18 $\text{kg}_{\text{dry}}/\text{kg}_{\text{wet}}$

$$C_{sample,i,wet} = 6.0\text{E-}02\,\frac{\mu\text{Ci}}{\text{kg}_{\text{dry}}} * 0.18\,\frac{\text{kg}_{\text{dry}}}{\text{kg}_{\text{wet}}} = 1.08\text{E-}02\,\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

Since:

$$1.08\text{E-}02\,\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} < 3.7\text{E-}02\,\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

The sample does not exceed the DIL when the apples are evaluated in the "as prepared for consumption" form.

This demonstrates the importance of comparing "wet apples to wet apples" when making decisions about whether a particular food product exceeds the DIL.

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METHOD 4.3 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) Daughter radionuclides must be "back-decayed" 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

The base assumption of this method is that both weathering and radioactive decay occur from deposition to sample collection, but that only radioactive decay affects the sample from the time of collection to analysis.

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 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, µCi/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.

$$Dp_{i,t_s} = \frac{Dp_{i,t_r}}{e^{-\lambda_i * (t_r - t_s)}} \quad \text{(Eq. 4.3-1)}$$

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

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 can be 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 F2.2.1 for a description of the default FRMAC Weathering Factor.

$$Dp_{i,t_0} = \frac{Dp_{i,t_s}}{\left(0.4 * e^{\text{-1.46E-08}*(t_s - t_0)} + 0.6 * e^{\text{-4.44E-10}*(t_s - t_0)}\right) * e^{-\lambda_i *(t_s - t_0)}} \quad \text{(Eq. 4.3-2)}$$

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

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;
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.

$$Dp_{i,t_n} = Dp_{i,t_0} * \left(0.4 * e^{\text{-1.46E-08}*t_n} + 0.6 * e^{\text{-4.44E-10}*t_n}\right) * e^{-\lambda_i * t_n} \quad \text{(Eq. 4.3-3)}$$

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

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

$\lambda_{Cs\text{-}134}$ = 1.07E-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:

$$Dp_{i,t_s} = \frac{0.70\,\frac{\mu\text{Ci}}{\text{m}^2}}{e^{-1.07\text{E-}08*(1.56\text{E+}07-1.30\text{E+}07)}} = 0.72\,\frac{\mu\text{Ci}}{\text{m}^2}$$

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:

$$Dp_{i,t_0} = \frac{0.72\,\frac{\mu\text{Ci}}{\text{m}^2}}{\left(0.4*e^{-1.46\text{E-}08*1.30\text{E+}07}+0.6*e^{-4.44\text{E-}10*1.30\text{E+}07}\right)*e^{-1.07\text{E-}08*1.30\text{E+}07}} = 0.89\,\frac{\mu\text{Ci}}{\text{m}^2}$$

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) 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]	$\mu Ci/m^2$	AAL = DRL x Resuspension Factor (1E-06 m^{-1} Default)	$\mu Ci/m^3$
Feed	$Milk\_DRL_{mass}$	$\mu Ci/kg_{wet}$	AAL = $Milk\_DRL_{mass}$	$\mu Ci/kg_{wet}$
Food	DIL	$\mu Ci/kg_{wet}$	AAL = DIL	$\mu Ci/kg_{wet}$
Milk	DIL	$\mu Ci/kg_{wet}$	AAL = DIL	$\mu Ci/kg_{wet}$
Soil "Short Term"	Deposition DRL "Short Term" [a]	$\mu Ci/m^2$	AAL = DRL x Sample Size (0.01 m^2 Default)	µCi/sample
Soil "Long Term"	Deposition DRL "Long Term" [b]	$\mu Ci/m^2$	AAL = DRL x Sample Size (0.01 m^2 Default)	µCi/sample
Cow Water	$Milk\_DRL_{water}$	µCi/l	AAL = $Milk\_DRL_{water}$	µCi/l
Drinking Water	EPA Guidelines			pCi/l

[a] Short Term Deposition Derived Response Levels are the minimum (most conservative) of the DRLs for the Early Phase and 1[st] Year Time Phases.

[b] Long Term Deposition Derived Response Levels are the minimum (most conservative) of the DRLs for the Early Phase, 1[st] Year, and 2[nd] Year Time phases as well as the $Milk\_DRL_{area}$

The calculated AAL should then be divided by the LC 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.

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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 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
   - 1.0E-02 m/s for Reactive Gasses (e.g., Iodine).
   - 0.0 m/s for Noble Gases which are assumed to remain airborne and are not deposited on the ground.

Inputs

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

1) Data: Integrated Air Activity (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 and Decision Makers endorse their use.

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

Outputs

Final

The final output of this method is either an Integrated Air Activity or a Deposition value for the passage of a plume of radioactive material.

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

Dp_{i,t_0} = Initial Deposition, the areal activity of radionuclide *i* at the time of deposition t_0, µCi/m^2;

Intermediate

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

None.

Method 4.5.1 Estimating missing data (Dp_i or $\tilde{A}_i$) from the known value

Calculation

Equation 4.5-1 shows the calculation of Integrated Air Activity from Deposition.

$$\tilde{A}_i = \frac{Dp_{i,t_0}}{V_d} \qquad \text{(Eq. 4.5-1)}$$

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

where:

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

$$Dp_i = \tilde{A}_i * V_d \qquad \text{(Eq. 4.5-2)}$$

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

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.

$$\bar{V}_d = \sum \left(V_{d_{PS}} * F_{PS} \right) \qquad \text{(Eq. 4.5-3)}$$

$$\frac{\text{m}}{\text{s}} = \frac{\text{m}}{\text{s}} * \text{unitless}$$

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	1.0E-02	8
Xe-133	1500	0	0

Remember, because different elements and chemical 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 <u>if you assume</u> 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 Four-Pathway 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.

$$\tilde{A}_i = \frac{\chi_{i,t_r}}{e^{-\lambda_i*(t_r - t_s)}} * \left(\frac{1 - e^{-\lambda_i * t_\Delta}}{\lambda_i} \right) \qquad \text{(Eq. 4.6-1a)}$$

$$\frac{\mu\text{Ci} \bullet \text{s}}{\text{m}^3} = \frac{\frac{\mu\text{Ci}}{\text{m}^3}}{\text{unitless}} * \frac{\text{unitless}}{\text{s}^{-1}}$$

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:

$$\tilde{A}_i = \chi_{i,t_r} * t_\Delta \qquad \text{(Eq. 4.6-1b)}$$

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:

$$\tilde{A}_i = \chi_{i,t_s} * \left(\frac{1 - e^{-\lambda_i * t_\Delta}}{\lambda_i} \right) \qquad \text{(Eq. 4.6-2)}$$

$$\frac{\mu\text{Ci} \bullet \text{s}}{\text{m}^3} = \frac{\mu\text{Ci}}{\text{m}^3} * \frac{\text{unitless}}{\text{s}^{-1}}$$

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/m^3 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)

$\lambda_{Tc\text{-}99m}$ = 3.2E-05 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.

$$\chi_{\text{Tc-99m},t_s} = \frac{1\frac{\mu\text{Ci}}{\text{m}^3}}{e^{-3.2\text{E-}05*(2.52\text{E+}04\text{-}1.44\text{E+}04)}} = 1.41\frac{\mu\text{Ci}}{\text{m}^3}$$

Step 2 – Integrate this value over the sample duration.

$$\tilde{A}_{\text{Tc-99m}} = 1.41\frac{\mu\text{Ci}}{\text{m}^3} * \left(\frac{1-e^{-3.2\text{E-}05*1.2\text{E+}03}}{3.2\text{E-}05\text{s}^{-1}} \right) = 1.66\text{E+}03\frac{\mu\text{Ci}\bullet\text{s}}{\text{m}^3}$$

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METHOD 4.7 RELATING MEASURED DOSE RATES TO AREAL ACTIVITY

This method is reserved for future development.

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GLOSSARY

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 Package)	An electronic database containing dose coefficients from ICRP Dosimetry Models.
Deposition	The contamination on the surface of the ground.
Derived Intervention Level (DIL)	The concentration of a radionuclide in food that could lead to an individual receiving a dose equal to the PAG.
Derived Response Level (DRL)	A calculated value (*e.g.*, dose rate or radionuclide concentration) that corresponds to an early health effect threshold, a PAG, or a DIL. DRLs can be used to relate environmental measurements or laboratory analysis to the potential for early health effects or need for protective actions. Used to facilitate prompt assessments.
Early 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.
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.
Protective Action Guide (PAG)	The projected dose, from an accidental release of radioactive material, where specific actions to reduce or avoid dose are warranted.
Quality Factor (QF)	The principal modifying factor that represents the biological effectiveness of different radiation types with respect to induction of stochastic effects. It is used to calculate the dose equivalent from the absorbed dose. The absorbed dose, expressed in rad or Gy, is multiplied by the appropriate quality factor to obtain the dose equivalent.
Relative Biological Effectiveness (RBE)	The RBE of a given type of ionizing radiation is a factor used to compare the biological effectiveness of absorbed radiation doses (i.e., rads) due to one type of ionizing radiation with that of other types of ionizing radiation; more specifically, it is the experimentally determined ratio of an absorbed dose of a radiation in question to the absorbed dose of a reference radiation required to produce an identical biological effect in a particular experimental organism or tissue.
Resuspension	Reintroduction to the 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, plant forage or water.

Turn-Back Guidance Guidance given to emergency workers indicating when they should seek areas of lower exposure rate or potential. This guidance is usually implemented via a DRL expressed as an integrated dose reading on a self-reading dosimeter, an exposure rate, or a deposition concentration indicating that the emergency worker should leave the area where further exposure is possible.

Weathering Reduction of dose from deposited radionuclides (external and resuspension) over time due to movement of contamination below the surface or binding on surface materials.

Weighting Factors The fraction of the overall health risk resulting from uniform whole body irradiation attributable to a specific organ.

Organ	Weighting Factor
Gonads	0.20
Red bone marrow	0.12
Colon	0.12
Lungs	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surfaces	0.01
Remainder[1]	0.05
Whole body[2]	1.00

Source: ICRP90, Table 2.

[1] "Remainder" means the following additional tissues and organs and their masses, in grams, following parenthetically: adrenals (14), brain (1400), extrathoracic airways (15), small intestine (640), kidneys (310), muscle (28,000), pancreas (100), spleen (180), thymus (20), and uterus (80). The equivalent dose to the remainder tissues ($H_{remainder}$) is normally calculated as the mass-weighted mean dose to the preceding ten organs and tissues. In those cases in which the most highly irradiated remainder tissue or organ receives the highest equivalent dose of all the organs, a weighting factor of 0.025 (half of remainder) is applied to that tissue or organ and 0.025 (half of remainder) to the mass-weighted equivalent dose in the rest of the remainder tissues and organs to give the remainder equivalent dose.

[2] For the case of uniform external irradiation of the whole body, a tissue weighting factor (w_T) equal to 1 may be used in determination of the effective dose.

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TERM	UNITS	DEFINITION	METHODS
$2Path\_DRL_{\tilde{A}}$	$\frac{\mu Ci}{m^2}$	Two-Pathway Air Derived Response Level, the integrated air activity ($\tilde{A}$) of radionuclide *i* at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.	1.1, 1.3, 1.4
$2Path\_DRL_{Dp}$	$\frac{\mu Ci}{m^2}$	Two-Pathway Deposition Derived Response Level, the areal activity, at time t_n, of radionuclide *i* at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.	1.1, 1.3, 1.4
$2Path\_DRL_{DR}$	$\frac{mrem}{hr}$	Two-Pathway Dose Rate Derived Response Level, the external dose rate one meter above the ground, at time t_n, at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.	1.2, 1.5
$2Path\_DRL_{XR}$	$\frac{mR}{hr}$	Two-Pathway 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 (considering only ground dose pathways) would equal the PAG over the time phase under consideration.	1.2, 1.5
$2Path\_DRL_{\alpha,\tilde{A}}$	$\frac{\mu Ci_{\alpha} \bullet s}{m^3}$	Two-Pathway Air Alpha Derived Response Level, the integrated air alpha activity of the mixture at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.	1.3
$2Path\_DRL_{\alpha,Dp}$	$\frac{\mu Ci_{\alpha}}{m^2}$	Two-Pathway Deposition Alpha Derived Response Level, the areal alpha activity of the mixture, at time t_n, at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.	1.3
$2Path\_DRL_{\beta,\tilde{A}}$	$\frac{\mu Ci_{\beta} \bullet s}{m^3}$	Two-Pathway Air Beta Derived Response Level, the integrated air beta activity of the mixture at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.	1.4

TERM	UNITS	DEFINITION	METHODS
$2Path\_DRL_{\beta,Dp}$	$\frac{\mu Ci_{\beta}}{m^2}$	Two-Pathway Deposition Beta Derived Response Level, the areal beta activity of the mixture, at time t_n, at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.	1.4
2Path_MTDP	mrem	Two-Pathway Mixture Total Dose Parameter, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration, from the radionuclide mixture.	1.1, 1.2
2Path_PPD	mrem	Two-Pathway Projected Public Dose, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration, from the radionuclide mixture.	1.5
$4Path\_DRL_{\tilde{A}}$	$\frac{\mu Ci \bullet s}{m^3}$	Four-Pathway Air Derived Response Level, the integrated air activity ($\tilde{A}$) of radionuclide *i* at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.	1.1, 1.3, 1.4
$4Path\_DRL_{Dp}$	$\frac{\mu Ci}{m^2}$	Four-Pathway Deposition Derived Response Level, the areal activity, at time t_n, of radionuclide *i* at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.	1.1, 1.3, 1.4
$4Path\_DRL_{DR}$	$\frac{mrem}{hr}$	Four-Pathway 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 (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.	1.2, 1.5
$4Path\_DRL_{XR}$	$\frac{mR}{hr}$	Four-Pathway 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 (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.	1.2, 1.5
$4Path\_DRL_{\alpha,\tilde{A}}$	$\frac{\mu Ci_{\alpha} \bullet s}{m^3}$	Four-Pathway Air Alpha Derived Response Level, the integrated air alpha activity of the mixture at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.	1.3

TERM	UNITS	DEFINITION	METHODS
$4Path\_DRL_{\alpha,Dp}$	$\frac{\mu Ci_{\alpha}}{m^2}$	Four-Pathway Deposition Alpha Derived Response Level, the areal alpha activity of the mixture, at time t_n, at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.	1.3
$4Path\_DRL_{\beta,\tilde{A}}$	$\frac{\mu Ci_{\beta} \cdot s}{m^3}$	Four-Pathway Air Beta Derived Response Level, the integrated air beta activity of the mixture at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.	1.4
$4Path\_DRL_{\beta,Dp}$	$\frac{\mu Ci_{\beta}}{m^2}$	Four-Pathway Deposition Beta Derived Response Level, the areal beta activity of the mixture, at time t_n, at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.	1.4
4Path_MTDP	mrem	Four-Pathway Mixture Total Dose Parameter, the sum of the external dose from submersion and groundshine and the committed dose from inhalation of plume-borne and resuspended material, over the time phase under consideration, from the radionuclide mixture.	1.1, 1.2
4Path_PPD	mrem	Four-Pathway Projected Public Dose, the sum of the external dose from submersion and groundshine and the committed dose from inhalation of plume-borne and resuspended material, over the time phase under consideration, from the radionuclide mixture.	1.5
$\tilde{A}_i$	$\frac{\mu Ci \cdot s}{m^3}$	Integrated air activity of radionuclide *i* in a release.	1.1, 4.5
AFDIR	$\frac{kg_{wet}}{d}$	Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed (including forage).	3.3, 3.4, 3.6, Appendix C
APF	unitless	Assigned Protection Factor, the level of respiratory protection that a respirator is expected to provide. (Default of 1 when no respirators are used.) **NOTE:** Consult Health and Safety personnel for appropriate values for APF.	2.2
ASDIR	$\frac{kg_{soil}}{d}$	Animal Soil Daily Ingestion Rate, the daily rate at which an animal consumes soil.	3.3, 3.4, 3.6, Appendix C

TERM	UNITS	DEFINITION	METHODS
$AWDIR$	$\frac{\text{L}}{\text{d}}$	Animal Water Daily Ingestion Rate, the daily rate at which an animal consumes water.	3.3, 3.4, 3.6, Appendix C
BR_{AA}	$\frac{\text{m}^3}{\text{s}}$	Activity-Averaged Breathing Rate, the average volume of air breathed per unit time by an adult male (ICRP94, Table B.16B).	1.1
BR_{LE}	$\frac{\text{m}^3}{\text{s}}$	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
χ	$\frac{\mu\text{Ci}}{\text{m}^3}$	Air concentration of radionuclide *i*.	4.1
C_{crop}	$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$	Projected Contamination level in a food crop (fresh produce), the level of activity of radionuclide *i* per mass in a food type harvested from contaminated ground.	3.6
C_f	$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$	Food Contamination, the level of contamination of radionuclide *i* in a specific food type (f). (May also be expressed in µCi/L.)	3.5
C_{meat}	$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$	Projected Contamination level in meat, the level of activity of radionuclide *i* per mass in an animal's meat from consuming radioactive material.	3.6
C_{milk}	$\frac{\mu\text{Ci}}{\text{L}}$	Projected Contamination level in milk, the level of activity of radionuclide *i* per volume in milk produced from animals consuming radioactive material.	3.6
C_S	$\frac{\mu\text{Ci}}{\text{kg}_{\text{soil}}}$	Measured Contamination level of radionuclide *i* in soil.	3.6
$C_{sample,dry}$	$\frac{\mu\text{Ci}}{\text{kg}_{\text{dry}}}$	Sample Contamination, the level of contamination of radionuclide *i* in a sample in terms of dry mass.	4.2
$C_{sample,wet}$	$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$	Sample Contamination, the level of contamination of radionuclide *i* in a sample in terms of wet mass.	4.2
C_W	$\frac{\mu\text{Ci}}{\text{L}}$	Measured Contamination level of radionuclide *i* in drinking water.	3.6
CRF	unitless	Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop.	3.2, 3.3, 3.4, 3.6

TERM	UNITS	DEFINITION	METHODS
$Crop\_DRL_{mat}$	$\frac{\mu Ci}{m^2}$	Ingestion Derived Response Level for mature Crop/Produce, the areal activity of radionuclide *i* that would cause the crop/produce growing in that area to equal the applicable DIL at the time of contamination.	3.2
$Crop\_DRL_{imm}$	$\frac{\mu Ci}{m^2}$	Ingestion Derived Response Level for immature Crop/Produce, the areal activity of radionuclide *i* that would cause the crop/produce growing in that area to equal the applicable DIL at the time of harvest.	3.2
DFIR	$\frac{kg_{wet}}{d}$	Daily Food Intake Rate, the daily intake rate (as prepared for consumption, i.e. wet mass) for a specific age group.	3.1, 3.5
$DFIR_{subgroup}$	$\frac{kg_{wet}}{d}$	Daily Food Intake Rate for a food subgroup (as prepared for consumption, i.e. wet mass) for a specific age group.	3.5
DIL	$\frac{\mu Ci}{kg_{wet}}$	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
d_m	m	Mixing Depth (See Appendix C, Table 11).	3.2, 3.3, 3.4, 3.6, 3.7, Appendix C
Dp_i	$\frac{\mu Ci}{m^2}$	Deposition, the activity of radionuclide *i* per unit area of ground (areal activity).	1.1, 1.2, 3.6, 4.1, 4.5
Dp_ExDC	$\frac{mrem \bullet m^2}{\mu Ci \bullet hr}$	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	mrem	Deposition External Dose Parameter, the external dose from groundshine from radionuclide *i*, over the time phase under consideration.	1.1, 2.2, Appendix C
Dp_InhDP	mrem	Deposition Inhalation Dose Parameter, the committed dose from radionuclide *i* deposited on the ground from the inhalation of the resuspended fraction of the radionuclide over the time phase under consideration.	1.1, 2.2, Appendix C
Dp_MExDF	$\frac{mrem}{hr}$	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

TERM	UNITS	DEFINITION	METHODS
Dp_TDP	mrem	Deposition Total Dose Parameter, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration, from the deposition of radionuclide *i*.	1.1, 1.5, Appendix C
DSIR	$\frac{kg_{soil}}{d}$	Daily Soil Intake Rate, the amount of soil inadvertently ingested by humans in a day.	3.7
E_{Ing}	mrem	Committed Effective Dose from ingestion, the dose to the whole body from ingestion of all radionuclides in all contaminated food types.	3.5
E_{soil}	mrem	Committed Effective Dose from inadvertent soil ingestion, the dose to the whole body from the ingestion of all radionuclides in contaminated soil.	3.7
EDI	d	Effective Days of Intake, the number of days required for radionuclide *i* to decay to <1% of its initial activity (maximum of 365).	3.1
ExDR	$\frac{mrem}{hr}$	External dose rate, the external dose rate from materials deposited on the ground.	1.5
$ExDR_a$	$\frac{mrem}{hr}$	External dose rate at time t_a (hours after detonation).	1.7
$ExDR_b$	$\frac{mrem}{hr}$	External dose rate at time t_b (hours after detonation).	1.7
$ExDR_r$	$\frac{mrem}{hr}$	Reference external dose rate at 1 hour after nuclear detonation.	1.7
$ExDR_{r,PAG}$	$\frac{mrem}{hr}$	Reference external dose rate at 1 hour after nuclear detonation which would produce a dose equal to the PAG over the time phase under consideration.	1.7
$ExDR_t$	$\frac{mrem}{hr}$	External dose rate at time *t* (hours after detonation).	1.7
ExTDCF	$\frac{mrem_{inh+external}}{mrem_{external}}$	External to Total Dose Conversion Factor, the ratio of the total dose (external + inhalation) to the external dose for a deposition of radioactive material over the time phase under consideration. **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.	2.2

TERM	UNITS	DEFINITION	METHODS
FDC	unitless	Fraction of Diet Contaminated, the fraction of a human's diet that is contaminated with radionuclide *i*. FDC is age and radionuclide dependent.	3.1, Appendix C
FDC_F	unitless	Fraction of Diet Contaminated (feed), the fraction of the animal's diet that is from feed (including forage) contaminated by radionuclide *i*	3.3, 3.4, 3.6, Appendix C
FDC_W	unitless	Fraction of Diet Contaminated (water), the fraction of an animal's diet that is from water contaminated by radionuclide *i*.	3.3, 3.4, 3.6, Appendix C
$FFC_{subgroup}$	unitless	Fraction of Food Subgroup contaminated by radionuclide *i*.	3.5, Appendix C
F_{PS}	unitless	Fraction of the mixture of a specific particle size.	4.5
GRF	unitless	Ground Roughness Factor, a constant (0.82) that compensates for the fact that the external exposure is not coming from an infinite flat plane (An02).	1.1, 1.2
H_T	mrem	Committed Equivalent Dose, the dose to organ *T* from the ingestion of all radionuclides in contaminated food.	3.5
$H_{T,soil}$	mrem	Committed Equivalent Dose from inadvertent soil ingestion, the dose to organ *T* from the ingestion of soil.	3.7
IngDC	$\frac{\text{mrem}}{\mu\text{Ci}}$	Ingestion Dose Coefficient, the ingestion pathway dose coefficient for the target organ for a specific age group for radionuclide *i*.	3.1, 3.5, 3.7
IngDP	$\frac{\text{mrem}\bullet\text{d}}{\text{kg}_{\text{wet}}}$	Ingestion Dose Parameter, the committed effective dose received from ingestion of all radionuclides in a specific food type (*f*) by a specific age group.	3.5
$IngDP_{avg}$	$\frac{\text{mrem}\bullet\text{d}}{\text{kg}_{\text{wet}}}$	Average Ingestion Dose Parameter for a food subgroup, the average of the individual *IngDPs* for each type of contaminated food in a subgroup for a specific age group.	3.5
InhDC	$\frac{\text{mrem}}{\mu\text{Ci}}$	Inhalation Dose Coefficient, the committed dose coefficient for inhalation of radionuclide *i*.	1.1, Appendix C
K_t	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

TERM	UNITS	DEFINITION	METHODS
KIPF	unitless	Potassium Iodide Protection Factor, default of 1 for all non-iodine isotopes or when no KI is administered. **NOTE:** Consult Health and Safety personnel for appropriate values for KIPF.	2.2
KP	$\frac{\mu Ci \bullet s}{m^3}$	Resuspension Parameter, value that adjusts the airborne radioactivity level of radionuclide *i* over the time phase under consideration for radioactive decay and in-growth and the resuspension factor.	1.1, Appendix F
λ_i	s^{-1} or d^{-1}	Decay constant for radionuclide *i*.	3.2, 3.3, 3.4, 3.5, 3.6, 3.7, 4.3, 4.6 Appendix C, Appendix F
λ_w	d^{-1}	Decay constant for weathering radioactive material off plants.	3.2, 3.4, 3.6, Appendix C
$MCF_{D\text{-}W}$	$\frac{kg_{dry}}{kg_{wet}}$	Mass Conversion Factor (dry to wet), the ratio of dry mass to wet mass for a food type or subgroup.	3.2, 4.2 Appendix C
$Meat\_DRL_{area}$	$\frac{\mu Ci}{m^2}$	Meat Ingestion Derived Response Level - Area, the areal activity of radionuclide *i* deposited over a grazing area that would result in a grazing animal's meat equaling the DIL for that radionuclide when the animal is harvested.	3.4
$Meat\_DRL_{mass}$	$\frac{\mu Ci}{kg_{wet}}$	Meat Ingestion Derived Response Level - Mass, the mass concentration of radionuclide *i* in animal feed (including forage) that would result in the animal's meat equaling the DIL for that radionuclide when the animal is harvested.	3.4
$Meat\_DRL_{water}$	$\frac{\mu Ci}{L}$	Meat Ingestion Derived Response Level - Water, the water concentration of radionuclide *i* in an animal's drinking water that would result in the animal's meat equaling the DIL for that radionuclide when the animal is harvested.	3.4
$Milk\_DRL_{area}$	$\frac{\mu Ci}{m^2}$	Milk Ingestion Derived Response Level - Area, the areal activity of radionuclide *i* deposited over a grazing area that would result in the grazing animal's milk equaling the DIL for that radionuclide.	3.3

TERM	UNITS	DEFINITION	METHODS
$Milk\_DRL_{mass}$	$\frac{\mu Ci}{kg_{wet}}$	Milk Ingestion Derived Response Level - Mass, the mass concentration of radionuclide *i* in animal feed (including forage) that would result in the grazing animal's milk equaling the DIL for that radionuclide.	3.3
$Milk\_DRL_{water}$	$\frac{\mu Ci}{L}$	Milk Ingestion Derived Response Level - Water, the water concentration of radionuclide *i* in an animal's drinking water that would result in the grazing animal's milk equaling the DIL for that radionuclide.	3.3
NF_DRL	$\frac{mrem}{hr}$	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
Pl_ExDC_i	$\frac{mrem \bullet m^3}{\mu Ci \bullet s}$	Plume External Dose Coefficient, the external dose rate from submersion in radionuclide *i* in the plume.	1.1, Appendix C
$Pl\_ExDP_{i,\,TP}$	mrem	Plume External Dose Parameter, the external dose from submersion from plume-borne radionuclide *i*.	1.1, Appendix C
$Pl\_InhDP_{i,TP}$	mrem	Plume Inhalation Dose Parameter, the committed dose from inhalation of plume-borne radionuclide *i*.	1.1, Appendix C
$Pl\_TDP_{i,\,TP}$	mrem	Plume Total Dose Parameter, the sum of the external dose from submersion in, and the committed dose from inhalation of, plume-borne radionuclide *i*.	1.1, 1.5, Appendix C
ρ_{milk}	$\frac{kg_{wet}}{L}$	Milk density.	3.3, Appendix C
ρ_{soil}	$\frac{kg_{soil}}{m^3}$	Soil Density.	3.2, 3.3, 3.4, 3.6, 3.7, Appendix C
ST	hr	Stay Time	2.1
t_0	NA	Release Time. The time the release begins. This time is usually assumed to correspond to the time of deposition.	1.1, 1.2, 3.6, 3.7, 4.3, 4.5, Appendix F
t_1	s or hr	Start Time. The start of the time phase (integration period) under consideration.	1.1, 1.7, 3.7, Appendix F
t_2	s or hr	End Time. The end of the time phase (integration period) under consideration.	1.1, 1.7, 2.7, Appendix F

TERM	UNITS	DEFINITION	METHODS
t_a, t_b	hr	Time after a nuclear detonation at which a measurement is made.	1.7
t_c	d	Consumption Time, the length of the food consumption period.	3.5
t_g	d	Grazing Time, the time the animal spends grazing in the contaminated field. or Growing Time, the time the crop spends growing in the contaminated field.	3.4, 3.6 3.2
t_h	d	Hold Time, the time elapsed from sample measurement to the beginning of the food consumption period.	3.5
t_m	d	Time to Market, the number of days from harvest to food consumption. See Appendix C, Table 11.	3.2, 3.3, 3.4, 3.6, Appendix C
t_n	s, hr, d	Evaluation Time, the point in time, relative to the start of the release, at which the measurement, prediction or evaluation is performed.	1.1, 1.2, 1.3, 1.4, 1.5, 1.7, 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
TBL_{DR}	$\frac{mrem}{hr}$	Dose Rate Turn-Back Limit, the Integrated Dose Turn-Back Limit divided by the Stay Time in the contaminated area.	2.1
TBL_{XR}	$\frac{mR}{hr}$	Exposure Rate Turn-Back Limit, the Integrated Exposure Turn-Back Limit divided by the Stay Time in the contaminated area.	2.1
TBL_D_{TP}	$mrem_{external}$	Turn-Back Limit for Integrated External Dose, the integrated external dose, as recorded by the self-reading dosimeter, received from a radionuclide mixture deposited on the ground over the time phase under consideration, which would result in the worker receiving their dose limit.	2.2
TBL_X_{TP}	mR	Turn-Back Limit for Integrated External Exposure, the integrated external exposure, as recorded by a self-reading exposure meter, received from a radionuclide mixture deposited on the ground over the time phase under consideration, which would result in the worker receiving their dose limit.	2.2

TERM	UNITS	DEFINITION	METHODS
TF_{crop}	$\frac{\mu Ci / kg_{dry}}{\mu Ci / kg_{soil}}$	Transfer Factor for a food crop, the fraction of radionuclide i deposited on the growing medium that is transferred to the plant during the growing season. **NOTE:** Transfer Factors for plants are in terms of edible dry plants (PNNL03).	3.2
TF_{Meat}	$\frac{\mu Ci / kg_{wet}}{\mu Ci / d}$	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
TF_{Milk}	$\frac{\mu Ci / L}{\mu Ci / d}$	Transfer Factor for milk, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the milk produced by the animal.	3.3, 3.6
V_d	m/s	Deposition velocity for a specific particle size.	4.5
$\bar{V}_d$	m/s	Weighted average deposition velocity.	4.5
WF	unitless	Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind).	1.1, 1.2, 3.7, Appendix F
WP	$\frac{\mu Ci \bullet s}{m^2}$	Weathering Parameter, the adjustment for radioactive decay and in-growth and the time-dependent weathering effects that change the amount of a radionuclide available to cause direct exposure or to be ingested over the time phase under consideration.	1.1, 3.7, Appendix F
x	unitless	Power function exponent, the value that represents the decay of fallout radioactivity at a given location. Default =1.2.	1.7
$XDCF_A$	$\frac{mrem}{mR}$	Exposure to Dose Conversion Factor (acute), the constant used to convert external exposure (mR) to midline (bone marrow) dose (mrem), 0.7.	1.2, 2.1, 2.2
$XDCF_C$	$\frac{mrem}{mR}$	Exposure to Dose Conversion Factor (chronic), the constant used to convert external exposure (mR) to deep tissue (1 cm) dose (mrem), 1.0.	1.2, 2.1, 2.2
Y	$\frac{kg_{wet}}{m^2}$	Crop Yield, the mass of crop grown per area of land.	3.2, 3.3, 3.4, 3.6, Appendix C
Y_α	$\frac{\mu Ci_\alpha}{\mu Ci_{nt}}$	Yield, the alpha activity per total (nuclear transformation) activity of radionuclide *i*.	1.3
Y_β	$\frac{\mu Ci_\beta}{\mu Ci_{nt}}$	Yield, the beta activity per total (nuclear transformation) activity of radionuclide *i*.	1.4

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Table 1 – Radiological Data [1]

Parent Radionuclide	$t_{1/2}$ (d)	λ (d^{-1})	Dp_ExDF [2,3] (Groundshine) (mrem·m²/μCi·hr)	Pl_ExDC [2] (Submersion) (mrem·m³/μCi·hr)	InhDC [2] (Inhalation) (mrem/μCi)
Am-241	1.6E+05	4.4E-06	2.4E-04	9.0E-03	3.6E+05
Ba-140	1.3E+01	5.4E-02	2.9E-02	1.8E+00	2.7E+01
Ce-141	3.3E+01	2.1E-02	7.6E-04	4.2E-02	1.4E+01
Ce-144	2.8E+02	2.4E-03	2.0E-03	4.3E-02	2.0E+02
Cf-252	9.6E+02	7.2E-04	4.7E-03	3.0E-01	1.4E+05
Cm-242	1.6E+02	4.3E-03	7.3E-06	5.2E-05	2.2E+04
Cm-244	6.6E+03	1.0E-04	6.4E-06	5.3E-05	2.1E+05
Co-60	1.9E+03	3.6E-04	2.5E-02	1.6E+00	1.1E+02
Cs-134	7.5E+02	9.2E-04	1.6E-02	9.4E-01	7.6E+01
Cs-136	1.3E+01	5.3E-02	2.2E-02	1.3E+00	1.0E+01
Cs-137	1.1E+04	6.3E-05	6.0E-03	3.4E-01	1.5E+02
Gd-153	2.4E+02	2.9E-03	1.0E-03	4.1E-02	8.8E+00
I-129	5.7E+09	1.2E-10	2.2E-04	3.8E-03	1.3E+02
I-131	8.0E+00	8.6E-02	4.0E-03	2.3E-01	2.7E+01
I-132	9.6E-02	7.2E+00	2.4E-02	1.4E+00	4.2E-01
I-133	8.7E-01	8.0E-01	6.8E-03	3.7E-01	5.4E+00
I-134	3.7E-02	1.9E+01	2.7E-02	1.6E+00	2.1E-01
I-135	2.8E-01	2.5E+00	1.7E-02	1.1E+00	1.2E+00
Ir-192	7.4E+01	9.4E-03	8.5E-03	4.8E-01	2.5E+01
La-140	1.7E+00	4.1E-01	2.4E-02	1.5E+00	4.2E+00
Mo-99	2.8E+00	2.5E-01	3.1E-03	1.6E-01	3.7E+00
Nb-95	3.5E+01	2.0E-02	7.9E-03	4.7E-01	6.5E+00
Np-237	7.8E+08	8.9E-10	6.5E-03	3.3E-01	1.3E+06
Np-239	2.4E+00	2.9E-01	1.8E-03	9.8E-02	3.8E+00
Pm-147	9.6E+02	7.2E-04	3.1E-07	1.2E-04	2.6E+01
Pu-238	3.2E+04	2.2E-05	6.5E-06	4.5E-05	4.0E+05
Pu-239	8.8E+06	7.9E-08	3.4E-06	5.0E-05	4.4E+05
Pu-241	5.3E+03	1.3E-04	4.9E-08	2.5E-06	8.5E+03
Ra-226	5.8E+05	1.2E-06	1.9E-02	1.1E+00	7.3E+04
Ru-103	3.9E+01	1.8E-02	5.2E-03	2.9E-01	1.1E+01
Ru-106	3.7E+02	1.9E-03	3.8E-03	1.4E-01	2.4E+02
Sb-127	3.8E+00	1.8E-01	7.5E-03	4.2E-01	7.4E+00
Sb-129	1.8E-01	3.9E+00	1.7E-02	9.5E-01	1.1E+00
Se-75	1.2E+02	5.8E-03	3.9E-03	2.2E-01	5.0E+00
Sr-89	5.1E+01	1.4E-02	7.5E-04	5.9E-03	2.9E+01
Sr-90	1.1E+04	6.5E-05	1.2E-03	1.2E-02	5.9E+02
Sr-91	4.0E-01	1.8E+00	1.2E-02	6.4E-01	1.5E+00
Te-129m	3.4E+01	2.1E-02	1.5E-03	4.7E-02	2.9E+01
Te-131m	1.3E+00	5.5E-01	1.6E-02	9.5E-01	4.0E+00
Te-132	3.3E+00	2.1E-01	2.7E-02	1.6E+00	8.0E+00
Tm-170	1.3E+02	5.4E-03	2.7E-04	4.3E-03	3.4E+01
Y-91	5.9E+01	1.2E-02	8.1E-04	8.0E-03	3.3E+01
Yb-169	3.2E+01	2.2E-02	3.2E-03	1.6E-01	1.1E+01
Zr-95	6.4E+01	1.1E-02	2.5E-02	1.5E+00	3.6E+01

[1] Values generated using DCFPAK Version 2.0.
[2] Values include dose contributions from all daughters that are considered to be in equilibrium (i.e., half-life shorter than ultimate parent (e.g., Cs-137 includes contribution from Ba-137m)).
[3] Deposition External Dose Factor - Values include adjustment of Deposition External Dose Coefficient for ground roughness (0.82).

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Table 2-1 Dose Limits for Workers Performing Emergency Services

TED (rem)	Activity	Condition
5	All occupational exposures.	All reasonably achievable actions have been taken to minimize dose.
10 [a]	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 [b]	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: EPA13, Table 2-2

[a] For potential doses >5 rem, medical monitoring programs should be considered.

[b] 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 2-2 PAGs

Time Phase	Protective Action	Limit (rem)	Comments
Early	Sheltering-in-place or evacuation of the public [a]	TED 1-5 [b]	Evacuation (or, for some situations, sheltering-in-place) should be initiated when projected dose is 1 rem
	Administration of stable iodine		Equivalent Dose to the thyroid from radioiodine. KI is most effective if taken prior to exposure. May require approval of state medical officials (or in accordance with established emergency plans).
		5	Pregnant or Lactating Women, Children 0-18 yrs
		10	Adults 18-40 yrs
		500	Adults over 40 yrs
1st Year	Relocate the general population [c]	2 [d]	Projected dose over one year.
	Apply simple dose reduction techniques [e]	<2	Should be taken to reduce doses to ALARA.
2nd Year	Relocate the general population [c]	0.5 [d]	Any single year after the 1st.
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).

Source: EPA13

[a] Should begin at 1 rem 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] Calculated dose is the projected sum of the effective dose from external radiation exposure (i.e., groundshine) and the committed effective dose from inhaled radioactive material.

[c] Persons previously evacuated from areas outside the relocation zone defined by this PAG may return to occupy their residences. Cases involving relocation of persons at high risk from such action (e.g., patients under intensive care) should be evaluated individually.

[d] The dose that would be received 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.

[e] 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 2-3 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
1st Year	12 hours	8772 hours (Day 365 + 12 hours)	12 hours	Ground Only
2nd 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 Submersion and Plume Inhalation.

[c] Ground Dose Pathways include Groundshine and Inhalation of resuspended material.

[d] EPA no longer specifies PAGs for the 50 year time phase. Included to enable calculations bound to previous version of the PAG Manual.

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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 hr	2-4 hr	1-2 hr	<1 hr to minutes
Duration		<24 hr	<24 hr	<48 hr	<48 hr
Lymphocyte Count	Unaffected	Minimally Decreased	<1000 at 24 hr	<500 at 24 hr	Decreases within hours
Central Nervous System Function	No Impairment	No Impairment	Cognitive Impairment for 6-20 hr	Cognitive Impairment for >20 hr	Rapid incapacitation
Mortality	None	Minimal	Low with aggressive therapy	High	Very High: Significant neurological symptoms indicate lethal dose

Source: EPA13, 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.

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Table 4 – Dose Parameters and DRLs

This series of Tables contains the Dose Parameters and DRLs for the Assessment Working Group's list of radionuclides. Values are provided for the 4 standard Time Phases (Early, 1st Year, 2nd Year and 50 Year.) All values calculated using DCFPAK Version 2.0.

NOTE: EPA no longer specifies a 50-Year PAG. 50 Year values are calculated based on an assumed Committed Effective Dose of 5 rem over 50 years.

These values are **only appropriate** when all of the following are true:

- the organ of interest is the Whole Body relating to a PAG for an Effective Dose,
- mixture of interest contains only 1 radionuclide (and any included daughters), and
  NOTE: Daughter radionuclides with half-lives less than the "root" parent are assumed to be at equilibrium and their dose contributions are included.
- the default Time Phases and Evaluation Times shown in Table 2-3 are used.

The terms contained in this series of Tables are defined below and on the next page:

Dose Parameters		
Dp_ExDP	$\frac{mrem \bullet m^2}{\mu Ci}$	Deposition External Dose Parameter, the external dose from groundshine, over the time phase under consideration (*TP*), per unit activity of radionuclide *i*.
Dp_InhDP	$\frac{mrem \bullet m^2}{\mu Ci}$	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.
DP_TDP	$\frac{mrem \bullet m^2}{\mu Ci}$	Deposition Total Dose Parameter, the sum of the external dose from groundshine and the committed dose from inhalation of resuspended material, over the time phase under consideration (*TP*), per unit activity of radionuclide *i* deposited on the ground.
Pl_ExDP	$\frac{mrem \bullet m^3}{\mu Ci \bullet s}$	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	$\frac{mrem \bullet m^3}{\mu Ci \bullet s}$	Plume Inhalation Dose Parameter, the committed dose, over the time phase under consideration (*TP*), from inhalation per unit activity of plume-borne radionuclide *i*.
Pl_TDP	$\frac{mrem \bullet m^3}{\mu Ci \bullet s}$	Plume Total Dose Parameter, the sum of the external dose from submersion and the committed dose from inhalation of the plume-borne material, over the time phase under consideration (*TP*), 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 $\mu Ci/m^2$ ($mrem \cdot m^2/\mu Ci$) in these Tables.

The values in the following tables account for the contributions of included daughter radionuclides at their appropriate equilibrium concentration (e.g., Ba-140 includes the contribution of 1 "unit" of Ba-140 and 1.15 "units" of La-140.)

DRLs		
4Path_DRL$_{Dp}$	$\frac{\mu Ci}{m^2}$	Four-Pathway Deposition Derived Response Level, the areal activity, at time t_n, of radionuclide *i* at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the Protective Action Guide (PAG) over the time phase under consideration.
4Path_DRL$_{\tilde{A}}$	$\frac{\mu Ci \bullet s}{m^3}$	Four-Pathway Air Derived Response Level, the integrated air activity ($\tilde{A}$) of radionuclide *i* at which the total dose from *all radionuclides* in a release (considering plume and ground dose pathways) would equal the Protective Action Guide (PAG) over the time phase under consideration.
4Path_DRL$_{DR}$	$\frac{mrem}{hr}$	Four-Pathway Dose Rate Derived Response Level, the external dose rate, at time t_n, at which the total dose from all radionuclides in a release (considering plume and ground dose pathways) would equal the PAG over the time phase under consideration.
2Path_DRL$_{Dp}$	$\frac{\mu Ci}{m^2}$	Two-Pathway Deposition Derived Response Level, the areal activity (Dp), at time t_n, of radionuclide *i* at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the Protective Action Guide (PAG) over the time phase under consideration.
2Path_DRL$_{\tilde{A}}$	$\frac{\mu Ci \bullet s}{m^3}$	Two-Pathway Air Derived Response Level, the integrated air activity ($\tilde{A}$) of radionuclide *i* at which the total dose from *all radionuclides* in a release (considering only ground dose pathways) would equal the Protective Action Guide (PAG) over the time phase under consideration.
2Path_DRL$_{DR}$	$\frac{mrem}{hr}$	Two-Pathway Dose Rate Derived Response Level, the external dose rate, at time t_n, at which the total dose from all radionuclides in a release (considering only ground dose pathways) would equal the PAG over the time phase under consideration.

Note:

DRLs in these tables were calculated assuming a deposition velocity of 3.0E-03 m/s, except for isotopes of Iodine, for which 1.0E-02 m/s was used.

NOTE: See Table 2-3 for descriptions of Time Phases.

Table 4-1 Plume Dose Parameters [a]

Parent Radionuclide	Pl_ExDP (mrem·m³/µCi·s)	Pl_InhDP (mrem·m³/µCi·s)	Pl_TDP (mrem·m³/µCi·s)
Am-241	2.5E-06	1.5E+02	1.5E+02
Ba-140	5.0E-04	1.1E-02	1.2E-02
Ce-141	1.2E-05	5.8E-03	5.8E-03
Ce-144	1.2E-05	8.1E-02	8.1E-02
Cf-252	8.3E-05	5.7E+01	5.7E+01
Cm-242	1.4E-08	9.1E+00	9.1E+00
Cm-244	1.5E-08	8.8E+01	8.8E+01
Co-60	4.4E-04	4.7E-02	4.8E-02
Cs-134	2.6E-04	3.1E-02	3.2E-02
Cs-136	3.6E-04	4.3E-03	4.7E-03
Cs-137	9.5E-05	6.0E-02	6.1E-02
Gd-153	1.2E-05	3.7E-03	3.7E-03
I-129	1.1E-06	5.5E-02	5.5E-02
I-131	6.3E-05	1.1E-02	1.1E-02
I-132	3.8E-04	1.8E-04	5.6E-04
I-133	1.0E-04	2.3E-03	2.4E-03
I-134	4.5E-04	8.6E-05	5.3E-04
I-135	2.9E-04	5.0E-04	7.9E-04
Ir-192	1.3E-04	1.0E-02	1.0E-02
La-140	4.1E-04	1.8E-03	2.2E-03
Mo-99	4.4E-05	1.6E-03	1.6E-03
Nb-95	1.3E-04	2.7E-03	2.8E-03
Np-237	9.2E-05	5.2E+02	5.2E+02
Np-239	2.7E-05	1.6E-03	1.6E-03
Pm-147	3.2E-08	1.1E-02	1.1E-02
Pu-238	1.2E-08	1.7E+02	1.7E+02
Pu-239	1.4E-08	1.8E+02	1.8E+02
Pu-241	7.1E-10	3.5E+00	3.5E+00
Ra-226	3.1E-04	3.0E+01	3.0E+01
Ru-103	8.2E-05	4.6E-03	4.6E-03
Ru-106	4.0E-05	1.0E-01	1.0E-01
Sb-127	1.2E-04	3.1E-03	3.2E-03
Sb-129	2.6E-04	4.5E-04	7.1E-04
Se-75	6.1E-05	2.1E-03	2.1E-03
Sr-89	1.6E-06	1.2E-02	1.2E-02
Sr-90	3.3E-06	2.4E-01	2.4E-01
Sr-91	1.8E-04	6.4E-04	8.2E-04
Te-129m	1.3E-05	1.2E-02	1.2E-02
Te-131m	2.6E-04	1.7E-03	1.9E-03
Te-132	4.3E-04	3.3E-03	3.8E-03
Tm-170	1.2E-06	1.4E-02	1.4E-02
Y-91	2.2E-06	1.4E-02	1.4E-02
Yb-169	4.4E-05	4.6E-03	4.6E-03
Zr-95	4.1E-04	1.5E-02	1.5E-02

Note:

[a] Plume Dose Parameters (External, Inhalation, and Total) 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., 2nd Year).

Table 4-2a Early Phase (Total Dose) Deposition Dose Parameters

Parent Radionuclide	Dp_ExDP (mrem·m²/µCi)	Dp_InhDP (mrem·m²/µCi)	Dp_TDP (mrem·m²/µCi)
Am-241	2.3E-02	2.8E+02	2.8E+02
Ba-140	2.5E+00	1.9E-02	2.5E+00
Ce-141	7.0E-02	1.0E-02	8.0E-02
Ce-144	1.9E-01	1.5E-01	3.4E-01
Cf-252	4.5E-01	1.1E+02	1.1E+02
Cm-242	6.9E-04	1.7E+01	1.7E+01
Cm-244	6.1E-04	1.6E+02	1.6E+02
Co-60	2.4E+00	8.8E-02	2.5E+00
Cs-134	1.5E+00	5.8E-02	1.6E+00
Cs-136	1.9E+00	7.2E-03	1.9E+00
Cs-137	5.8E-01	1.1E-01	6.9E-01
Gd-153	9.6E-02	6.8E-03	1.0E-01
I-129	2.1E-02	1.0E-01	1.2E-01
I-131	3.2E-01	1.8E-02	3.4E-01
I-132	7.9E-02	1.3E-05	7.9E-02
I-133	2.0E-01	1.3E-03	2.0E-01
I-134	3.4E-02	2.4E-06	3.4E-02
I-135	1.9E-01	1.0E-04	1.9E-01
Ir-192	8.0E-01	1.9E-02	8.2E-01
La-140	1.1E+00	1.7E-03	1.1E+00
Mo-99	1.9E-01	1.9E-03	1.9E-01
Nb-95	7.3E-01	4.8E-03	7.4E-01
Np-237	6.2E-01	9.6E+02	9.7E+02
Np-239	1.0E-01	1.8E-03	1.0E-01
Pm-147	2.9E-05	2.0E-02	2.0E-02
Pu-238	6.3E-04	3.1E+02	3.1E+02
Pu-239	3.2E-04	3.4E+02	3.4E+02
Pu-241	4.9E-06	6.6E+00	6.6E+00
Ra-226	1.8E+00	5.6E+01	5.8E+01
Ru-103	4.8E-01	8.2E-03	4.9E-01
Ru-106	3.6E-01	1.9E-01	5.5E-01
Sb-127	5.2E-01	4.2E-03	5.2E-01
Sb-129	1.0E-01	8.6E-05	1.0E-01
Se-75	3.7E-01	3.8E-03	3.7E-01
Sr-89	7.0E-02	2.2E-02	9.2E-02
Sr-90	1.2E-01	4.5E-01	5.7E-01
Sr-91	1.6E-01	3.4E-04	1.6E-01
Te-129m	1.3E-01	2.2E-02	1.6E-01
Te-131m	6.5E-01	3.0E-03	6.5E-01
Te-132	1.7E+00	4.3E-03	1.7E+00
Tm-170	2.6E-02	2.6E-02	5.2E-02
Y-91	7.6E-02	2.5E-02	1.0E-01
Yb-169	3.0E-01	8.2E-03	3.0E-01
Zr-95	2.4E+00	2.7E-02	2.4E+00

Table 4-2b Early Phase (Total Dose) DRLs

Parent Radionuclide	4Path_DRL$_{Dp}$ (µCi/m^2)	4Path_DRL$_{\tilde{A}}$ (µCi•s/m^3)	4Path_DRL$_{DR}$ (mrem/hr)
Am-241	2.0E-02	6.7E+00	4.8E-06
Ba-140	1.5E+02	5.2E+04	4.4E+00
Ce-141	4.9E+02	1.7E+05	3.7E-01
Ce-144	3.6E+01	1.2E+04	7.1E-02
Cf-252	5.2E-02	1.7E+01	2.5E-04
Cm-242	3.3E-01	1.1E+02	2.4E-06
Cm-244	3.4E-02	1.1E+01	2.2E-07
Co-60	5.4E+01	1.8E+04	1.4E+00
Cs-134	8.2E+01	2.7E+04	1.3E+00
Cs-136	2.8E+02	9.7E+04	6.2E+00
Cs-137	4.8E+01	1.6E+04	2.9E-01
Gd-153	7.4E+02	2.5E+05	7.5E-01
I-129	1.8E+02	1.8E+04	3.8E-02
I-131	6.4E+02	6.7E+04	2.6E+00
I-132	2.0E+02	7.4E+05	4.7E+00
I-133	1.5E+03	2.3E+05	1.0E+01
I-134	8.6E-01	1.1E+06	2.3E-02
I-135	1.1E+03	3.8E+05	1.8E+01
Ir-192	2.3E+02	7.8E+04	2.0E+00
La-140	4.4E+02	1.8E+05	1.0E+01
Mo-99	1.2E+03	4.6E+05	3.8E+00
Nb-95	5.9E+02	2.0E+05	4.7E+00
Np-237	5.7E-03	1.9E+00	3.7E-05
Np-239	1.3E+03	5.2E+05	2.4E+00
Pm-147	2.8E+02	9.2E+04	8.5E-05
Pu-238	1.8E-02	6.0E+00	1.2E-07
Pu-239	1.6E-02	5.4E+00	5.4E-08
Pu-241	8.4E-01	2.8E+02	4.1E-08
Ra-226	9.8E-02	3.3E+01	1.8E-03
Ru-103	4.9E+02	1.6E+05	2.5E+00
Ru-106	2.9E+01	9.7E+03	1.1E-01
Sb-127	5.7E+02	2.1E+05	4.3E+00
Sb-129	4.3E+02	9.8E+05	7.1E+00
Se-75	9.2E+02	3.1E+05	3.6E+00
Sr-89	2.4E+02	8.0E+04	1.8E-01
Sr-90	1.2E+01	4.1E+03	1.5E-02
Sr-91	9.6E+02	7.7E+05	1.1E+01
Te-129m	2.3E+02	7.8E+04	3.4E-01
Te-131m	5.9E+02	2.6E+05	9.4E+00
Te-132	3.0E+02	1.1E+05	8.1E+00
Tm-170	2.1E+02	6.9E+04	5.6E-02
Y-91	2.1E+02	7.1E+04	1.7E-01
Yb-169	5.3E+02	1.8E+05	1.7E+00
Zr-95	1.3E+02	4.4E+04	3.3E+00

Table 4-3a Early Phase (Avoidable Dose) Deposition Dose Parameters

Parent Radionuclide	Dp_ExDP (mrem·m²/µCi)	Dp_InhDP (mrem·m²/µCi)	Dp_TDP (mrem·m²/µCi)
Am-241	2.3E-02	2.7E+02	2.7E+02
Ba-140	2.4E+00	1.7E-02	2.5E+00
Ce-141	6.9E-02	9.9E-03	7.9E-02
Ce-144	1.9E-01	1.5E-01	3.3E-01
Cf-252	4.5E-01	1.0E+02	1.0E+02
Cm-242	6.9E-04	1.6E+01	1.6E+01
Cm-244	6.1E-04	1.6E+02	1.6E+02
Co-60	2.4E+00	8.5E-02	2.5E+00
Cs-134	1.5E+00	5.6E-02	1.6E+00
Cs-136	1.8E+00	6.8E-03	1.8E+00
Cs-137	5.7E-01	1.1E-01	6.8E-01
Gd-153	9.6E-02	6.6E-03	1.0E-01
I-129	2.1E-02	9.9E-02	1.2E-01
I-131	3.1E-01	1.7E-02	3.3E-01
I-132	2.1E-03	3.3E-07	2.1E-03
I-133	1.4E-01	8.7E-04	1.4E-01
I-134	2.6E-06	1.8E-10	2.6E-06
I-135	6.4E-02	2.8E-05	6.4E-02
Ir-192	7.9E-01	1.8E-02	8.1E-01
La-140	9.0E-01	1.3E-03	9.0E-01
Mo-99	1.7E-01	1.6E-03	1.7E-01
Nb-95	7.2E-01	4.6E-03	7.3E-01
Np-237	6.2E-01	9.3E+02	9.3E+02
Np-239	8.6E-02	1.5E-03	8.8E-02
Pm-147	2.9E-05	1.9E-02	1.9E-02
Pu-238	6.3E-04	3.0E+02	3.0E+02
Pu-239	3.2E-04	3.3E+02	3.3E+02
Pu-241	4.9E-06	6.3E+00	6.3E+00
Ra-226	1.8E+00	5.4E+01	5.6E+01
Ru-103	4.8E-01	7.8E-03	4.8E-01
Ru-106	3.6E-01	1.8E-01	5.4E-01
Sb-127	4.7E-01	3.7E-03	4.7E-01
Sb-129	1.5E-02	3.4E-05	1.5E-02
Se-75	3.7E-01	3.7E-03	3.7E-01
Sr-89	7.0E-02	2.1E-02	9.1E-02
Sr-90	1.2E-01	4.4E-01	5.6E-01
Sr-91	6.6E-02	2.4E-04	6.7E-02
Te-129m	1.3E-01	2.1E-02	1.5E-01
Te-131m	5.0E-01	2.8E-03	5.1E-01
Te-132	1.6E+00	3.7E-03	1.6E+00
Tm-170	2.6E-02	2.5E-02	5.1E-02
Y-91	7.6E-02	2.4E-02	1.0E-01
Yb-169	2.9E-01	7.8E-03	3.0E-01
Zr-95	2.4E+00	2.6E-02	2.4E+00

Table 4-3b Early Phase (Avoidable Dose) DRLs

Parent Radionuclide	$2Path\_DRL_{Dp}$ (µCi/m²)	$2Path\_DRL_{\tilde{A}}$ (µCi•s/m³)	$2Path\_DRL_{DR}$ (mrem/hr)
Am-241	3.7E+00	1.2E+03	8.9E-04
Ba-140	4.0E+02	1.3E+05	1.2E+01
Ce-141	1.3E+04	4.2E+06	9.5E+00
Ce-144	3.0E+03	1.0E+06	5.9E+00
Cf-252	9.7E+00	3.2E+03	4.6E-02
Cm-242	6.1E+01	2.0E+04	4.5E-04
Cm-244	6.3E+00	2.1E+03	4.1E-05
Co-60	4.0E+02	1.3E+05	1.0E+01
Cs-134	6.2E+02	2.1E+05	1.0E+01
Cs-136	5.3E+02	1.8E+05	1.2E+01
Cs-137	1.5E+03	4.9E+05	8.8E+00
Gd-153	9.8E+03	3.3E+06	9.8E+00
I-129	8.3E+03	8.3E+05	1.8E+00
I-131	2.9E+03	2.9E+05	1.2E+01
I-132	1.3E+04	1.3E+06	3.0E+02
I-133	4.9E+03	4.9E+05	3.3E+01
I-134	2.9E+04	2.9E+06	7.9E+02
I-135	4.4E+03	4.4E+05	7.4E+01
Ir-192	1.2E+03	4.1E+05	1.0E+01
La-140	9.1E+02	3.0E+05	2.1E+01
Mo-99	5.2E+03	1.7E+06	1.6E+01
Nb-95	1.4E+03	4.5E+05	1.1E+01
Np-237	1.1E+00	3.6E+02	7.0E-03
Np-239	9.8E+03	3.3E+06	1.7E+01
Pm-147	5.2E+04	1.7E+07	1.6E-02
Pu-238	3.3E+00	1.1E+03	2.2E-05
Pu-239	3.0E+00	1.0E+03	1.0E-05
Pu-241	1.6E+02	5.3E+04	7.7E-06
Ra-226	1.8E+01	5.9E+03	3.3E-01
Ru-103	2.0E+03	6.8E+05	1.1E+01
Ru-106	1.8E+03	6.1E+05	7.0E+00
Sb-127	1.9E+03	6.4E+05	1.5E+01
Sb-129	9.6E+03	3.2E+06	1.6E+02
Se-75	2.7E+03	9.0E+05	1.0E+01
Sr-89	1.1E+04	3.6E+06	8.2E+00
Sr-90	1.8E+03	6.0E+05	2.2E+00
Sr-91	6.3E+03	2.1E+06	7.2E+01
Te-129m	6.4E+03	2.1E+06	9.4E+00
Te-131m	1.5E+03	5.0E+05	2.4E+01
Te-132	5.7E+02	1.9E+05	1.5E+01
Tm-170	2.0E+04	6.5E+06	5.3E+00
Y-91	1.0E+04	3.3E+06	8.1E+00
Yb-169	3.3E+03	1.1E+06	1.1E+01
Zr-95	4.2E+02	1.4E+05	1.1E+01

Table 4-4a First Year Deposition Dose Parameters

Parent Radionuclide	Dp_ExDP (mrem·m²/µCi)	Dp_InhDP (mrem·m²/µCi)	Dp_TDP (mrem·m²/µCi)
Am-241	1.9E+00	1.1E+03	1.1E+03
Ba-140	1.2E+01	4.4E-02	1.2E+01
Ce-141	8.3E-01	3.2E-02	8.6E-01
Ce-144	1.0E+01	5.8E-01	1.1E+01
Cf-252	3.3E+01	4.2E+02	4.5E+02
Cm-242	3.0E-02	6.4E+01	6.4E+01
Cm-244	5.0E-02	6.5E+02	6.5E+02
Co-60	1.9E+02	3.5E-01	1.9E+02
Cs-134	1.1E+02	2.3E-01	1.1E+02
Cs-136	9.5E+00	1.7E-02	9.5E+00
Cs-137	4.8E+01	4.5E-01	4.8E+01
Gd-153	5.1E+00	2.6E-02	5.1E+00
I-129	1.7E+00	4.1E-01	2.2E+00
I-131	1.1E+00	3.6E-02	1.1E+00
I-132	2.1E-03	3.3E-07	2.1E-03
I-133	1.5E-01	9.0E-04	1.5E-01
I-134	2.6E-06	1.8E-10	2.6E-06
I-135	6.4E-02	2.8E-05	6.4E-02
Ir-192	2.0E+01	6.6E-02	2.0E+01
La-140	1.1E+00	1.5E-03	1.1E+00
Mo-99	2.6E-01	2.2E-03	2.6E-01
Nb-95	9.3E+00	1.5E-02	9.3E+00
Np-237	5.2E+01	3.9E+03	3.9E+03
Np-239	1.2E-01	2.2E-03	1.3E-01
Pm-147	2.2E-03	7.9E-02	8.1E-02
Pu-238	5.2E-02	1.2E+03	1.2E+03
Pu-239	2.7E-02	1.4E+03	1.4E+03
Pu-241	1.8E-03	2.6E+01	2.6E+01
Ra-226	1.5E+02	2.3E+02	3.8E+02
Ru-103	6.8E+00	2.7E-02	6.8E+00
Ru-106	2.2E+01	7.3E-01	2.3E+01
Sb-127	9.2E-01	6.3E-03	9.3E-01
Sb-129	1.7E-02	9.2E-05	1.7E-02
Se-75	1.3E+01	1.4E-02	1.3E+01
Sr-89	1.3E+00	7.5E-02	1.3E+00
Sr-90	9.7E+00	1.8E+00	1.1E+01
Sr-91	7.7E-02	6.8E-04	7.8E-02
Te-129m	1.6E+00	6.9E-02	1.7E+00
Te-131m	7.0E-01	6.4E-03	7.0E-01
Te-132	2.7E+00	5.5E-03	2.7E+00
Tm-170	9.8E-01	9.8E-02	1.1E+00
Y-91	1.6E+00	8.6E-02	1.6E+00
Yb-169	3.5E+00	2.6E-02	3.5E+00
Zr-95	5.2E+01	9.5E-02	5.2E+01

Table 4-4b First Year DRLs

Parent Radionuclide	$2Path\_DRL_{Dp}$ (µCi/m²)	$2Path\_DRL_{\tilde{A}}$ (µCi•s/m³)	$2Path\_DRL_{DR}$ (mrem/hr)
Am-241	1.8E+00	6.0E+02	4.3E-04
Ba-140	1.6E+02	5.2E+04	4.6E+00
Ce-141	2.3E+03	7.7E+05	1.8E+00
Ce-144	1.8E+02	6.0E+04	3.5E-01
Cf-252	4.4E+00	1.5E+03	2.1E-02
Cm-242	3.1E+01	1.0E+04	2.3E-04
Cm-244	3.1E+00	1.0E+03	2.0E-05
Co-60	1.1E+01	3.5E+03	2.6E-01
Cs-134	1.8E+01	6.0E+03	2.9E-01
Cs-136	2.0E+02	6.8E+04	4.4E+00
Cs-137	4.2E+01	1.4E+04	2.5E-01
Gd-153	3.9E+02	1.3E+05	3.9E-01
I-129	9.3E+02	9.3E+04	2.0E-01
I-131	1.8E+03	1.8E+05	7.0E+00
I-132	2.5E+04	2.5E+06	6.0E+02
I-133	8.9E+03	8.9E+05	6.0E+01
I-134	5.8E+04	5.8E+06	1.6E+03
I-135	8.9E+03	8.9E+05	1.5E+02
Ir-192	9.9E+01	3.3E+04	8.4E-01
La-140	1.5E+03	4.9E+05	3.4E+01
Mo-99	6.7E+03	2.2E+06	2.1E+01
Nb-95	2.1E+02	7.1E+04	1.7E+00
Np-237	5.1E-01	1.7E+02	3.3E-03
Np-239	1.4E+04	4.5E+06	2.4E+01
Pm-147	2.5E+04	8.2E+06	7.5E-03
Pu-238	1.6E+00	5.4E+02	1.1E-05
Pu-239	1.5E+00	4.9E+02	4.9E-06
Pu-241	7.6E+01	2.5E+04	3.7E-06
Ra-226	5.3E+00	1.8E+03	9.9E-02
Ru-103	2.9E+02	9.7E+04	1.5E+00
Ru-106	8.7E+01	2.9E+04	3.3E-01
Sb-127	2.0E+03	6.6E+05	1.5E+01
Sb-129	1.7E+04	5.7E+06	2.8E+02
Se-75	1.5E+02	5.0E+04	5.8E-01
Sr-89	1.5E+03	5.0E+05	1.1E+00
Sr-90	1.7E+02	5.8E+04	2.1E-01
Sr-91	1.1E+04	3.6E+06	1.2E+02
Te-129m	1.2E+03	3.9E+05	1.7E+00
Te-131m	2.2E+03	7.2E+05	3.5E+01
Te-132	6.6E+02	2.2E+05	1.8E+01
Tm-170	1.9E+03	6.2E+05	5.0E-01
Y-91	1.2E+03	4.0E+05	9.9E-01
Yb-169	5.7E+02	1.9E+05	1.8E+00
Zr-95	3.8E+01	1.3E+04	9.6E-01

Table 4-5a Second Year Deposition Dose Parameters

Parent Radionuclide	Dp_ExDP (mrem·m²/µCi)	Dp_InhDP (mrem·m²/µCi)	Dp_TDP (mrem·m²/µCi)
Am-241	1.6E+00	6.9E+00	8.5E+00
Ba-140	2.6E-08	8.3E-14	2.6E-08
Ce-141	3.0E-04	1.9E-08	3.0E-04
Ce-144	3.7E+00	1.1E-03	3.7E+00
Cf-252	2.2E+01	1.8E+00	2.4E+01
Cm-242	5.7E-03	8.4E-02	9.0E-02
Cm-244	4.2E-02	3.9E+00	3.9E+00
Co-60	1.4E+02	1.8E-03	1.4E+02
Cs-134	6.8E+01	9.1E-04	6.8E+01
Cs-136	3.4E-08	5.7E-14	3.4E-08
Cs-137	4.0E+01	2.7E-03	4.0E+01
Gd-153	1.5E+00	4.0E-05	1.5E+00
I-129	1.5E+00	2.6E-03	1.5E+00
I-131	8.5E-13	5.0E-19	8.5E-13
I-132	NA	NA	NA
I-133	1.5E-23	8.4E-134	1.5E-23
I-134	NA	NA	NA
I-135	1.3E-12	2.0E-13	1.5E-12
Ir-192	5.6E-01	5.2E-06	5.6E-01
La-140	3.8E-66	2.5E-72	3.8E-66
Mo-99	1.9E-10	3.7E-11	2.3E-10
Nb-95	6.0E-03	1.7E-08	6.0E-03
Np-237	4.5E+01	2.4E+01	6.9E+01
Np-239	6.2E-09	2.3E-06	2.3E-06
Pm-147	1.4E-03	3.4E-04	1.8E-03
Pu-238	4.5E-02	7.7E+00	7.7E+00
Pu-239	2.3E-02	8.5E+00	8.6E+00
Pu-241	4.1E-03	1.7E-01	1.7E-01
Ra-226	1.3E+02	1.4E+00	1.3E+02
Ru-103	9.3E-03	6.6E-08	9.3E-03
Ru-106	9.6E+00	1.8E-03	9.6E+00
Sb-127	3.6E-04	2.0E-07	3.6E-04
Sb-129	9.2E-07	6.3E-11	9.2E-07
Se-75	1.4E+00	5.4E-06	1.4E+00
Sr-89	7.2E-03	9.3E-07	7.2E-03
Sr-90	8.1E+00	1.1E-02	8.2E+00
Sr-91	1.3E-04	1.7E-08	1.3E-04
Te-129m	7.6E-04	5.2E-08	7.6E-04
Te-131m	1.5E-13	9.2E-20	1.5E-13
Te-132	4.8E-34	5.3E-40	4.8E-34
Tm-170	1.2E-01	4.5E-05	1.2E-01
Y-91	1.8E-02	2.4E-06	1.8E-02
Yb-169	1.1E-03	1.3E-08	1.1E-03
Zr-95	8.6E-01	4.0E-06	8.6E-01

Table 4-5b Second Year DRLs

Parent Radionuclide	2Path_DRL$_{Dp}$ (µCi/m²)	2Path_DRL$_{\tilde{A}}$ (µCi•s/m³)	2Path_DRL$_{DR}$ (mrem/hr)
Am-241	5.9E+01	2.0E+04	1.4E-02
Ba-140	1.9E+10	6.3E+12	5.5E+08
Ce-141	1.7E+06	5.6E+08	1.3E+03
Ce-144	1.3E+02	4.5E+04	2.6E-01
Cf-252	2.1E+01	6.9E+03	9.8E-02
Cm-242	5.5E+03	1.8E+06	4.0E-02
Cm-244	1.3E+02	4.3E+04	8.2E-04
Co-60	3.5E+00	1.2E+03	8.8E-02
Cs-134	7.3E+00	2.4E+03	1.2E-01
Cs-136	1.4E+10	4.8E+12	3.1E+08
Cs-137	1.2E+01	4.2E+03	7.5E-02
Gd-153	3.3E+02	1.1E+05	3.3E-01
I-129	3.3E+02	3.3E+04	7.2E-02
I-131	5.6E+14	5.6E+16	2.2E+12
I-132	NA	NA	NA
I-133	2.2E+25	2.2E+27	1.5E+23
I-134	NA	NA	NA
I-135	9.7E+13	9.7E+15	1.6E+12
Ir-192	8.9E+02	3.0E+05	7.5E+00
La-140	1.1E+68	3.6E+70	2.5E+66
Mo-99	1.9E+12	6.5E+14	6.1E+09
Nb-95	8.3E+04	2.8E+07	6.6E+02
Np-237	7.2E+00	2.4E+03	4.7E-02
Np-239	1.9E+08	6.3E+10	3.3E+05
Pm-147	2.8E+05	9.4E+07	8.6E-02
Pu-238	6.5E+01	2.2E+04	4.2E-04
Pu-239	5.8E+01	1.9E+04	2.0E-04
Pu-241	2.9E+03	9.6E+05	1.4E-04
Ra-226	3.8E+00	1.3E+03	7.2E-02
Ru-103	5.3E+04	1.8E+07	2.8E+02
Ru-106	5.2E+01	1.7E+04	2.0E-01
Sb-127	1.3E+06	4.3E+08	9.6E+03
Sb-129	8.0E+07	2.7E+10	1.3E+06
Se-75	3.6E+02	1.2E+05	1.4E+00
Sr-89	6.9E+04	2.3E+07	5.2E+01
Sr-90	6.1E+01	2.0E+04	7.5E-02
Sr-91	1.6E+06	5.5E+08	1.9E+04
Te-129m	6.5E+05	2.2E+08	9.6E+02
Te-131m	2.5E+15	8.5E+17	4.1E+13
Te-132	9.3E+35	3.1E+38	2.5E+34
Tm-170	4.2E+03	1.4E+06	1.2E+00
Y-91	2.8E+04	9.4E+06	2.3E+01
Yb-169	4.5E+05	1.5E+08	1.5E+03
Zr-95	5.8E+02	1.9E+05	1.5E+01

Table 4-6a Fifty Year Deposition Dose Parameters

Parent Radionuclide	Dp_ExDP (mrem·m²/µCi)	Dp_InhDP (mrem·m²/µCi)	Dp_TDP (mrem·m²/µCi)
Am-241	4.5E+01	1.1E+03	1.2E+03
Ba-140	1.2E+01	4.4E-02	1.2E+01
Ce-141	8.3E-01	3.2E-02	8.6E-01
Ce-144	1.6E+01	5.8E-01	1.7E+01
Cf-252	1.1E+02	4.2E+02	5.3E+02
Cm-242	4.2E-02	6.4E+01	6.4E+01
Cm-244	6.4E-01	6.6E+02	6.6E+02
Co-60	1.1E+03	3.5E-01	1.1E+03
Cs-134	3.1E+02	2.3E-01	3.1E+02
Cs-136	9.5E+00	1.7E-02	9.5E+00
Cs-137	7.6E+02	4.5E-01	7.6E+02
Gd-153	7.3E+00	2.6E-02	7.3E+00
I-129	4.3E+01	4.2E-01	4.3E+01
I-131	1.1E+00	3.6E-02	1.1E+00
I-132	2.1E-03	3.3E-07	2.1E-03
I-133	1.5E-01	9.0E-04	1.5E-01
I-134	2.6E-06	1.8E-10	2.6E-06
I-135	6.4E-02	2.8E-05	6.4E-02
Ir-192	2.1E+01	6.6E-02	2.1E+01
La-140	1.1E+00	1.5E-03	1.1E+00
Mo-99	2.6E-01	2.2E-03	2.6E-01
Nb-95	9.3E+00	1.5E-02	9.3E+00
Np-237	1.3E+03	3.9E+03	5.2E+03
Np-239	1.2E-01	2.2E-03	1.3E-01
Pm-147	7.3E-03	8.0E-02	8.7E-02
Pu-238	1.1E+00	1.3E+03	1.3E+03
Pu-239	6.6E-01	1.4E+03	1.4E+03
Pu-241	8.4E-01	2.7E+01	2.7E+01
Ra-226	3.6E+03	2.3E+02	3.9E+03
Ru-103	6.8E+00	2.7E-02	6.8E+00
Ru-106	4.0E+01	7.4E-01	4.1E+01
Sb-127	9.2E-01	6.3E-03	9.3E-01
Sb-129	1.7E-02	9.2E-05	1.7E-02
Se-75	1.5E+01	1.4E-02	1.5E+01
Sr-89	1.3E+00	7.5E-02	1.3E+00
Sr-90	1.5E+02	1.8E+00	1.5E+02
Sr-91	7.7E-02	6.8E-04	7.8E-02
Te-129m	1.6E+00	6.9E-02	1.7E+00
Te-131m	7.0E-01	6.4E-03	7.0E-01
Te-132	2.7E+00	5.5E-03	2.7E+00
Tm-170	1.1E+00	9.8E-02	1.2E+00
Y-91	1.6E+00	8.6E-02	1.7E+00
Yb-169	3.5E+00	2.6E-02	3.5E+00
Zr-95	5.3E+01	9.5E-02	5.3E+01

Table 4-6b Fifty Year DRLs

Parent Radionuclide	2Path_DRL$_{Dp}$ (µCi/m^2)	2Path_DRL$_{\tilde{A}}$ (µCi•s/m^3)	2Path_DRL$_{DR}$ (mrem/hr)
Am-241	4.3E+00	1.4E+03	1.0E-03
Ba-140	3.9E+02	1.3E+05	1.1E+01
Ce-141	5.8E+03	1.9E+06	4.4E+00
Ce-144	2.9E+02	9.8E+04	5.7E-01
Cf-252	9.3E+00	3.1E+03	4.4E-02
Cm-242	7.8E+01	2.6E+04	5.7E-04
Cm-244	7.6E+00	2.5E+03	4.8E-05
Co-60	4.7E+00	1.6E+03	1.2E-01
Cs-134	1.6E+01	5.3E+03	2.6E-01
Cs-136	5.1E+02	1.7E+05	1.1E+01
Cs-137	6.6E+00	2.2E+03	3.9E-02
Gd-153	6.8E+02	2.3E+05	6.8E-01
I-129	1.2E+02	1.2E+04	2.5E-02
I-131	4.4E+03	4.4E+05	1.7E+01
I-132	6.3E+04	6.3E+06	1.5E+03
I-133	2.2E+04	2.2E+06	1.5E+02
I-134	1.5E+05	1.5E+07	4.0E+03
I-135	2.2E+04	2.2E+06	3.7E+02
Ir-192	2.4E+02	8.1E+04	2.0E+00
La-140	3.7E+03	1.2E+06	8.6E+01
Mo-99	1.7E+04	5.5E+06	5.2E+01
Nb-95	5.3E+02	1.8E+05	4.2E+00
Np-237	9.6E-01	3.2E+02	6.3E-03
Np-239	3.4E+04	1.1E+07	6.0E+01
Pm-147	5.7E+04	1.9E+07	1.8E-02
Pu-238	4.0E+00	1.3E+03	2.6E-05
Pu-239	3.6E+00	1.2E+03	1.2E-05
Pu-241	1.8E+02	6.1E+04	8.8E-06
Ra-226	1.3E+00	4.3E+02	2.4E-02
Ru-103	7.3E+02	2.4E+05	3.8E+00
Ru-106	1.2E+02	4.1E+04	4.7E-01
Sb-127	4.9E+03	1.6E+06	3.7E+01
Sb-129	4.3E+04	1.4E+07	7.0E+02
Se-75	3.3E+02	1.1E+05	1.3E+00
Sr-89	3.7E+03	1.2E+06	2.8E+00
Sr-90	3.2E+01	1.1E+04	3.9E-02
Sr-91	2.7E+04	8.9E+06	3.1E+02
Te-129m	2.9E+03	9.6E+05	4.2E+00
Te-131m	5.4E+03	1.8E+06	8.6E+01
Te-132	1.7E+03	5.5E+05	4.4E+01
Tm-170	4.1E+03	1.4E+06	1.1E+00
Y-91	3.0E+03	1.0E+06	2.4E+00
Yb-169	1.4E+03	4.7E+05	4.6E+00
Zr-95	9.3E+01	3.1E+04	2.4E+00

This Table is RESERVED for the future inclusion of Skin Dose Data.

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Shielding/Protection Factors are the ratio of the exterior dose to the interior dose at the location in question. For example, a Factor of 20 would reduce an exterior dose of 100 rem to 5 rem.

Table 6-1 Gamma Cloud Source Shielding Factors

Structure or Location	Shielding Factor [a]
Outside	1.0
Vehicles	1.0
Wood frame house [b] (no basement)	1.1
Basement of wood frame house	1.67
Masonry house (no basement)	1.67
Basement of masonry house	2.5
Large office or industrial building	5

[a] EGG75

[b] A wood frame house with brick or stone veneer is approximately equivalent to a masonry house for shielding purposes.

Table 6-2 Surface Deposition Shielding Factors for Vehicles

Vehicle	Representative Shielding Factor [a]
Cars on fully contaminated road	2
Cars on fully decontaminated 50-foot road	4
Trains	2.5

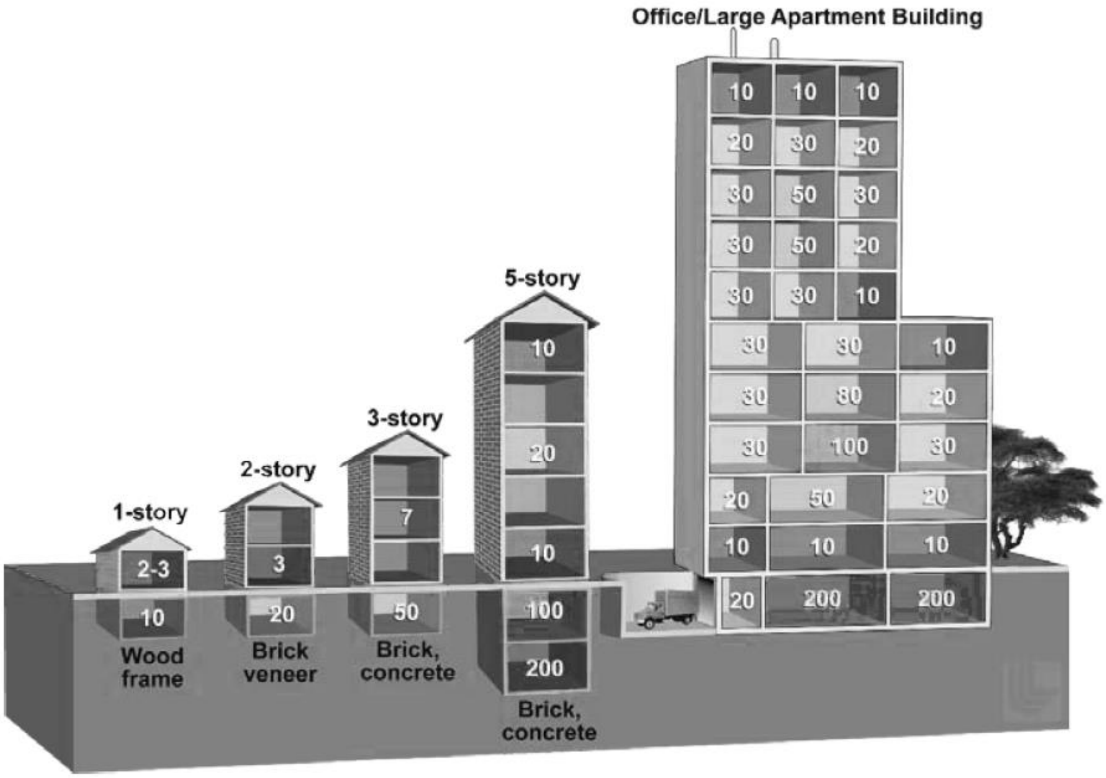
[a] EGG75

Table 6-3 Fallout Protection Factors for Buildings [a]

Structure	Basement	1st Floor	2nd Floor	3rd Floor
Vinyl-sided 2-story home	22-46	2-4	2-3	N/A
Brick-sided 2-story home	31-62	3-8	3-5	N/A
Brick-walled urban row home	N/A	12-70	12-70	5-30
Vinyl-sided 3-storey apt building	N/A	3-7	2-6	3-5
Brick-sided 3-story apt building	N/A	4-11	4-9	4-8
3-story office (brick-sided concrete walls)	N/A	8-126	4-43	3-7

[a] LLNL11

Figure 6-1 Approximate Protection Factors for locations in different Building Types



Source: LLNL11

Table 7 – Breathing Rates by Age Group

This table lists the breathing rates for all age groups from ICRP Publication 66 (ICRP94).

Age Group	Activity								Total Volume	Activity Avg. Rate
	Sleeping		Sitting		Light Exercise		Heavy Exercise			
	Rate m^3/hr	Time hr/day	Rate m^3/hr	Time hr/day	Rate m^3/hr	Time hr/day	Rate m^3/hr	Time hr/day	m^3/day	m^3/hr
Newborn (3 month)	0.09	17.0	NA	NA	0.19	7.0	NA	NA	**2.86**	**0.12**
Infant (1 year)	0.15	14.0	0.22	3.33	0.35	6.67	NA	NA	**5.20**	**0.22**
5 yr old	0.24	12.0	0.32	4.0	0.57	8.0	NA	NA	**8.76**	**0.37**
10 yr old	0.31	10.0	0.38	4.67	1.12	9.33	NA	NA	**15.28**	**0.64**
15 yr old (m)	0.42	10.0	0.48	5.5	1.38	7.5	2.92	1.0	**20.10**	**0.84**
15 yr 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.										

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Table 8 – Ingestion Pathway – DILs, DRLs, and Transfer Factors

This table includes an abbreviated list of radionuclides compared to the list tabulated in other sections of this appendix. Parent radionuclides with a half-life less than 6 hours are excluded from ingestion pathway analysis because it is unlikely 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.

Daughter radionuclides in transient (or secular) equilibrium are excluded from independent ingestion pathway analysis because their contribution to dose is included in the dose coefficient of the ultimate parent. Daughter radionuclides with a half-life greater than 6 hours **are included in the list below separately from the parent radionuclide** because it may be possible to disperse a quantity of these radionuclides that is sufficient to cause an ingestion concern before significant decay occurs without the parent radionuclide being present.

Radionuclide (units)	FDA Listed	DIL[a] (µCi/ kg_{wet})	Mature Crop DRL[b] (µCi/m^2)	Leafy TF (kg_{soil}/ kg_{dry})	Fruit TF (kg_{soil}/ kg_{dry})	Root TF (kg_{soil}/ kg_{dry})	Grain TF (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 TF [d] (d/kg_{wet})
Am-241	Y[e]	5.4E-05	5.4E-04	4.7E-04	2.5E-04	3.5E-04	2.2E-05	1.0E+00	7.5E-01	6.2E-01	1.5E-06	4.0E-05
Ba-140	Y	1.9E-01	2.0E+00	1.5E-01	1.5E-02	1.5E-02	1.5E-02	1.2E+01	9.0E+00	7.5E+00	4.8E-04	2.0E-04
Ce-141	Y	1.9E-01	2.0E+00	2.0E-02	2.0E-02	2.0E-02	2.0E-02	1.9E+02	1.4E+02	1.2E+02	3.0E-05	2.0E-05
Ce-144	Y	1.4E-02	1.4E-01	2.0E-02	2.0E-02	2.0E-02	2.0E-02	1.3E+01	9.4E+00	7.8E+00	3.0E-05	2.0E-05
Cf-252		1.0E-04	1.0E-03	4.7E-04[f]	2.5E-04	3.5E-04	2.2E-05	1.9E+00	1.4E+00	1.2E+00	1.5E-06	4.0E-05
Cm-242	Y	5.1E-04	5.2E-03	7.7E-04	1.5E-05	4.3E-04	2.1E-05	7.4E-01	5.4E-01	4.5E-01	2.0E-05	4.0E-05
Cm-244	Y	5.4E-05	5.4E-04	7.7E-04	1.5E-05	4.3E-04	2.1E-05	7.7E-02	5.6E-02	4.7E-02	2.0E-05	4.0E-05
Co-60		2.0E-02	2.0E-01	2.3E-01	7.0E-03	6.7E-02	3.7E-03	1.9E+00	1.4E+00	1.2E+00	3.0E-04	1.0E-02
Cs-134	Y[g]	2.5E-02	2.5E-01	4.6E-01	2.2E-01	1.3E-01	2.6E-02	9.1E-02	6.6E-02	5.5E-02	7.9E-03	5.0E-02
Cs-136		3.1E-01	3.3E+00	4.6E-01	2.2E-01	1.3E-01	2.6E-02	1.3E+00	9.2E-01	7.6E-01	7.9E-03	5.0E-02
Cs-137	Y[g]	3.7E-02	3.7E-01	4.6E-01	2.2E-01	1.3E-01	2.6E-02	1.3E-01	9.7E-02	8.0E-02	7.9E-03	5.0E-02
Gd-153		3.6E-01	3.6E+00	2.0E-02	2.0E-02	2.0E-02	2.0E-02	3.5E+02	2.5E+02	2.1E+02	3.0E-05	2.0E-05
I-129	Y	1.5E-03	3.0E-03	4.0E-02	4.0E-02	4.0E-02	4.0E-02	2.4E-03	3.5E-03	2.9E-03	9.0E-03	4.0E-02
I-131	Y	4.6E-03	1.0E-02	4.0E-02	4.0E-02	4.0E-02	4.0E-02	8.8E-03	1.3E-02	1.0E-02	9.0E-03	4.0E-02
I-133	Y	1.9E-01	8.4E-01	4.0E-02	4.0E-02	4.0E-02	4.0E-02	1.5E+00	2.2E+00	1.8E+00	9.0E-03	4.0E-02
I-135		3.2E+00	8.0E+01	4.0E-02	4.0E-02	4.0E-02	4.0E-02	7.9E+02	1.1E+03	9.5E+02	9.0E-03	4.0E-02
Ir-192		7.9E-02	8.0E-01	5.5E-02	1.5E-02	1.5E-02	1.5E-02	1.2E+03	8.4E+02	7.0E+02	2.0E-06	1.5E-03
La-140		1.8E+00	2.7E+01	5.2E-03	4.0E-03	3.5E-04	4.0E-03	5.9E+03	4.3E+03	3.6E+03	2.0E-05	2.0E-03
Mo-99		4.0E+00	5.1E+01	8.0E-01	5.0E-02	8.0E-01	8.0E-01	1.1E+02	8.0E+01	6.7E+01	1.7E-03	1.0E-03

Radionuclide (units)	FDA Listed	DIL[a] (µCi/ kg_{wet})	Mature Crop DRL[b] (µCi/m^2)	Leafy TF (kg_{soil}/ kg_{dry})	Fruit TF (kg_{soil}/ kg_{dry})	Root TF (kg_{soil}/ kg_{dry})	Grain TF (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 TF [d] (d/kg_{wet})
Nb-95	Y	3.2E-01	3.3E+00	2.5E-02	2.5E-02	2.5E-02	2.5E-02	2.3E+04	1.7E+04	1.4E+04	4.1E-07	3.0E-07
Nb-95m		2.3E+00	2.8E+01	2.5E-02	2.5E-02	2.5E-02	2.5E-02	2.3E+05	1.7E+05	1.4E+05	4.1E-07	3.0E-07
Np-237	Y	1.1E-04	1.1E-03	3.2E-02	1.0E-02	1.3E-02	2.7E-03	6.2E-01	4.5E-01	3.7E-01	5.0E-06	1.0E-03
Np-239	Y	7.6E-01	1.0E+01	3.2E-02	1.0E-02	1.3E-02	2.7E-03	7.8E+03	5.7E+03	4.7E+03	5.0E-06	1.0E-03
Pa-233		1.9E-01	2.0E+00	4.7E-04	2.5E-04	3.5E-04	2.2E-05	1.2E+03	8.4E+02	7.0E+02	5.0E-06	4.0E-05
Pm-147		3.0E-01	3.0E+00	2.0E-02	2.0E-02	2.0E-02	2.0E-02	2.8E+02	2.1E+02	1.7E+02	3.0E-05	2.0E-05
Pu-238	Y[e]	6.8E-05	6.8E-04	6.0E-05	4.5E-05	1.1E-03	8.6E-06	1.8E+00	1.3E+00	1.1E+00	1.1E-06	1.0E-05
Pu-239	Y[e]	6.0E-05	5.9E-04	6.0E-05	4.5E-05	1.1E-03	8.6E-06	1.5E+00	1.1E+00	9.3E-01	1.1E-06	1.0E-05
Pu-241	Y	3.2E-03	3.3E-02	6.0E-05	4.5E-05	1.1E-03	8.6E-06	8.4E+01	6.2E+01	5.1E+01	1.1E-06	1.0E-05
Ra-226		5.5E-05	5.5E-04	4.9E-02	6.1E-03	2.0E-03	1.2E-03	1.2E-03	8.8E-04	7.3E-04	1.3E-03	9.0E-04
Ru-103	Y[h]	1.8E-01	1.9E+00	4.0E-02	4.0E-02	4.0E-02	5.0E-03	1.6E+03	1.2E+03	1.0E+03	3.3E-06	5.0E-02
Ru-106	Y[h]	1.2E-02	1.2E-01	4.0E-02	4.0E-02	4.0E-02	5.0E-03	1.1E+02	7.7E+01	6.4E+01	3.3E-06	5.0E-02
Sb-127		8.5E-01	1.0E+01	1.3E-04	8.0E-05	5.6E-04	3.0E-02	1.4E+03	1.0E+03	8.5E+02	2.5E-05	1.0E-03
Se-75		5.5E-02	5.5E-01	2.5E-01	5.0E-02	5.0E-02	2.5E-01	4.0E-01	2.9E-01	2.4E-01	4.0E-03	1.5E-02
Sr-89	Y	3.8E-02	3.8E-01	3.0E+00	2.0E-01	5.0E-01	2.1E-01	4.0E-01	2.9E-01	2.4E-01	2.8E-03	8.0E-03
Sr-90	Y	4.3E-03	4.3E-02	3.0E+00	2.0E-01	5.0E-01	2.1E-01	4.4E-02	3.2E-02	2.7E-02	2.8E-03	8.0E-03
Sr-91		2.9E+01	1.7E+03	3.0E+00	2.0E-01	5.0E-01	2.1E-01	9.8E+03	7.1E+03	5.9E+03	2.8E-03	8.0E-03
Tc-99m		1.2E+03	1.8E+05	2.1E+02	1.5E+00	2.4E-01	7.3E-01	5.9E+07	4.3E+07	3.6E+07	1.4E-04	1.0E-04
Te-127		1.0E+02	6.0E+03	2.5E-02	4.0E-03	4.0E-03	4.0E-03	2.2E+05	1.6E+05	1.4E+05	4.5E-04	7.0E-03
Te-129m		4.0E-02	4.1E-01	2.5E-02	4.0E-03	4.0E-03	4.0E-03	2.7E+00	1.9E+00	1.6E+00	4.5E-04	7.0E-03
Te-131m		1.8E+00	3.2E+01	2.5E-02	4.0E-03	4.0E-03	4.0E-03	3.5E+02	2.6E+02	2.1E+02	4.5E-04	7.0E-03
Te-132	Y	1.2E-01	1.5E+00	2.5E-02	4.0E-03	4.0E-03	4.0E-03	1.2E+01	8.4E+00	7.0E+00	4.5E-04	7.0E-03
Tm-170[i]		5.6E-02	5.7E-01	2.0E-02	2.0E-02	2.0E-02	2.0E-02	5.5E+01	3.9E+01	3.3E+01	3.0E-05	2.0E-05
U-237		9.2E-01	1.0E+01	8.3E-03	4.0E-03	1.2E-02	1.3E-03	8.0E+01	5.8E+01	4.9E+01	4.0E-04	3.0E-04
Y-90		6.2E-01	8.0E+00	1.0E-02	1.0E-02	1.0E-02	1.0E-02	1.5E+03	1.1E+03	9.0E+02	2.0E-05	1.0E-03
Y-91	Y	3.2E-02	3.3E-01	1.0E-02	1.0E-02	1.0E-02	1.0E-02	4.7E+01	3.5E+01	2.9E+01	2.0E-05	1.0E-03
Yb-169[i]		2.4E-01	2.5E+00	2.0E-02	2.0E-02	2.0E-02	2.0E-02	2.4E+02	1.7E+02	1.5E+02	3.0E-05	2.0E-05
Zr-95	Y	1.1E-01	1.1E+00	1.0E-03	1.0E-03	1.0E-03	1.0E-03	5.7E+03	4.2E+03	3.5E+03	5.5E-07	1.0E-06

Notes:

[a] Calculated DILs are based on the ICRP 60+ dosimetry model for the most sensitive organ of the most sensitive age group. Fraction of Diet Contaminated is assumed to be 0.3 except for ^{132}Te, ^{131}I, ^{133}I and ^{239}Np in the diet of an Infant, where it is assume to be 1.0. (See Volume 1, Method 4.1.)

[b] Assumes Crops are ready to harvest. (See Volume 1, Method 4.2 for assumptions and default inputs.)

[c] Values for Cow's Milk. See Volume 1, Method 4.3. Transfer Factors from PNNL-13421.

[d] Values for Beef. See Volume 1, Method 4.4. Transfer Factors from PNNL-13421.

[e] These radionuclides are grouped for evaluation purposes. When more than one of these nuclides is present the TOTAL amount of the radionuclides is compared to a group DIL of 5.4E-05 µCi/kg_{wet}.

[f] Two values for Cf are reported in the reference. The most conservative is in the table, the other is 2.5E-04.

[g] These radionuclides are grouped for evaluation purposes. When more than one of these nuclides is present the TOTAL amount of the radionuclides is compared to a group DIL of 3.2E-02 µCi/kg_{wet}.

[h] ^{103}Ru and ^{106}Ru DIL is based on Sum of Fractions (^{103}Ru /0.18) + (^{106}Ru /0.012) <1. For the purposes of this table, we are assuming only ONE isotope is present.

[i] No specific Transfer Factors listed in PNNL-13421. Lanthanides are assigned the Ce Transfer Factor value per Section 1.3 of the document.

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Table 9-1 Dry-to-Wet Mass [a]

Plant Type	Mass Conversion Factor kg_{dry}/kg_{wet}
Leafy vegetables	0.2
Other/root vegetables	0.25
Fruit	0.18
Grain	0.91
Animal Feed	
Forage	0.22
Stored hay	0.22
Stored grain	0.91

[a] Values from PNNL03, Table 2.1.

Inverse values for converting from wet to dry:

Table 9-2 Wet-to-Dry Mass

Plant Type	Mass Conversion Factor kg_{wet}/kg_{dry}
Leafy vegetables	5
Other/root vegetables	4
Fruit	5.56
Grain	1.1
Animal Feed	
Forage	4.55
Stored hay	4.55
Stored grain	1.1

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Table 10 – Daily Food Intake Rates

This table lists the average DFIR for populations of various ages in the United States.

Food Category	Daily Consumption (kg/day)					
	3 months	1 year	5 years	10 years	15 years	Adult
Total Dairy	**5.7E-01**	**4.9E-01**	**4.6E-01**	**5.0E-01**	**4.8E-01**	**2.9E-01**
Fresh Cow's Milk	2.7E-01	3.2E-01	4.1E-01	4.5E-01	4.3E-01	2.4E-01
Other	3.0E-01	1.7E-01	4.4E-02	5.0E-02	5.3E-02	5.2E-02
Fresh Eggs	**4.9E-03**	**1.2E-02**	**1.8E-02**	**1.8E-02**	**2.2E-02**	**2.9E-02**
Total Meat	**4.5E-02**	**6.9E-02**	**1.1E-01**	**1.4E-01**	**1.7E-01**	**1.9E-01**
Beef	1.8E-02	3.0E-02	5.3E-02	7.3E-02	9.1E-02	9.8E-02
Pork	5.8E-03	9.7E-03	1.6E-02	2.0E-02	2.6E-02	3.1E-02
Poultry	1.8E-02	1.9E-02	2.2E-02	2.7E-02	3.2E-02	3.3E-02
Other	2.6E-03	1.0E-02	2.0E-02	2.4E-02	2.7E-02	2.7E-02
Total Fish	**9.0E-04**	**3.8E-03**	**8.8E-03**	**1.2E-02**	**1.5E-02**	**1.9E-02**
Fin Fish	6.0E-04	3.5E-03	8.2E-03	1.1E-02	1.3E-02	1.6E-02
Shellfish	3.0E-04	3.0E-04	6.0E-04	1.1E-03	1.7E-03	3.0E-03
Total Produce	**1.6E-01**	**1.6E-01**	**1.9E-01**	**2.4E-01**	**2.6E-01**	**2.9E-01**
Leafy	3.2E-03	6.2E-03	1.5E-02	2.3E-02	2.9E-02	4.2E-02
Exposed	7.6E-02	6.6E-02	6.2E-02	7.3E-02	7.4E-02	8.3E-02
Protected	5.1E-02	7.3E-02	1.1E-01	1.4E-01	1.5E-01	1.5E-01
Other	2.6E-02	1.5E-02	6.2E-03	7.8E-03	7.2E-03	6.5E-03
Total Grains	**5.6E-02**	**1.1E-01**	**1.9E-01**	**2.3E-01**	**2.5E-01**	**2.1E-01**
Breads	1.6E-02	6.0E-02	1.3E-01	1.7E-01	1.9E-01	1.6E-01
Cereals	3.8E-02	3.8E-02	3.9E-02	3.8E-02	3.3E-02	2.6E-02
Other	1.8E-03	8.3E-03	1.9E-02	2.4E-02	2.7E-02	2.5E-02
Total Beverages	**3.1E-01**	**5.2E-01**	**8.0E-01**	**9.4E-01**	**1.1**	**1.5**
Tap Water	1.7E-01	3.0E-01	4.8E-01	5.7E-01	6.4E-01	6.8E-01
Water-Based Drinks	8.3E-03	5.3E-02	1.1E-01	1.3E-01	1.7E-01	4.7E-01
Soups	1.0E-02	2.7E-02	4.0E-02	3.6E-02	3.5E-02	4.4E-02
Other	1.2E-01	1.4E-01	1.8E-01	2.1E-01	2.9E-01	3.3E-01
Miscellaneous	**5.5E-03**	**1.6E-02**	**3.1E-02**	**3.9E-02**	**3.9E-02**	**3.4E-02**
Total Daily Intake (kg/d)	**1.1**	**1.4**	**1.8**	**2.1**	**2.4**	**2.6**
Total Annual Intake (kg/yr)	**420**	**510**	**660**	**780**	**870**	**940**

Sources: EPA84, FDA98 (Rounded to 2 significant figures.)

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Table 11 – Ingestion Pathway Default Assumptions

The parameters in this table can vary depending on several environmental factors. The FRMAC Assessment Working Group has determined that these values are reasonable over a wide variety of conditions and should be used as the defaults for the methods in this Manual.

Parameter	Description	Value [a]
Animal Feed Daily Ingestion Rate (AFDIR)	Milk Cow	50 kg/d
	Beef Cow	50 kg/d
	Goat	6 kg/d
Animal Soil Daily Ingestion Rate (ASDIR)	Milk Cow	0.5 kg/d [b]
	Beef Cow	0.5 kg/d [b]
	Goat	0.06 kg/d [b,c]
Animal Water Daily Ingestion Rate (AWDIR)	Milk Cow	60 l/d
	Beef Cow	50 l/d
	Goat	8 l/d
Consumption Time	Time contaminated food is consumed.	365 d
Crop Retention Factor (CRF)	Pastureland	0.5 [d]
	Pastureland, Iodines	1.0
	Fresh produce, particulates	0.2
	Fresh produce, Iodines	1.0
	Crops planted AFTER deposition	0.0
Crop Weathering Decay Constant	Corresponds to a 15 day half-life.	4.62E-02 d^{-1} [e]
Crop Yield (Y)	Produce	2.0 kg/m^2
	Pastureland	0.7 kg/m^2
Density of Milk (ρ_{milk})		1.04 kg/L [f]
Density of Soil (ρ_{soil})		1600 kg/m^3 [f]
Fraction of Diet Contaminated (FDC)	I-131, I-133, Te-132, and Np-239 in the diet of an infant (3 mo and 1 yr old).	1.0 [g]
	All other Radionuclide/Age Group combinations.	0.3 [g]
Fraction of Diet Contaminated (Feed (including forage)) or (Water)	Cow Feed (FDC_F) Cow Water (FDC_W)	1.0
Fraction of Subgroup Contaminated ($FFC_{subgroup}$)		1.0 [f]
Mixing Depth (d_m)	Paved	1.0E-04 [h]
	Unpaved (First Growing Season)	1.0E-03 [h]
	After Plowing (plow depth)	0.15
Daily Soil Intake Rate (DSIR)	Adult	5.0E-05 kg/d [i]
	Child	1.0E-04 kg/d [i]
Time to Market (t_m)	Crop/Produce	1 d
	Milk	2 d
	Meat	20 d

Notes:

[a] All values from NRC77 unless otherwise indicated.

[b] ANL01

[c] Goat value estimated based on ratio of Feed to Soil for Cows (100:1).

[d] Ng77 (Appendix B, page 113)

[e] NCRP07 (Page 165)

[f] FRMAC Assumption

[g] FDA98 (Appendix E, page 2)

[h] EPA89

[i] EPA11 (Table ES-1)

This section reserved for potential inclusion of Worksheets in the future.

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SI PREFIXES

E	exa	10^{18}
P	peta	10^{15}
T	tera	10^{12}
G	giga	10^{9}

M	mega	10^{6}
k	kilo	10^{3}
c	centi	10^{-2}
m	milli	10^{-3}

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/yr)/(µCi/m^2)	=	0.114 (rem/hr)/(Ci/m^2)

TIME

		s	min	hr	d	yr
1 s	=	1	1.67E-02	2.78E-04	1.16E-05	3.17E-08
1 m	=	60	1	1.67E-02	6.94E-04	1.90E-06
1 hr	=	3600	60	1	4.17E-02	8760
1 d	=	8.64E+04	1.44E+03	24	1	2.74E-03
1 yr	=	3.15E+07	5.26E+05	8760	365	1

TEMPERATURE & PRESSURE

°K = °C + 273
°F = (°C x 1.8) + 32
°C = (°F -32)/1.8

		lb/in^2	atm	bar	kPa	mm (Hg)
1 lb/in^2	=	1	6.80E-02	6.89E-02	6.89	51.7
1 atm	=	14.7	1	1.01	101	760
1 bar	=	14.5	0.99	1	100	752
1 kPa	=	0.145	9.90E-03	0.01	1	7.52
1 mm (Hg)	=	1.93E-02	1.32E-03	1.33E-03	0.133	1

LENGTH

		in	ft	yd	mile (s)	mile (n)	cm	m	km
1 in	=	1	8.33E-02	2.78E-02	1.58E-05	1.37E-05	2.54	2.54E-02	2.54E-06
1 ft	=	12	1	0.333	1.89E-04	1.65E-04	30.5	0.305	3.05E-04
1 yd	=	36	3	1	5.68E-04	4.94E-04	91.4	0.914	9.14E-04
1 mile (statute)	=	6.34E+04	5.28E+03	1.76E+03	1	0.869	1.61E+05	1.61E+03	1.61
1 mile (nautical)	=	7.29E+04	6.08E+03	2.03E+03	1.15	1	1.85E+05	1.85E+03	1.85
1 cm	=	0.394	3.28E-02	1.09E-02	6.21E-06	5.40E-06	1	1.0E-02	1.0E-05
1 m	=	39.4	3.28	1.09	6.21E-04	5.40E-04	100	1	1.0E-03
1 km	=	3.94E+04	3.28E+03	1.09E+03	0.621	0.540	1.0E+05	1.0E+03	1

AREA

		in^2	ft^2	yd^2	acre	mi^2 (s)	cm^2	m^2	ha	km^2
1 in^2	=	1	6.94E-03	7.72E-04	1.59E-07	2.49E-10	6.45	6.45E-04	6.45E-08	6.45E-10
1 ft^2	=	144	1	0.111	2.30E-05	3.59E-08	929	9.29E-02	9.29E-06	9.29E-08
1 yd^2	=	1.30E+03	9	1	2.07E-04	3.23E-07	8.36E+03	0.836	8.36E-05	8.36E-07
1 acre	=	6.27E+06	4.36E+04	4.84E+03	1	1.56E-03	4.05E+07	4.05E+03	0.405	4.05E-03
1 mi^2 (statute)	=	4.01E+09	2.79E+07	3.10E+06	640	1	2.59E+10	2.59E+06	259	2.59
1 cm^2	=	0.155	1.08E-03	1.20E-04	2.47E-08	3.86E-11	1	1.0E-04	1.0E-09	1.0E-10
1 m^2	=	1.55E+03	10.8	1.20	2.47E-04	3.86E-07	1.0E+04	1	1.0E-04	1.0E-06
1 ha	=	1.55E+07	1.08E+05	1.20E+04	2.47	3.86E-03	1.0E+08	1.0E+04	1	0.01
1 km^2	=	1.55E+09	1.08E+07	1.20E+06	247	0.386	1.0E+10	1.0E+06	100	1

VOLUME

		in^3	fl oz	ft^3	qt	gal	bu	mL	L
1 in^3	=	1	0.554	5.79E-04	1.73E-02	6.92E-02	4.65E-04	16.4	1.64E-02
1 fl oz	=	1.80	1	1.04E-03	3.13E-02	7.81E-03	8.39E-04	29.6	2.96E-02
1 ft^3	=	1.73E+03	957	1	29.9	7.48	0.802	2.83E+04	28.3
1 qt	=	57.8	32	3.34E-02	1	0.25	2.69E-02	9.47E+02	0.947
1 gal	=	231	128	0.134	4	1	0.107	3.79E+03	3.79
1 bu		2.15E+03	1.19E+03	1.24	37.2	9.31	1	3.52E+04	35.2
1 mL	=	6.10E-02	3.38E-02	3.53E-05	1.06E-03	2.64E-04	2.84E-05	1	1.0E-03
1 L	=	61.0	33.8	3.53E-02	1.06	0.264	2.84E-02	1.0E+03	1

NOTE: 1 Bushel (bu) = 8 dry gallons

VELOCITY

		ft/s	m/s	km/h	mile/h	knot
1 ft/s	=	1	0.305	1.10	0.682	0.592
1 m/s	=	3.28	1	3.6	2.24	1.94
1 km/h	=	0.911	0.278	1	0.621	0.540
1 mile/h	=	1.47	0.447	1.61	1	0.869
1 knot	=	1.69	0.514	1.85	1.15	1

FLOW RATE

		gal/min	ft^3/min	L/s	m^3/hr
1 gal/min	=	1	0.134	6.32E-02	0.227
1 ft^3/min	=	7.48	1	0.472	1.70
1 L/s	=	15.8	2.12	1	3.60
1 m^3/hr	=	4.40	0.589	0.278	1

WEIGHT

		oz	lb	ton (US)	kg	ton (metric)
oz	=	1	6.25E-02	3.13E-05	2.84E-02	2.84E-05
lb	=	16	1	5.0E-04	0.454	4.54E-04
ton (US)	=	3.2E+04	2.0E+03	1	907	0.907
kg	=	35.2	2.20	1.10E-03	1	1.0E-03
ton (metric)	=	3.52E+04	2.20E+03	1.10	1.0E+03	1

DENSITY

		lb/in^3	lb/ft^3	g/cm^3	kg/m^3
1 lb/in^3	=	1	5.79E-04	27.7	2.77E+04
1 lb/ft^3	=	1.73E+03	1	1.60E-02	16.0
1 g/cm^3	=	3.61E-02	62.4	1	1.0E+03
1 kg/m^3	=	3.61E-05	6.24E-02	1.0E-03	1

Misc

Water Density = (1 g/cm^3 at 4°C)

1 ft^3 = 7.48 gal = 62.4 lb

1 gal = 8.33 lb

Avogadro ’s number

6.02E+23 per g-mole

Air Density = (0.001293 g/cm^3 at STP)

1 ft^3 = 0.0807 lb

1 m^3 = 1.29 kg

Molar Volume

22.4 L/g-mole

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SUPPLEMENTS

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SUPPLEMENT 1 – DECAY AND IN-GROWTH CALCULATIONS

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:

$$A_{p,t_n} = A_{p,0} * e^{-\lambda_p t_n} \qquad \text{(Eq. 1)}$$

The activity of its first generation daughter, including Branching Ratio (BrR_{d1}), at t_n is:

$$A_{d_1,t_n} = A_{p,0} * \left(\lambda_{d_1} * BrR_{d_1}\right) * \left(\frac{e^{-\lambda_p t_n} - e^{-\lambda_{d_1} t_n}}{\lambda_{d_1} - \lambda_p}\right) \qquad \text{(Eq. 2)}$$

The activity of its second generation daughter, including Branching Ratio (BrR_{d2}), at t_n is:

$$A_{d_2,t_n} = A_{p,0} * \left(\lambda_{d_1} * BrR_{d_1} * \lambda_{d_2} * BrR_{d_2}\right) * \left[\frac{e^{-\lambda_p t_n}}{\left(\lambda_{d_1} - \lambda_p\right)\left(\lambda_{d_2} - \lambda_p\right)} + \frac{e^{-\lambda_{d_1} t_n}}{\left(\lambda_p - \lambda_{d_1}\right)\left(\lambda_{d_2} - \lambda_{d_1}\right)} + \frac{e^{-\lambda_{d_2} t_n}}{\left(\lambda_p - \lambda_{d_2}\right)\left(\lambda_{d_1} - \lambda_{d_2}\right)}\right] \qquad \text{(Eq. 3)}$$

Because this second generation daughter (d_2) is the first generation daughter of radionuclide d_1, the activity of d_2 at t_n due to the initial amount of d_1 can be determined from equation 3 as:

$$A_{d_2,t_n} = A_{d_1,0} * \left(\lambda_{d_2} * BrR_{d_2}\right) * \left(\frac{e^{-\lambda_{d_1} t_n} - e^{-\lambda_{d_2} t_n}}{\lambda_{d_2} - \lambda_{d_1}}\right) \qquad \text{(Eq. 4)}$$

The activity of d_2 as a parent at t_n is:

$$A_{d_2,t_n} = A_{d_2,0} * e^{-\lambda_{d_2} t_n} \qquad \text{(Eq. 5)}$$

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:

$$A_{d_2,t_n} = \left\{ \begin{aligned} & A_{p,0} * \left(\lambda_{d_1} * BrR_{d_1} * \lambda_{d_2} * BrR_{d_2} \right) \\ & * \left[\frac{e^{-\lambda_p t_n}}{\left(\lambda_{d_1} - \lambda_p\right)\left(\lambda_{d_2} - \lambda_p\right)} + \frac{e^{-\lambda_{d_1} t_n}}{\left(\lambda_p - \lambda_{d_1}\right)\left(\lambda_{d_2} - \lambda_{d_1}\right)} + \frac{e^{-\lambda_{d_2} t_n}}{\left(\lambda_p - \lambda_{d_2}\right)\left(\lambda_{d_1} - \lambda_{d_2}\right)} \right] \end{aligned} \right\}$$
$$+ \left[A_{d_1,0} * \left(\lambda_{d_2} * BrR_{d_2} \right) * \left(\frac{e^{-\lambda_{d_1} t_n} - e^{-\lambda_{d_2} t_n}}{\lambda_{d_2} - \lambda_{d_1}} \right) \right] \quad \text{(Eq. 6)}$$
$$+ A_{d_2,0} * e^{-\lambda_{d_2} t_n}$$

In the general case, the activity of the "nth" daughter (assuming an initial mix of parent only) at time t_n would be:

$$A_{d_n,t_n} = A_{p,0} * \left(C_1 e^{-\lambda_p t_n} + C_2 e^{-\lambda_{d_1} t_n} + C_3 e^{-\lambda_{d_2} t_n} + \ldots + C_n e^{-\lambda_{d_n} t_n} \right)$$

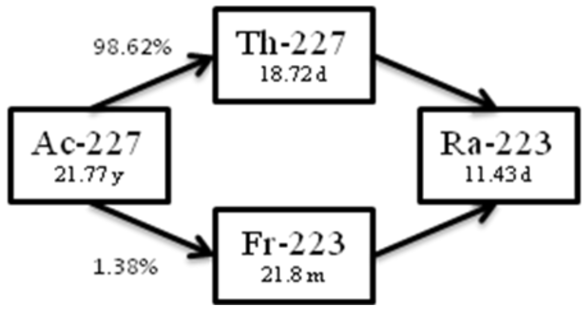
where:

$$C_1 = \frac{\lambda_{d_1} \lambda_{d_2} \ldots \lambda_{d_n}}{(\lambda_{d_1} - \lambda_p)(\lambda_{d_2} - \lambda_p)\ldots(\lambda_{d_n} - \lambda_p)}$$
$$C_2 = \frac{\lambda_{d_1} \lambda_{d_2} \ldots \lambda_{d_n}}{(\lambda_p - \lambda_{d_1})(\lambda_{d_2} - \lambda_{d_1})\ldots(\lambda_{d_n} - \lambda_{d_1})} \quad \text{(Eq. 7)}$$
$$\vdots$$
$$C_n = \frac{\lambda_{d_1} \lambda_{d_2} \ldots \lambda_{d_n}}{(\lambda_p - \lambda_{d_n})(\lambda_{d_1} - \lambda_{d_n})\ldots(\lambda_{d_{n-1}} - \lambda_{d_n})}$$

IMPORTANT: Remember that when a radionuclide chain branches, each chain must be evaluated separately and then activities of radionuclides that are produced by more than one branch must be summed over all of the production methods to determine the total activity present at a given time.

EXAMPLE 1

Using the following decay chain in which Ra-223 is formed from two decay pathways:



What is the activity of Ra-223 100 days after a 1 Ci pure Ac-227 sample is created?

Given:

λ_{Ac} = 8.72E-05 d^{-1}

λ_{Th} = 3.7E-02 d^{-1} $BrR_{Ac,Th}$ = 0.9862

λ_{Fr} = 45.8 d^{-1} $BrR_{Ac,Fr}$ = 0.0138

λ_{Ra} = 6.06E-02 d^{-1} $BrR_{Th,Ra}$ = 1 $BrR_{Fr,Ra}$ = 1

Because this chain branches, it is necessary to calculate the amount of Ra-223 produced from each branch of the decay.

For the Th-227 branch, from equation 3 above:

$$A_{\text{Ra, 100 days, Th}} = 1\text{ Ci} * \left(3.7\text{E-02 d}^{-1} * 0.9862 * 6.06\text{E-02 d}^{-1} * 1\right) * \left[\begin{array}{l} \dfrac{e^{-8.72\text{E-05 d}^{-1} * 100\text{ d}}}{\left(3.7\text{E-02 d}^{-1} - 8.72\text{E-05 d}^{-1}\right)\left(6.06\text{E-02 d}^{-1} - 8.72\text{E-05 d}^{-1}\right)} \\ + \dfrac{e^{-3.7\text{E-02 d}^{-1} * 100\text{ d}}}{\left(8.72\text{E-05 d}^{-1} - 3.7\text{E-02 d}^{-1}\right)\left(6.06\text{E-02 d}^{-1} - 3.7\text{E-02 d}^{-1}\right)} \\ + \dfrac{e^{-6.06\text{E-02 d}^{-1} * 100\text{ d}}}{\left(8.72\text{E-05 d}^{-1} - 6.06\text{E-02 d}^{-1}\right)\left(3.7\text{E-02 d}^{-1} - 6.06\text{E-02 d}^{-1}\right)} \end{array} \right]$$

$$= 0.922\text{ Ci}$$

For the Fr-223 branch, from equation 4 above:

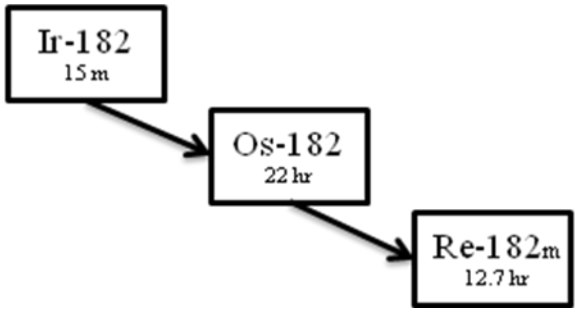
$$A_{\text{Ra, 100 days, Fr}} = 1\text{ Ci} * \left(45.8\text{ d}^{-1} * 0.0138 * 6.06\text{E-02 d}^{-1} * 1\right) * \left[\begin{array}{l} \dfrac{e^{-8.72\text{E-05 d}^{-1} * 100\text{ d}}}{\left(45.8\text{ d}^{-1} - 8.72\text{E-05 d}^{-1}\right)\left(6.06\text{E-02 d}^{-1} - 8.72\text{E-05 d}^{-1}\right)} \\ + \dfrac{e^{-3.7\text{E-02 d}^{-1} * 100\text{ d}}}{\left(8.72\text{E-05 d}^{-1} - 45.8\text{ d}^{-1}\right)\left(6.06\text{E-02 d}^{-1} - 45.8\text{ d}^{-1}\right)} \\ + \dfrac{e^{-6.06\text{E-02 d}^{-1} * 100\text{ d}}}{\left(8.72\text{E-05 d}^{-1} - 6.06\text{E-02 d}^{-1}\right)\left(45.8\text{ d}^{-1} - 6.06\text{E-02 d}^{-1}\right)} \end{array} \right]$$

$$= 0.0137\text{ Ci}$$

The total Ra-223 activity after 100 days is then the sum of these two quantities, 0.936 Ci.

EXAMPLE 2

Using this decay chain:



What is the Re-182m activity 6 hours after the following sample activity is measured?

Ir-182	6.25E-02 Ci	$\lambda_{Ir} = 2.77\ hr^{-1}$
Os-182	1.04E-02 Ci	$\lambda_{Os} = 3.15E\text{-}02\ hr^{-1}$
Re-182m	3.97E-04 Ci	$\lambda_{Re} = 5.46E\text{-}02\ hr^{-1}$

From equation 6 above:

$$A_{Re,\,6hr} = \left\{ 6.25E\text{-}02\ Ci * \left(3.15E\text{-}02\ hr^{-1} * 1 * 5.46E\text{-}02hr^{-1} * 1\right) * \left[\frac{e^{-2.77\ hr^{-1}*6\ hr}}{\left(3.15E\text{-}02\ hr^{-1} - 2.77\ hr^{-1}\right)\left(5.46E\text{-}02hr^{-1} - 2.77\ hr^{-1}\right)} + \frac{e^{-3.15E\text{-}02\ hr^{-1}*6\ hr}}{\left(2.77\ hr^{-1} - 3.15E\text{-}02\ hr^{-1}\right)\left(5.46E\text{-}02hr^{-1} - 3.15E\text{-}02\ hr^{-1}\right)} + \frac{e^{-5.46E\text{-}02hr^{-1}*6\ hr}}{\left(2.77\ hr^{-1} - 5.46E\text{-}02hr^{-1}\right)\left(3.15E\text{-}02\ hr^{-1} - 5.46E\text{-}02hr^{-1}\right)} \right] \right\}$$

$$+ \left[1.04E\text{-}02\ Ci * \left(5.46E\text{-}02hr^{-1} * 1\right) * \left(\frac{e^{-3.15E\text{-}02\ hr^{-1}*6\ hr} - e^{-5.46E\text{-}02hr^{-1}*6\ hr}}{5.46E\text{-}02hr^{-1} - 3.15E\text{-}02\ hr^{-1}} \right) \right]$$

$$+ 3.97E\text{-}04\ Ci * e^{-5.46E\text{-}02hr^{-1}*6\ hr}$$

$$= 3.10E\text{-}03\ Ci$$

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SUPPLEMENT 2 – CALCULATION OF RESUSPENSION AND 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.

F2.1 Resuspension Parameter

The Resuspension Parameter (KP) adjusts the inhalation dose for radioactive decay ($e^{-\lambda t}$) and the time-dependent Resuspension Factor (K) over the time phase under consideration.

NOTE: This KP model is the default approach, but may not be appropriate for the environmental conditions existing in the area under investigation. An alternate KP model may be substituted, with approval from local authorities, if it can be shown to more accurately predict the resuspension in the area under investigation.

$$KP_{i,TP} = \int_{t_1}^{t_2} \left(K_t * Dp_{i,t} \right) dt \qquad \text{(Eq. 1)}$$

$$\frac{\mu\text{Ci}\bullet\text{s}}{\text{m}^3} = \int_{\text{s}}^{\text{s}} \left(\frac{1}{\text{m}} * \frac{\mu\text{Ci}}{\text{m}^2} \right)$$

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.

F2.1.1 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:

$$K_t = \left(1.0\text{E-}05 * e^{-8.1\text{E-}07 * t} \right) + \left(7.0\text{E-}09 * e^{-2.31\text{E-}08 * t} \right) + 1.0\text{E-}09 \qquad \text{(Eq. 2)}$$

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.

F2.1.2 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:

$$KP_{i,TP} = Dp_{i,t_0} * \int_{t_1}^{t_2} \begin{bmatrix} 1.0\text{E-}05 * e^{\left(-t*\left(\lambda_i + 8.1\text{E-}07\right)\right)} \\ +7.0\text{E-}09 * e^{\left(-t*\left(\lambda_i + 2.31\text{E-}08\right)\right)} \\ +1.0\text{E-}09 * e^{\left(-t*\left(\lambda_i\right)\right)} \end{bmatrix} dt \qquad \text{(Eq. 3b)}$$

Integrating over the time phase under consideration yields the following:

$$KP_{i,TP} = Dp_{i,t_0} * \left[\begin{array}{l} \dfrac{1.0\text{E-}05 * \left(e^{\left(-t_2*\left(\lambda_i + 8.1\text{E-}07\right)\right)} - e^{\left(-t_1*\left(\lambda_i + 8.1\text{E-}07\right)\right)} \right)}{-\left(\lambda_i + 8.1\text{E-}07\right)} \\ + \dfrac{7.0\text{E-}09 * \left(e^{\left(-t_2*\left(\lambda_i + 2.31\text{E-}08\right)\right)} - e^{\left(-t_1*\left(\lambda_i + 2.31\text{E-}08\right)\right)} \right)}{-\left(\lambda_i + 2.31\text{E-}08\right)} \\ + \dfrac{1.0\text{E-}09 * \left(e^{\left(-t_2*\left(\lambda_i\right)\right)} - e^{\left(-t_1*\left(\lambda_i\right)\right)} \right)}{-\left(\lambda_i\right)} \end{array} \right] \qquad \text{(Eq. 3c)}$$

$$\frac{\mu\text{Ci}\bullet\text{s}}{\text{m}^3} = \frac{\mu\text{Ci}}{\text{m}^2} * \left[\frac{\text{m}^{-1} * \text{unitless}}{\text{s}^{-1}} + \frac{\text{m}^{-1} * \text{unitless}}{\text{s}^{-1}} + \frac{\text{m}^{-1} * \text{unitless}}{\text{s}^{-1}} \right]$$

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).

F2.2 Weathering Parameter

The Weathering Parameter (WP) adjusts for radioactive decay and in-growth and the time-dependent weathering factor (WF) over the time phase under consideration.

$$WP_{i,TP} = \int_{t_1}^{t_2} \left(WF_t * Dp_{i,t} \right) dt \qquad \text{(Eq. 4)}$$

$$\frac{\mu\text{Ci}\bullet\text{s}}{\text{m}^2} = \int_{s}^{s} \left(\text{unitless} * \frac{\mu\text{Ci}}{\text{m}^2} \right)$$

where:

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

F2.2.1 Weathering Factor

The Weathering Factor (WF) adjusts for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind). The FRMAC's default WF model was developed using data from the Nevada Test Site and the Chernobyl nuclear power plant accident (An02).

NOTE: This WF model is the default approach, but may not be appropriate for the environmental conditions existing in the area under investigation. An alternate WF model may be substituted, with approval from local authorities, if it can be shown to more accurately predict the weathering in the area under investigation.

$$WF_t = 0.4 * e^{-1.46\text{E-}08t} + 0.6 * e^{-4.44\text{E-}10t} \quad \text{(Eq. 5)}$$

$$\text{unitless} = \text{unitless} * \left(e^{-\left(s^{-1} * s\right)} \right) + \text{unitless} * \left(e^{-\left(s^{-1} * s\right)} \right)$$

where:

WF = Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind), unitless; and

t = Time, the time elapsed from initial deposition, s.

NOTE: Ignoring Weathering: If desired, the WF can be ignored when calculating the external dose from groundshine. To ignore weathering, set the WF value to 1 (constant over time). This will cause the WP to be simply a radioactive decay and in-growth adjustment for each radionuclide over the time phase under consideration.

F2.2.2 Combining the Weathering Factor and Radioactive Decay and In-growth to produce the Weathering Parameter

If weathering is addressed, the math in this part of the calculation is a little more complicated so the intermediate steps have been included.

For a **parent radionuclide**, multiplying the WF by the radioactive decay yields:

$$WP_{i,TP} = \int_{t_1}^{t_2} \left[\begin{pmatrix} 0.4 * e^{-1.46\text{E-}08t} \\ +0.6 * e^{-4.44\text{E-}10t} \end{pmatrix} * \left(Dp_{i,t_0} * e^{-\lambda_i t} \right) \right] dt \quad \text{(Eq. 6a)}$$

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:

$$WP_{i,TP} = Dp_{i,t_0} * \int_{t_1}^{t_2} \left[\begin{matrix} 0.4 * e^{\left(-t*\left(\lambda_i + 1.46\text{E-}08\right)\right)} \\ +0.6 * e^{\left(-t*\left(\lambda_i + 4.44\text{E-}10\right)\right)} \end{matrix} \right] dt \quad \text{(Eq. 6b)}$$

Integrating over the time phase under consideration yields the following:

$$WP_{i,TP} = Dp_{i,t_0} * \left[\frac{0.4*\left(e^{\left(-t_2*\left(\lambda_i+1.46\text{E-08}\right)\right)} - e^{\left(-t_1*\left(\lambda_i+1.46\text{E-08}\right)\right)}\right)}{-\left(\lambda_i+1.46\text{E-08}\right)} + \frac{0.6*\left(e^{\left(-t_2*\left(\lambda_i+4.44\text{E-10}\right)\right)} - e^{\left(-t_1*\left(\lambda_i+4.44\text{E-10}\right)\right)}\right)}{-\left(\lambda_i+4.44\text{E-10}\right)} \right] \quad \text{(Eq. 6c)}$$

$$\frac{\mu\text{Ci}\bullet\text{s}}{\text{m}^2} = \frac{\mu\text{Ci}}{\text{m}^2} * \left[\frac{\text{unitless} * \text{unitless}}{\text{s}^{-1}} + \frac{\text{unitless} * \text{unitless}}{\text{s}^{-1}} \right]$$

Calculations for daughters may be performed in the same manner by substituting the appropriate Bateman equation (Found in Appendix F – Supplement 1) for ($Dp_{i,t0}*e^{-\lambda t}$) in the equations above.

Reference	Title
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ANL01	Yu, C., et.al, *User's Manual for RESRAD*, ver. 6, Argonne National Laboratory, Argonne, IL, 2001.
Ba1910	H. Bateman, *"Solution of a System of Differential Equations Occurring in the Theory of Radioactive Transformations,"* Proc. Cambridge Phil. Soc. IS, 423 (1910)
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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.
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EPA11	*Exposure Factors Handbook*, EPA/600/R-090/052F, U.S. Environmental Protection Agency, Washington, DC, September 2011.
EPA13	*Protective Action Guides and Planning Guidance for Radiological Incidents*, Draft for Interim Use and public comment, U.S. Environmental Protection Agency, Washington, DC, March 2013.
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ICRP94 — *Human Respiratory Tract Model for Radiological Protection,* ICRP Publication 66, International Commission on Radiological Protection, Ottawa, Ontario, Canada, 1994.

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Me95 — Mettler, F. A. and Upton, A. C., *Medical Effects of Ionizing Radiation*, 2nd ed., W. B. Saunders & Co., Philadelphia, PA, 1995.

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