

**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**

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FRMAC Assessment Manual

Overview and Methods

Volume 1



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

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PREFACE

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

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

The primary purposes of this volume are:

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

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

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

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

Users are urged to update their manual as appropriate.

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

U.S. Department of Energy
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ACRONYMS AND ABBREVIATIONS

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

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

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Introduction

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

This manual:

- Is intended for use by trained FRMAC Assessment Scientists. It is basis for training FRMAC Assessment Scientists, and defines the technical methods used when responding to radiological incidents.
- Represents the technical consensus of multiple federal agencies with expertise in and authority over aspects of radiological emergency response.
- Is only intended to address the early and intermediate phases of a radiological incident. It does not address recovery phase issues such as remediation.
- Defaults to the International Commission on Radiological Protection (ICRP) 60+ dosimetry model based on agreement with the EPA. ICRP 60+ refers to ICRP 60 (ICRP90) and the collection of ICRP documents relating to the ICRP 60 dosimetry model published subsequently. ICRP 60+ terminology is used throughout the manual.
- Is not prescriptive. Situations may arise when the methods described in the Assessment Manual will not be sufficient, so the user may employ alternative methods or assumptions. Assessment Scientists must be sufficiently skilled in health physics to recognize when, which, and how alternative methods or assumptions may be employed. Possible alternatives may include dosimetry models, weathering factor, and resuspension factor.

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

- Section 1 – Plume Phase Evaluations (RESERVED);
- Section 2 – Population Protection;
- Section 3 – Emergency Worker Protection;
- Section 4 – Ingestion Pathway Analysis; and
- Section 5 – Sample Management.

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

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

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

- A nuclear power plant accident,

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

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

Overview of Assessment

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

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

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

Assessment Objectives

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

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

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

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

Manual Objectives

The objectives of the FRMAC Assessment Manual are:

- Provide technical basis for assessments

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

The Turbo FRMAC Software Package, which was developed under the NA-42 Technology Integration Program, automates the calculations in the assessment manual allowing for rapid computation of important dose assessment data. Turbo FRMAC allows the assessment scientist to vary inputs and change default values to accommodate incident-specific conditions.
- Document the assessment process

The manual defines the Assessment Division's operations and provides descriptions of organization, functions, and objectives.
- Orientation and Training guide for Assessment Division members

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

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

Utilization

Using this Manual

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

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

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

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

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

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

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

Using Data Products

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

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

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

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

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

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

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

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

Differences between FRMAC approach and other published guidance

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

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

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

SECTION 1. PLUME PHASE METHODS

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THIS SECTION IS RESERVED FOR FUTURE DEVELOPMENT.

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Introduction to Public Protection Methods

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

Methods in this section have been developed to address hazards from exposure to deposited radioactive material and from inhalation of radioactive material that has been resuspended in the air.

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 method include contributions from external exposure (groundshine) and the inhalation of resuspended material.
- 2) Inhalation of material from the passage of a plume of radioactive material is not considered in these calculations. The plume is considered to have already passed. Dose consequences from direct inhalation, submersion, and cloud shine are not included in the calculations. (See Section 1 of this Volume for Plume Phase calculations.)
- 3) The effects of radioactive decay, weathering and resuspension are included in the calculations.
- 4) Ingestion is not included in these methods. If ingestion is a significant dose pathway (i.e., >10% of the total dose), it should be addressed separately and included in protective action decisions. (See Ingestion Methods, Section 4.)
- 5) Default calculations assume:
 - a. the receptor is outside in the contaminated area continuously during the time phase under consideration without any protective measures (e.g., shielding, respiratory protection);
 - b. chronic exposure; calculations addressing acute exposures are planned for future methods.
 - c. use of ICRP 60+ dosimetry model;
 - d. adult receptor;
 - e. an Activity Averaged Breathing Rate of 0.92 m³/hr; and
 - f. inhalation of 1-micron Activity Median Aerodynamic Diameter (AMAD) particles in the Maximum lung clearance class.
- 6) Parent – Daughter inclusion rules:
 - Daughter radionuclides are included in calculations if:

- a. Daughter's half-life is less than the half-life of the ultimate parent (i.e., first parent in decay series), and
 - b. Daughter's half-life is less than 1.5 yr.
- Daughter radionuclides that meet these rules are considered to be in equilibrium (secular, or transient when branching ratio $\neq 1$) at deposition ($t = 0$, i.e., the daughter radionuclides are not grown in to equilibrium activities), and are assigned the parent's half life and decay constants for calculations.
 - Daughter radionuclides that do not meet these rules are excluded from the calculations (as are all subsequent daughter radionuclides, regardless of half life).
 - Optionally, an alternate calculation that models the decay and in-growth of the entire radionuclide decay chain may be used when the using the default Parent – Daughter inclusion rules stated above is not desired. See Appendix F, Supplement 1 for details on the calculation.
- 7) FRMAC's public protection methods generally assume that the organ of interest is the whole body. However, other organs may be evaluated against applicable Protective Action Guides (PAGs) by changing the Dose Coefficients and PAGs used. (See Method 2.1 Example 1, Section E1.6.)

Inputs

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

- Data – This information may come from predictive analysis (models) or field data (monitoring and/or samples):
 - Composition of the deposited radionuclide mixture (radionuclides and areal radioactivity, concentration, activity ratio or mass ratio) and/or external dose (or exposure) rates.
- Other Factors:
 - Ground roughness;
 - Weathering;
 - Resuspension; and
 - Decay of radionuclides during the time period under consideration.
- Constants:
 - Breathing rate;
 - Inhalation dose coefficient;
 - External dose coefficient;
 - Dose limits (e.g., PAGs); and
 - Exposure to Dose conversion factor (1.0 mrem/mR).
- Time Phase:
 - Evaluation Time (t_n) – The point in time, relative to the start of the event, for which the calculation is being performed; and
 - The start (t_1) and end (t_2) time of period under consideration. The EPA and DHS have established certain time phases (early, intermediate, etc.) with specified

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

The calculations presented in these methods are applicable to all EPA-defined as well as any user-defined time phases. To accommodate calculations for varying time phases, adjust the beginning (t_1) and ending (t_2) of the integration period to the desired values. For example, to calculate a value for the second year, set t_1 and t_2 to 366 and 730 days, respectively.

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

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METHOD 2.1 DEPOSITION DERIVED RESPONSE LEVEL

Application

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

The Dp_DRL:

- Represents the ground concentration, or areal activity ($\mu\text{Ci}/\text{m}^2$), at a given time (t_n) of a marker radionuclide in a mixture of radionuclides that will be expected to cause the entire mixture to produce a dose equal to the appropriate Protective Action Guide (PAG) over the time phase under consideration.
- Is derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA92) or the Department of Homeland Security (DHS) (DHS08). A projected or measured deposition value greater than the Dp_DRL indicates that the PAG has the potential to be exceeded.
- Is used to create data products and define contamination levels for a marker radionuclide to assist decision makers in determining where it may be advisable to implement protective actions (e.g., sheltering, evacuation, relocation).

Discussion

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

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

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

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

Assumptions

There are no additional assumptions beyond the default assumptions.

Inputs

There are no additional inputs beyond the default inputs.

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

Outputs

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

Final

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

Intermediate

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

MTDP_Dp = Mixture Total Dose Parameter for all radionuclides in the mixture of interest ($\text{mrem}\cdot\text{m}^2/\mu\text{Ci}$)

TDP_Dp = Total Dose Parameter for each radionuclide ($\text{mrem}\cdot\text{m}^2/\mu\text{Ci}$)

InhDP_Dp = Inhalation Dose Parameter ($\text{mrem}\cdot\text{m}^2/\mu\text{Ci}$)

ExDP_Dp = External Dose Parameter ($\text{mrem}\cdot\text{m}^2/\mu\text{Ci}$)

Calculation

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

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

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

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

where:

$Dp_DRL_{E,i(m),t_n}$ = Deposition Derived Response Level, the areal activity (radioactivity per unit area) at time t_n of a marker radionuclide $i(m)$ at which the dose to the whole body (E) from all radionuclides in mixture would result in a dose equal to the PAG for the time phase under consideration (t_1 to t_2), $\mu\text{Ci}/\text{m}^2$;

NOTE: The default value for t_n is the start of the time phase under consideration (t_1), but it may be set to any time (before, during, or after the time phase).

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

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

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

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

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

WF_{t_n} = Weathering adjustment from t_0 (deposition) to t_n (time of measurement, prediction, or evaluation), unitless; and

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

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

$$Dp_DRL = \frac{PAG * (Dp_{i(m)} * e^{-\lambda_{i(m)}t_n} * WF_{t_n})}{\sum_i \left\{ \left[[BR * InhDC] * \left[\int_{t_1}^{t_2} (K * e^{-\lambda t}) dt \right] + \left[\int_{t_1}^{t_2} (WF * e^{-\lambda t}) dt \right] * [ExDC * GRF] \right] * Dp_i \right\}} \quad (\text{Eq. 2.1-2})$$

Described in words, this equation would be:

The Deposition Derived Response Level equals:

The appropriate Protective Action Guide times the time-adjusted Deposition (areal activity) of the Marker Radionuclide ($D_{p_{i(m)}}$)

divided by the sum of the products of

The initial Deposition (areal activity) of each radionuclide in the mixture (D_{p_i}) and the following nuclide specific quantity:

Inhalation Dose ([Breathing Rate times Inhalation Dose Coefficient] times [Resuspension Factor times Decay])

plus

External Dose ([Weathering Factor times Decay] times [External Dose Coefficient times Ground Roughness Factor]).

NOTE: These terms are defined below as they are introduced into the calculation.

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

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

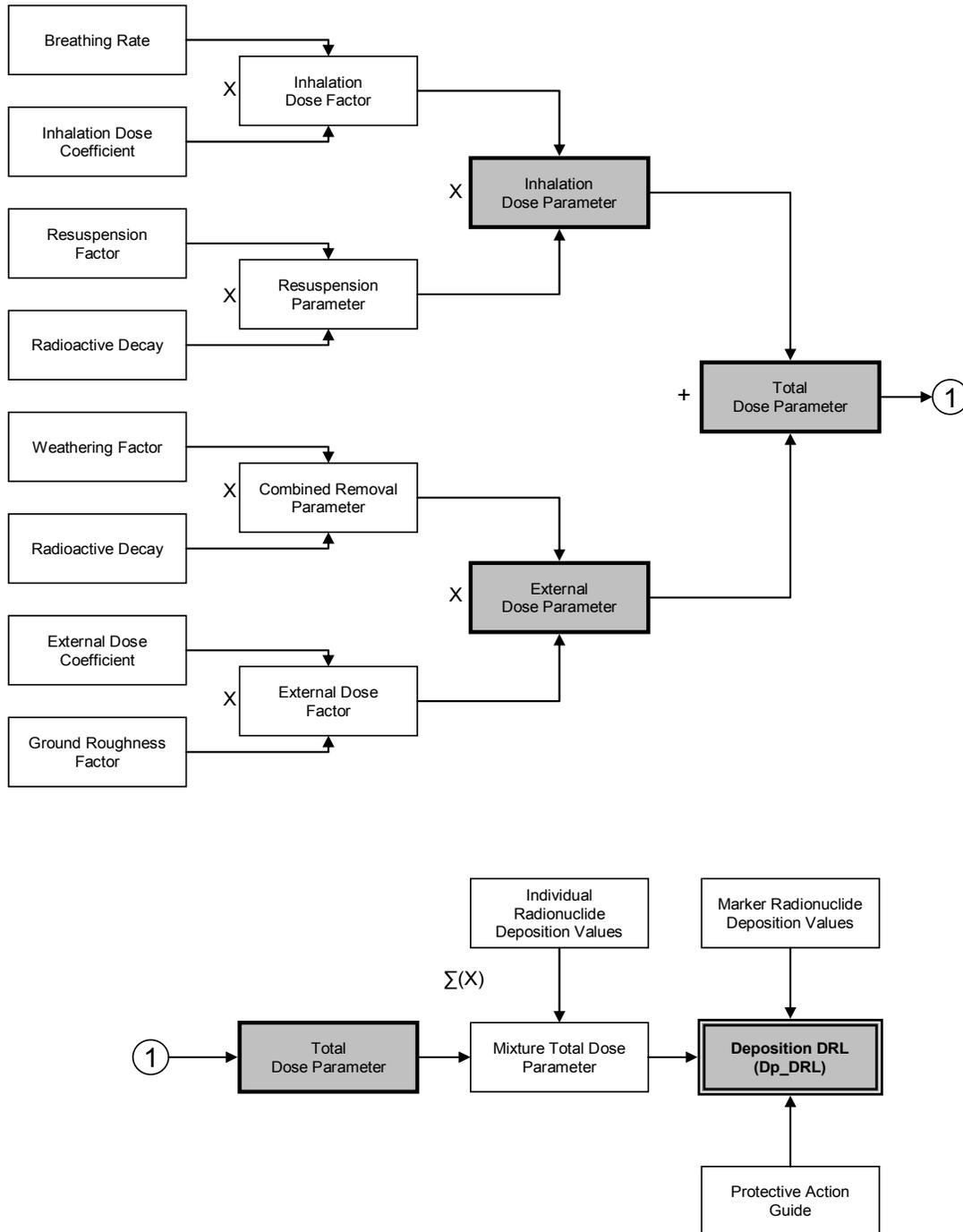


Figure 2.1-1 Deposition Derived Response Level Calculation Tree

1.0 CALCULATING THE DEPOSITION DERIVED RESPONSE LEVEL

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

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

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

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

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

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

Inhalation Dose Parameter

The Inhalation Dose Parameter ($InhDP_Dp$) calculation multiplies an Inhalation Dose Factor ($InhDF$) and a Resuspension Parameter (KP) to calculate the committed effective dose component from inhaling resuspended radioactivity over the time phase under consideration.

$$InhDP_Dp_{E,i,TP} = InhDF_{E,i} * KP_{i,TP} \quad (\text{Eq. 2.1-3})$$

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

where:

$InhDP_Dp_{E,i,TP}$ = Inhalation Dose Parameter for Deposition, the committed effective dose received by the whole body (E), over the time phase under consideration

- (*TP*), per unit activity of radionuclide *i* deposited on the ground from the inhalation of the resuspended radionuclide, $\text{mrem}\cdot\text{m}^2/\mu\text{Ci}$;
- $\text{InhDF}_{E,i}$ = Inhalation Dose Factor, the committed effective dose rate from breathing (at a specified rate) air contaminated with a unit activity of radionuclide *i*, to the whole body (*E*), $\text{mrem}\cdot\text{m}^3/\text{s}\cdot\mu\text{Ci}$; and
- $\text{KP}_{i,TP}$ = Resuspension Parameter, value that adjusts the airborne radioactivity level of radionuclide *i* over the time phase (*TP*) under consideration for radioactive decay and the time-dependent resuspension factor (*K*) (value obtained numerically from Turbo FRMAC), s/m.

1.1.1 Inhalation Dose Factor

The Inhalation Dose Factor combines the dose coefficient for individual radionuclides per volume of air breathed with a daily-average value for volume of air breathed. The activity-weighted average volume of air breathed is based on the ICRP lung model and considers the breathing rate during different activities (e.g., sleep, heavy activity) and the fraction of time spent each day performing those activities.

$$\text{InhDF}_{E,i} = \text{BR} * \text{InhDC}_{E,i} * \text{CF} \quad (\text{Eq. 2.1-4})$$

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

where:

- $\text{InhDF}_{E,i}$ = Inhalation Dose Factor, the committed effective dose rate from breathing (at a specified rate) air contaminated with a unit activity of radionuclide *i*, to the whole body (*E*), $\text{mrem}\cdot\text{m}^3/\text{s}\cdot\mu\text{Ci}$;
- BR = Breathing Rate, the activity-weighted average volume of air breathed per unit time by an adult male (ICRP, 1994, Table B.16B), $2.56\text{E-}04 \text{ m}^3/\text{s}$;
- $\text{InhDC}_{E,i}$ = Inhalation Dose Coefficient, the committed effective dose coefficient for the whole body (*E*), for radionuclide *i* (values from ICRP 60+ dosimetry models, DCFPAK), Sv/Bq ; and
- CF = Unit Conversion Factor, converts Sv/Bq to $\text{mrem}/\mu\text{Ci}$: $3.7\text{E}+09 \text{ mrem}/\mu\text{Ci}$ per Sv/Bq ,

$$\frac{\text{mrem}}{\mu\text{Ci}} = \frac{\text{Sv}}{\text{Bq}} * \frac{10^5 \text{ mrem}}{\text{Sv}} * \frac{3.7\text{E}+04 \text{ Bq}}{\mu\text{Ci}} \Rightarrow \frac{3.7\text{E}+09 \text{ mrem}}{\text{Sv}/\text{Bq}} \mu\text{Ci}$$

1.1.2 Resuspension Parameter

The Resuspension Parameter (*KP*) adjusts the inhalation dose for radioactive decay ($e^{-\lambda t}$) and the time-dependent Resuspension Factor (*K*) over the time phase under consideration.

NOTE: The KP integral below does not have an exact solution when K is in a time-dependent form (as in the standard approach used here). Therefore the integral cannot be solved analytically and must be solved using a software program that is capable of numerical integration.

$$KP_{i,TP} = \int_{t_1}^{t_2} K * e^{-\lambda_i t} dt \quad (\text{Eq. 2.1-5})$$

$$\frac{s}{m} = \int_s^s \frac{1}{m} * e^{-(s^{-1} * s)} dt$$

where:

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

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

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

K = Resuspension Factor, value based on the time-varying formula from NCRP Report No. 129, *Recommended Screening Limits for Contaminated Surface Soil and Review of Factors Relevant to Site-Specific Studies*, (NCRP99), m^{-1} :

- $K = 1E-06 m^{-1}$ for $t < 1$ day, or
- $K = 1E-06 m^{-1}/t$ for $t > 1$ and $\leq 1,000$ day, or
- $K = 1E-09 m^{-1}$ for $t > 1,000$ day.

The K model used here is the standard approach, but may not be appropriate for the environmental conditions existing in the area under investigation. An alternate K model may be substituted, with approval from local decision makers, if the alternate model can be shown to more accurately model the resuspension in the area under investigation; and

λ_i = Decay constant for radionuclide i , s^{-1} .

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

External Dose Parameter

The External Dose Parameter (ExDP_Dp) multiplies the Combined Removal Parameter (CRP) and the External Dose Factor (ExDF) to calculate the effective dose from groundshine per unit activity deposited on the ground over the time period under consideration.

$$ExDP_Dp_{E,i,TP} = CRP_{i,TP} * ExDF_{E,i} \quad (\text{Eq. 2.1-6})$$

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

where:

$ExDP_{Dp_{E,i,TP}}$ = External Dose Parameter for Deposition, the groundshine dose received by the whole body (E), over the time phase under consideration (TP), per unit of radioactivity of radionuclide i deposited on the ground and adjusted for the ground roughness factor, $\text{mrem}\cdot\text{m}^2/\mu\text{Ci}$;

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

$ExDF_{E,i}$ = External Dose Factor for Deposition, the effective dose rate to the whole body (E) from the external exposure to radionuclide i per unit activity deposited on the surface and adjusted for the ground roughness factor, $\text{mrem}\cdot\text{m}^2/\text{s}\cdot\mu\text{Ci}$.

1.2.1 Combined Removal Parameter

In this Method, the Combined Removal Parameter (CRP) adjusts the external (groundshine) dose for radioactive decay ($e^{-\lambda t}$) and the time-dependent weathering factor (WF) over the time phase under consideration.

$$CRP_{i,TP} = \int_{t_1}^{t_2} (WF_{i,TP} * e^{-\lambda_i t}) dt \quad (\text{Eq. 2.1-7})$$

$$s = \int_s^s (\text{unitless} * e^{-(s^{-1} * s)}) dt$$

where:

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

$WF_{i,TP}$ = Weathering Factor, value that adjusts the groundshine dose from radionuclide i for weathering forces that reduce the radionuclide activity near the surface over the time phase (TP) and thereby decreases the external dose rate, unitless (An02);

λ_i = Decay Constant for radionuclide i , s^{-1} ;

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

t_2 = the end of the time phase (integration period) under consideration, s .

1.2.1.1 Weathering Factor

The Weathering Factor (WF) adjusts the external exposure rate for the decrease that occurs over time as the deposited material migrates deeper into the soil column. The FRMAC's default WF model was developed using data from the Nevada Test Site and the Chernobyl nuclear power plant accident (An02).

NOTE: This WF model is the default approach, but may not be appropriate for the environmental conditions existing in the area under investigation. An alternate WF model may be substituted, with approval from local authorities, if the alternate model can be shown to more accurately model the weathering in the area under investigation.

$$WF = 0.4 * e^{(-1.46E-08 * t_n)} + 0.6 * e^{(-4.44E-10 * t_n)} \quad (\text{Eq. 2.1-8})$$

$$\text{unitless} = \text{unitless} * \left(e^{-(s^{-1} * s)} \right) + \text{unitless} * \left(e^{-(s^{-1} * s)} \right)$$

where:

- WF = Weathering Factor, value that adjusts the groundshine dose for weathering forces that reduce the radionuclide activity near the surface and thereby decrease the external dose rate, unitless;
- 0.4 = Fraction of material that undergoes rapid weathering, unitless;
- 0.6 = Fraction of material that undergoes slow weathering, unitless;
- 1.46E-08 = Rate constant representing the removal rate for the fraction of material that is rapidly ($t_{1/2} = 1.5$ y) weathered, s^{-1} ;
- 4.44E-10 = Rate constant representing the removal rate for the fraction of material that is slowly ($t_{1/2} = 50$ y) weathered, s^{-1} ; and
- t_n = Evaluation Time, the point in time, relative to the start of the event, at which the measurement, prediction or evaluation is performed, s.

NOTE: Ignoring Weathering: If desired, the WF can be ignored when calculating the external dose from groundshine. To ignore weathering, set the WF value to 1 (constant over time). This will cause the CRP to be simply a radioactive decay adjustment for each radionuclide over the time phase under consideration.

1.2.1.2 Combining the Weathering Factor and Radioactive Decay

If weathering is addressed, the math in this part of the calculation is a little more complicated so the intermediate steps have been included.

Multiplying the WF by the radioactive decay yields:

$$CRP_{i,IP} = \int_{t_1}^{t_2} \left[\left(0.4 * e^{(-1.46E-08 * t_n)} + 0.6 * e^{(-4.44E-10 * t_n)} \right) * e^{(-\lambda_i * t_n)} \right] dt \quad (\text{Eq. 2.1-9a})$$

This simplifies to:

$$CRP_{i,TP} = \int_{t_1}^{t_2} \left[0.4 * e^{(-t_n * (\lambda_i + 1.46E-08))} + 0.6 * e^{(-t_n * (\lambda_i + 4.44E-10))} \right] dt \quad (\text{Eq. 2.1-9b})$$

Integrating over the time phase under consideration yields the following:

$$CRP_{i,TP} = \frac{0.4 * \left(e^{(-t_2 * (\lambda_i + 1.46E-08))} - e^{(-t_1 * (\lambda_i + 1.46E-08))} \right)}{-(\lambda_i + 1.46E-08)} + \frac{0.6 * \left(e^{(-t_2 * (\lambda_i + 4.44E-10))} - e^{(-t_1 * (\lambda_i + 4.44E-10))} \right)}{-(\lambda_i + 4.44E-10)}$$

$$s = \frac{\text{unitless} * \left(e^{(s * (s^{-1} + s^{-1}))} - (s * (s^{-1} + s^{-1})) \right)}{-(s^{-1} + s^{-1})} + \frac{\text{unitless} * \left(e^{(s * (s^{-1} + s^{-1}))} - (s * (s^{-1} + s^{-1})) \right)}{-(s^{-1} + s^{-1})} \quad (\text{Eq. 2.1-9c})$$

1.2.2 External Dose Factor

The External Dose Factor (ExDF) gives the effective rate dose from groundshine per unit activity deposited on the ground by combining the External Dose Coefficient (ExDC) with a ground roughness factor (GRF).

$$ExDF_{E,i} = GRF * ExDC_{E,i} * CF$$

$$\frac{\text{mrem} \cdot \text{m}^2}{\text{s} \cdot \mu\text{Ci}} = \text{unitless} * \frac{\text{Sv} \cdot \text{m}^2}{\text{s} \cdot \text{Bq}} * \frac{\text{mrem} \cdot \text{Bq}}{\text{Sv} \cdot \mu\text{Ci}} \quad (\text{Eq. 2.1-10})$$

where:

$ExDF_{E,i}$ = External Dose Factor for Deposition, the effective dose rate to the whole body (E) from the external exposure to radionuclide i per unit activity deposited on the ground and adjusted for the ground roughness factor, $\text{mrem} \cdot \text{m}^2 / \text{s} \cdot \mu\text{Ci}$;

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;

$ExDC_{E,i}$ = External Dose Coefficient, the effective dose rate to the whole body (E) from the external exposure to radionuclide i per unit activity deposited on the ground (values from DCFPAK using ICRP 60+ dosimetry models), $\text{Sv} \cdot \text{m}^2 / \text{s} \cdot \text{Bq}$; and

CF = Unit Conversion Factor to convert Sv / Bq to $\text{mrem} / \mu\text{Ci}$, $3.7E+09 \text{ mrem} / \mu\text{Ci}$ per Sv / Bq .

$$\frac{\text{mrem}}{\mu\text{Ci}} = \frac{\text{Sv}}{\text{Bq}} * 1.0\text{E}+05 \frac{\text{mrem}}{\text{Sv}} * 3.7\text{E}+04 \frac{\text{Bq}}{\mu\text{Ci}} \Rightarrow 3.7\text{E}+09 \frac{\text{mrem}/\mu\text{Ci}}{\text{Sv}/\text{Bq}}$$

1.3 Combining Internal and External Components of the Total Dose Parameter

Total Dose Parameter

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

$$TDP_Dp_{E,i,TP} = InhDP_Dp_{E,TP,i} + ExDP_Dp_{E,i,TP} \quad (\text{Eq. 2.1-11})$$

where:

- $TDP_Dp_{E,i,TP}$ = Total Dose Parameter for Deposition, the sum of the external dose from groundshine and the internal (committed effective) dose from inhalation of resuspended material received, by the whole body (*E*), over the time phase under consideration (*TP*), per unit of areal activity of radionuclide *i* deposited on the ground, mrem•m²/μCi;
- $InhDP_Dp_{E,i,TP}$ = Inhalation Dose Parameter for Deposition, the committed effective dose received by the whole body (*E*), over the time phase under consideration (*TP*), per unit activity of radionuclide *i* deposited on the ground from the inhalation of the resuspended radionuclide, mrem•m²/μCi; and
- $ExDP_Dp_{E,i,TP}$ = External Dose Parameter for Deposition, the groundshine dose received by the whole body (*E*), over the time phase under consideration (*TP*), per unit of radioactivity of radionuclide *i* deposited on the ground and adjusted for the ground roughness factor, mrem•m²/μCi.

1.4 Calculating the Total Dose Parameter for the Mixture

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

Mixture Total Dose Parameter for Deposition (MTDP_Dp)

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

$$\begin{aligned}
 MTDP_Dp_{E,TP} &= \sum_i^{P+D} (Dp_i * TDP_Dp_{E,i,TP}) \\
 \text{mrem} &= \frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}} * \frac{\mu\text{Ci}}{\text{m}^2}
 \end{aligned}
 \tag{Eq. 2.1-12}$$

where:

- \sum_i^{P+D} = Represents the summation of values from all parent (P) and short-lived daughter (D) radionuclide(s);
- $MTDP_Dp_{E,TP}$ = Mixture Total Dose Parameter for Deposition, the sum of the external dose from groundshine and the internal dose from inhalation of resuspended material received by the whole body (E), over the time phase under consideration (TP), from the areal activity level of the mixture, mrem;
- Dp_i = Deposition, the areal activity of radionuclide i, $\mu\text{Ci}/\text{m}^2$; and
- $TDP_Dp_{E,i,TP}$ = Total Dose Parameter for Deposition, the sum of the external dose from groundshine and the internal (committed effective) dose from inhalation of resuspended material received, by the whole body (E), over the time phase under consideration (TP), per unit of areal activity of radionuclide i deposited on the ground, $\text{mrem}\cdot\text{m}^2/\mu\text{Ci}$.

1.5 Comparing the MTDP_Dp to the PAG

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

$$\begin{aligned}
 Dp_DRL_{E,i(m),t_n} &= \frac{PAG_{E,TP} * Dp_{i(m)} * e^{-\lambda_{i(m)}t_n} * WF_{t_n}}{MTDP_Dp_{E,TP}} \\
 \frac{\mu\text{Ci}}{\text{m}^2} &= \frac{\text{mrem} * \frac{\mu\text{Ci}}{\text{m}^2} * \text{unitless} * \text{unitless}}{\text{mrem}}
 \end{aligned}
 \tag{Eq. 2.1-13}$$

where:

- $Dp_DRL_{E, i(m), t_n}$ = Deposition Derived Response Level, the areal activity (radioactivity per unit area) at time t_n of a marker radionuclide $i(m)$, at which the dose to the whole body (E) from all radionuclides in mixture would result in a dose equal to the PAG for the time phase under consideration (t_1 to t_2), $\mu\text{Ci}/\text{m}^2$;
NOTE: The default value for t_n is the start of the time phase under consideration (t_1), but it may be set to any time (before, during, or after the time phase).
- $Dp_{i(m)}$ = Deposition, the areal activity of a marker radionuclide $i(m)$ per unit area of ground at t_0 (deposition), $\mu\text{Ci}/\text{m}^2$;
- $PAG_{E, TP}$ = Protective Action Guide, as specified by the EPA or local authorities, for the whole body (E), for the time phase (TP) under consideration, mrem;
- $\lambda_{i(m)}$ = Decay constant for the marker radionuclide, s^{-1} ;
- t_n = Evaluation Time, the point in time, relative to the start of the event, at which the measurement, prediction or evaluation is performed, s;
- $e^{-\lambda t_n}$ = Radioactive Decay adjustment for radionuclide i from t_0 (deposition) to t_n (time of measurement, prediction, or evaluation), unitless;
- WF_{t_n} = Weathering adjustment from t_0 (deposition) to t_n (time of measurement, prediction or evaluation), unitless; and
- $MTDP_Dp_{E, TP}$ = Mixture Total Dose Parameter for Deposition, the sum of the external dose from groundshine and the internal dose from inhalation of resuspended material received by the whole body (E), over the time phase under consideration (TP), from the areal activity level of the mixture, mrem.

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

EXAMPLE 1

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

Table 2.1-E1

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

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

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

Table 2.1-E2

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

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

E1.1 Calculating InhDP_Dp (Equation 2.1-3)

This calculation requires the Inhalation Dose Factor (InhDF) and Resuspension Parameter (KP).

E1.1.1 Calculating the Inhalation Dose Factor Portion of InhDP_Dp Using Equation 2.1-4

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

$$InhDF_{241Am} = 2.57E-04 \frac{m^3}{s} * 9.64E-05 \frac{Sv}{Bq} * 3.7E+09 \frac{mrem/\mu Ci}{Sv/Bq} = 91.6 \frac{mrem \cdot m^3}{s \cdot \mu Ci}$$

Table 2.1-E3

Radionuclide	Breathing Rate (m ³ /s)	Inhalation Dose Coefficient ^a (Sv/Bq)	Conversion Factor (mrem/μCi per Sv/Bq)	Inhalation Dose Factor (mrem • m ³ /μCi • s)
²⁴¹ Am	2.56E-04	9.64E-05	3.70E+09	91.6
⁶⁰ Co	2.56E-04	3.07E-08	3.70E+09	2.92E-02
⁹⁰ Sr	2.56E-04	1.57E-07	3.70E+09	1.49E-01
⁹⁰ Y	2.56E-04	1.50E-09	3.70E+09	1.43E-03

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

E1.1.2 Calculating the Resuspension Factor Portion of InhDP_Dp Using Equation 2.1-5

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

Table 2.1-E4

Radionuclide	λ _i (s ⁻¹)	t ₁ (s)	t ₂ (s)	KP _i – First Year ^a (s/m)
²⁴¹ Am	5.08E-11	0	3.16E+07	0.596
⁶⁰ Co	4.17E-09	0	3.16E+07	0.585
⁹⁰ Sr	7.54E-10	0	3.16E+07	0.594
⁹⁰ Y	7.54E-10 ^b	0	3.16E+07	0.594

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

E1.1.3 Combining Inhalation Dose Factor and Resuspension Factor to yield InhDP_Dp Using Equation 2.1-3

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

$$InhDP_Dp_{241Am} = 91.6 \frac{mrem \cdot m^3}{s \cdot \mu Ci} * 0.596 \frac{s}{m} = 54.6 \frac{mrem \cdot m^2}{\mu Ci}$$

Table 2.1.E5

Radionuclide	KP _i for First Year ^a (s/m)	Inhalation Dose Factor (mrem • m ³ /μCi • s)	InhDP_Dp – First Year (mrem • m ² /μCi)
²⁴¹ Am	0.596	91.6	54.6
⁶⁰ Co	0.585	2.92E-02	1.74E-02
⁹⁰ Sr	0.594	1.49E-01	8.88E-02
⁹⁰ Y	0.594	1.43E-03	8.52E-04

^a Value from Turbo FRMAC 2.1.

E1.2 Calculating ExDP_Dp (Equation 2.1-6)

This calculation requires the Combined Removal Parameter (CRP) and the External Dose Factor (ExDF).

E1.2.1 Calculating the Combined Removal Parameter Portion of ExDP_Dp Using Equations 2.1-(7-9)

Table 2.1-E6

Radionuclide	λ _i (s ⁻¹)	t ₁ (s)	t ₂ (s)	CRP – First Year (s)
²⁴¹ Am	5.08E-11	0	3.16E+07	2.89E+07
⁶⁰ Co	4.17E-09	0	3.16E+07	2.71E+07
⁹⁰ Sr	7.54E-10	0	3.16E+07	2.86E+07
⁹⁰ Y	7.54E-10 ^a	0	3.16E+07	2.86E+07

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

E1.2.2 Calculating the External Dose Factor Portion of the ExDP_Dp Using Equation 2.1-10

Example ExDF calculation for ²⁴¹Am and ExDF values for the radionuclide mixture for the first-year time phase.

$$ExDF_{241Am} = 0.82 * 2.33E-17 \frac{Sv \cdot m^2}{s \cdot Bq} * 3.7E+09 \frac{mrem}{\mu Ci} \frac{Sv}{Bq} = 7.07E-08 \frac{mrem \cdot m^2}{s \cdot \mu Ci}$$

Table 2.1-E7

Radionuclide	GRF (unitless)	ExDC ^a (Sv • m ² /s • Bq)	CF (mrem/μCi) per (Sv/Bq)	ExDF (mrem • m ² /μCi • s)
²⁴¹ Am	0.82	2.33E-17	3.70E+09	7.07E-08
⁶⁰ Co	0.82	2.30E-15	3.70E+09	6.98E-06
⁹⁰ Sr	0.82	1.64E-18	3.70E+09	4.97E-09
⁹⁰ Y	0.82	1.10E-16	3.70E+09	3.34E-07

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

E1.2.3 Combining Combined Removal Parameter and the External Dose Factor to Determine ExDP_Dp Using Equation 2.1-6

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

$$ExDP_Dp_{241Am} = 2.89E+07s * 7.07E-08 \frac{mrem \cdot m^2}{s \cdot \mu Ci} = 2.04 \frac{mrem \cdot m^2}{\mu Ci}$$

Table 2.1-E8

Radionuclide	CRP – 1 st Year (s)	ExDF (mrem • m ² /s • μCi)	ExDP_Dp – First Year (mrem • m ² /μCi)
²⁴¹ Am	2.89E+07	7.07E-08	2.04
⁶⁰ Co	2.71E+07	6.98E-06	1.89E+02
⁹⁰ Sr	2.86E+07	4.97E-09	1.42E-01
⁹⁰ Y	2.86E+07	3.34E-07	9.55

E1.3 Calculating TDP_Dp (Equation 2.1-11)

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

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

Table 2.1-E9

Radionuclide	InhDP_Dp First Year (mrem • m ² /μCi)	ExDP_Dp First Year (mrem • m ² /μCi)	TDP_Dp First Year (mrem • m ² /μCi)
²⁴¹ Am	54.6	2.04	56.64
⁶⁰ Co	1.74E-02	1.89E+02	1.89E+02
⁹⁰ Sr	8.88E-02	1.42E-01	2.31E-01
⁹⁰ Y	8.52E-04	9.55	9.55

E1.4 Calculating MTDP_Dp (Equation 2.1-12)

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

Table 2.1-E10

Radionuclide	Dp _i (μCi/m ²)	TDP_Dp – First Year (mrem • m ² /μCi)	Dp _i • TDP_Dp – First Year (mrem)
²⁴¹ Am	4.15E-02	56.64	2.35
⁶⁰ Co	2.74E+04	1.89E+02	5.18E+06
⁹⁰ Sr	9.25E+04	2.31E-01	2.14E+04
⁹⁰ Y	9.25E+04	9.55	8.83E+05
MTDP_Dp (Σ)			6.08E+06

E1.5 Calculating Dp_DRL (Equation 2.1-1 or 2.1-13)

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

PAG = 2000 mrem

MTDP_Dp = 6.08E+06 mrem

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

Table 2.1-E11

Radionuclide	Dp _i ($\mu\text{Ci}/\text{m}^2$)	e ^{-λt_n}	WF _{tn}	1 st Year Dp _i DRL ^a ($\mu\text{Ci}/\text{m}^2$)
²⁴¹ Am	4.15E-02	1	1	1.36E-05
⁶⁰ Co	2.74E+04	1	1	9.01
⁹⁰ Sr	9.25E+04	1	1	30.4
⁹⁰ Y	9.25E+04	1	1	30.4

^a Because the first year time phase starts at t₀ (deposition), there is no adjustment for radioactive decay or weathering.

E1.6 Calculating a Dp_i DRL for an Individual Organ

The preceding calculations assume that the organ of interest is the whole body. The generic approach can be modified to calculate a Derived Response Level for a specific organ (e.g., skin, thyroid, etc.).

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

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

Organ of Interest: Skin
PAG: 50 rem

Table 2.1-E3 would become **Table 2.1-E3a:**

Radionuclide	Breathing Rate (m^3/s)	Inhalation Dose Coefficient ^a (Sv/Bq)	Conversion Factor (mrem/ μCi per Sv/Bq)	Inhalation Dose Factor (mrem \cdot m^3 / $\mu\text{Ci} \cdot \text{s}$)
²⁴¹ Am	2.56E-04	7.41E-06	3.70E+09	7.05
⁶⁰ Co	2.56E-04	5.54E-09	3.70E+09	5.27E-03
⁹⁰ Sr	2.56E-04	5.95E-10	3.70E+09	5.66E-04
⁹⁰ Y	2.56E-04	3.28E-11	3.70E+09	3.12E-05

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

Because the Resuspension Parameter (KP) and Combined Removal Parameter (CRP) are not affected by the organ of interest,

Table 2.1-E5 would become **Table 2.1-E5a**:

Radionuclide	KP _i for First Year ^a (s/m)	Inhalation Dose Factor (mrem • m ³ /μCi • s)	InhDP_Dp – First Year (mrem • m ² /μCi)
²⁴¹ Am	0.596	7.05	4.20
⁶⁰ Co	0.585	5.27E-03	3.08E-03
⁹⁰ Sr	0.594	5.66E-04	3.36E-04
⁹⁰ Y	0.594	3.12E-05	1.85E-05

^a Value from Turbo FRMAC 2.1.

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

Radionuclide	GRF (unitless)	ExDC ^a (Sv • m ² /s • Bq)	CF (mrem/μCi) per (Sv/Bq)	ExDF (mrem • m ² /μCi • s)
²⁴¹ Am	0.82	8.32E-17	3.70E+09	2.52E-07
⁶⁰ Co	0.82	2.76E-15	3.70E+09	8.37E-06
⁹⁰ Sr	0.82	1.40E-16	3.70E+09	4.25E-07
⁹⁰ Y	0.82	1.05E-14	3.70E+09	3.19E-05

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

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

Radionuclide	CRP – First Year (s)	ExDF (mrem • m ² /s • μCi)	ExDP_Dp – First Year (mrem • m ² /μCi)
²⁴¹ Am	2.89E+07	2.52E-07	7.30
⁶⁰ Co	2.71E+07	8.37E-06	2.27E+02
⁹⁰ Sr	2.86E+07	4.25E-07	12.1
⁹⁰ Y	2.86E+07	3.19E-05	9.11E+02

Adding the InhDP_Dp and ExDP_Dp yields the TDP_DP, thus

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

Radionuclide	InhDP_Dp – First Year (mrem • m ² /μCi)	ExDP_Dp – First Year (mrem • m ² /μCi)	TDP_DP – First Year (mrem • m ² /μCi)
²⁴¹ Am	4.20	7.30	11.5
⁶⁰ Co	3.08E-03	2.27E+02	2.27E+02
⁹⁰ Sr	3.36E-04	12.1	12.1
⁹⁰ Y	1.85E-05	9.11E+02	9.11E+02

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

Table 2.1-E10 would become Table 2.1-E10a:

Radionuclide	Dp _i (μCi/m ²)	TDP_Dp – First Year (mrem • m ² /μCi)	Dp _i • TDP_Dp – First Year (mrem)
²⁴¹ Am	4.15E-02	11.5	4.77E-01
⁶⁰ Co	2.74E+04	2.27E+02	6.22E+06
⁹⁰ Sr	9.25E+04	12.1	1.12E+06
⁹⁰ Y	9.25E+04	9.11E+02	8.43E+07
MTDP_Dp (Σ)			9.16E+07

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

$$PAG_{(skin)} = 50,000 \text{ mrem}$$

$$MTDP_Dp_{(skin)} = 9.16E+07 \text{ mrem}$$

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

Table 2.1-E11 would become Table 2.1-E11a:

Radionuclide	Dp _i (μCi/m ²)	e ^{-λtn}	WF _{tn}	Dp_DRL – First Year ^a (μCi/m ²)
²⁴¹ Am	4.15E-02	1	1	2.27E-05
⁶⁰ Co	2.74E+04	1	1	15.0
⁹⁰ Sr	9.25E+04	1	1	50.5
⁹⁰ Y	9.25E+04	1	1	50.5

^a Because the first year time phase starts at t₀ (deposition) there is no adjustment for radioactive decay or weathering.

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

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

Table 2.1-E12

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

EXAMPLE 2

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

Table 2.1-E1 (repeated)

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

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

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

Table 2.1-E2 (repeated)

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

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

E2.1 Calculating InhDP_Dp (Equation 2.1-3)

This calculation requires the Inhalation Dose Factor (InhDF) and Resuspension Parameter (KP).

E2.1.1 Calculating the Inhalation Dose Factor Portion of InhDP_Dp Using Equation 2.1-4

Example InhDF calculation for ^{241}Am and InhDF values for the radionuclide mixture for the second-year time phase.

$$InhDF_{241Am} = 2.57E-04 \frac{m^3}{s} * 9.64E-05 \frac{Sv}{Bq} * 3.7E+09 \frac{mrem/\mu Ci}{Sv/Bq} = 91.6 \frac{mrem \cdot m^3}{s \cdot \mu Ci}$$

Table 2.1-E13

Radionuclide	Breathing Rate (m ³ /s)	Inhalation Dose Coefficient ^a (Sv/Bq)	Conversion Factor (mrem/μCi) per (Sv/Bq)	Inhalation Dose Factor (mrem • m ³ /μCi • s)
²⁴¹ Am	2.56E-04	9.64E-05	3.70E+09	91.6
⁶⁰ Co	2.56E-04	3.07E-08	3.70E+09	2.92E-02
⁹⁰ Sr	2.56E-04	1.57E-07	3.70E+09	1.49E-01
⁹⁰ Y	2.56E-04	1.50E-09	3.70E+09	1.43E-03

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

E2.1.2 Calculating the Resuspension Factor Portion of InhDP_Dp Using Equation 2.1-5

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

Table 2.1-E14

Radionuclide	λ _i (s ⁻¹)	t ₁ (s)	t ₂ (s)	KP _i – 2 nd Year ^a (s/m)
²⁴¹ Am	5.08E-11	3.16E+07	6.32E+07	5.97E-02
⁶⁰ Co	4.17E-09	3.16E+07	6.32E+07	4.96E-02
⁹⁰ Sr	7.54E-10	3.16E+07	6.32E+07	5.79E-02
⁹⁰ Y	7.54E-10 ^b	3.16E+07	6.32E+07	5.79E-02

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

E2.1.3 Combining Inhalation Dose Factor and Resuspension Factor to Give InhDP_Dp Using Equation 2.1-3

Example InhDP_Dp calculation for ²⁴¹Am and InhDP_Dp values for the radionuclide mixture for the second-year time phase.

$$InhDP_Dp_{241Am} = 91.6 \frac{mrem \cdot m^3}{s \cdot \mu Ci} * 5.97E-02 \frac{s}{m} = 5.47 \frac{mrem \cdot m^2}{\mu Ci}$$

Table 2.1.E15

Radionuclide	KP _i for 2 nd Year ^a (s/m)	Inhalation Dose Factor (mrem • m ³ /μCi • s)	InhDP_Dp – 2 nd Year (mrem • m ² /μCi)
²⁴¹ Am	5.97E-02	91.6	5.47
⁶⁰ Co	4.96E-02	2.92E-02	1.45E-03
⁹⁰ Sr	5.79E-02	1.49E-01	8.63E-03
⁹⁰ Y	5.79E-02	1.43E-03	8.25E-5

^a Value from Turbo FRMAC 2.1.

E2.2 Calculating ExDP_Dp (Equation 2.1-6)

This calculation requires the Combined Removal Parameter (CRP) and the External Dose Factor (ExDF).

E2.2.1 Calculating the Combined Removal Parameter Portion of ExDP_Dp Using Equations 2.1-(7-9)

Table 2.1-E16

Radionuclide	λ _i (s ⁻¹)	t ₁ (s)	t ₂ (s)	CRP – 2 nd Year (s)
²⁴¹ Am	5.08E-11	3.16E+07	6.32E+07	2.49E+07
⁶⁰ Co	4.17E-09	3.16E+07	6.32E+07	2.05E+07
⁹⁰ Sr	7.54E-10	3.16E+07	6.32E+07	2.40E+07
⁹⁰ Y	7.54E-10 ^a	3.16E+07	6.32E+07	2.40E+07

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

E2.2.2 Calculating the External Dose Factor Portion of the ExDP_Dp Using Equation 2.1-10

Example ExDF calculation for ²⁴¹Am and ExDF values for the radionuclide mixture for the first-year time phase.

$$ExDF_{241Am} = 0.82 * 2.33E-17 \frac{Sv \cdot m^2}{s \cdot Bq} * 3.7E+09 \frac{mrem}{\mu Ci} \frac{Sv}{Bq} = 7.07E-08 \frac{mrem \cdot m^2}{s \cdot \mu Ci}$$

Table 2.1-E17

Radionuclide	GRF (unitless)	ExDC ^a (Sv • m ² /s • Bq)	CF (mrem/μCi) per (Sv/Bq)	ExDF (mrem • m ² /μCi • s)
²⁴¹ Am	0.82	2.33E-17	3.70E+09	7.07E-08
⁶⁰ Co	0.82	2.30E-15	3.70E+09	6.98E-06
⁹⁰ Sr	0.82	1.64E-18	3.70E+09	4.97E-09
⁹⁰ Y	0.82	1.10E-16	3.70E+09	3.34E-07

^a Values from DCFFPAK 1.6 Update 1 (ICRP 60+).

E2.2.3 Combining Combined Removal Parameter and the External Dose Factor to Determine ExDP_Dp Using Equation 2.1-6

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

$$ExDP_Dp_{241Am} = 2.49E+07\text{ s} * 7.07E-08 \frac{\text{mrem}\cdot\text{m}^2}{\text{s}\cdot\mu\text{Ci}} = 1.76 \frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}}$$

Table 2.1-E18

Radionuclide	CRP – 2 nd Year (s)	ExDF (mrem • m ² /s • μCi)	ExDP_Dp – 2 nd Year (mrem • m ² /μCi)
²⁴¹ Am	2.49E+07	7.07E-08	1.76
⁶⁰ Co	2.05E+07	6.98E-06	1.43E+02
⁹⁰ Sr	2.40E+07	4.97E-09	1.20E-01
⁹⁰ Y	2.40E+07	3.34E-07	8.03

E2.3 Calculating TDP_Dp (Equation 2.1-11)

Example TDP_DP calculation for ²⁴¹Am and TDP_Dp values for the radionuclide mixture for the first-year time phase.

$$TDP_Dp_{241Am} = 5.47 \frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}} + 1.76 \frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}} = 7.23 \frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}}$$

Table 2.1-E19

Radionuclide	InhDP_Dp 2 nd Year (mrem • m ² /μCi)	ExDP_Dp 2 nd Year (mrem • m ² /μCi)	TDP_Dp 2 nd Year (mrem • m ² /μCi)
²⁴¹ Am	5.47	1.76	7.23
⁶⁰ Co	1.45E-03	1.43E+02	1.43E+02
⁹⁰ Sr	8.63E-03	1.20E-01	1.28E-01
⁹⁰ Y	8.25E-5	8.03	8.03

E2.4 Calculating MTDP_Dp (Equation 2.1-12)

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

Table 2.1-E20

Radionuclide	Dp _i (μCi/m ²)	TDP_Dp – 2 nd Year (mrem • m ² /μCi)	Dp _i • TDP_Dp – 2 nd Year (mrem)
²⁴¹ Am	4.15E-02	7.23	3.00E-01
⁶⁰ Co	2.74E+04	1.43E+02	3.92E+06
⁹⁰ Sr	9.25E+04	1.28E-01	1.18E+04
⁹⁰ Y	9.25E+04	8.03	7.43E+05
MTDP_Dp (Σ)			4.67E+06

E2.5 Calculating Dp_DRL (Equation 2.1-1 or 2.1-13)

Example Dp_DRL calculation for ⁶⁰Co (marker) and Dp_DRL values for the radionuclide mixture for the start of the second-year time phase.

$$\begin{aligned} \text{PAG} &= 500 \text{ mrem} \\ \text{MTDP_Dp} &= 4.67\text{E}+06 \text{ mrem} \end{aligned}$$

$$Dp_DRL_{60\text{Co}} = \frac{500 \text{ mrem} * 2.74\text{E}+04 \frac{\mu\text{Ci}}{\text{m}^2} * 0.877 * 0.844}{4.67\text{E}+06 \text{ mrem}} = 2.17 \frac{\mu\text{Ci}}{\text{m}^2}$$

Table 2.1-E21

Radionuclide	Dp _i (μCi/m ²)	e ^{-λt_n}	WF _{t_n}	2 nd Year Dp_DRL (t ₁ = 366 days) ^a (μCi/m ²)
²⁴¹ Am	4.15E-02	0.998	0.844	3.74E-06
⁶⁰ Co	2.74E+04	0.877	0.844	2.17
⁹⁰ Sr	9.25E+04	0.976	0.844	8.15
⁹⁰ Y	9.25E+04	0.976	0.844	8.15

^a Because the second year time phase starts at t₁ = 366 days there is a need to adjust for radioactive decay and weathering to determine the Dp_DRL at the start of the time phase.

NOTE: These values are correct for day 366. To calculate a value that can be compared to values for other time phases and plotted on the same data products, see section E2.6 below.

E2.6 Adjusting the Dp_DRL to Correspond to the Start of the Other Standard Time Phases (t₁ = 0) (Equation 2.1-15)

Example Dp_DRL calculation for ⁶⁰Co (marker) and Dp_DRL values for the radionuclide mixture for the second-year time phase, calculated for the time of deposition.

PAG = 500 mrem
 MTDP_Dp = 4.67E+06 mrem

$$Dp_DRL_{60Co} = \frac{500 \text{ mrem} * 2.74E+04 \frac{\mu\text{Ci}}{\text{m}^2} * 1 * 1}{4.67E+06 \text{ mrem}} = 2.93 \frac{\mu\text{Ci}}{\text{m}^2}$$

Table 2.1-E22

Radionuclide	Dp _i (μCi/m ²)	e ^{-λt_n}	WF _{t_n}	2 nd Year Dp_DRL (t ₁ = 366 days) Corrected to t ₁ =0 ^a (μCi/m ²)
²⁴¹ Am	4.15E-02	1	1	4.44E-06
⁶⁰ Co	2.74E+04	1	1	2.93
⁹⁰ Sr	9.25E+04	1	1	9.90
⁹⁰ Y	9.25E+04	1	1	9.90

^a Because the other time phases start at t₁ = t₀ (deposition) there is no adjustment for radioactive decay or weathering to determine the Dp_DRL at that time.

NOTE: These values are correct for day 0. These values represent the concentration present at t₀ (deposition) that would cause the mixture to produce a dose of 500 mrem (the 2nd year PAG) over the 2nd year (day 366-730). These values are appropriate for plotting on the same data products with DRLs for other time phases with start times of t₀.

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METHOD 2.2 EXPOSURE RATE DERIVED RESPONSE LEVEL

Application

This method has been developed to calculate an Exposure Rate Derived Response Level (XR_DRL) for a deposition of radioactive material.

The XR_DRL:

- Represents the exposure rate (mR/hr, measured at 1 m above the ground) at a given time (t_n), from all radionuclides in the mixture that will be expected to produce a dose equal to the appropriate Protective Action Guide (PAG) over the time phase under consideration.
- Is derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA92) or the Department of Homeland Security (DHS) (DHS08). A projected or measured exposure rate value greater than the XR_DRL indicates that the PAG has the potential to be exceeded.
- Is used to create data products and define exposure rates to assist decision makers in determining where implementing protective actions (e.g., sheltering, evacuation, relocation) may be advisable.
- Is calculated from the Mixture Total Dose Parameter for Deposition (MTDP_Dp) value calculated in Method 2.1.

Discussion

The XR_DRL relates a measured exposure rate to the external dose from material deposited on the ground (i.e., groundshine) and the dose from the inhalation of resuspended material.

The XR_DRL combines an External Exposure Factor (ExXF), with the deposition (areal activity) values for each radionuclide present in a mixture and relates that product (MExXF_Dp) to the PAG for the time phase under consideration and the Mixture Total Dose Parameter (MTDP_Dp – calculated in Method 2.1).

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

Assumptions

There are no additional assumptions beyond the default assumptions.

Inputs

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

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

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

Outputs

The final output of this method is the XR_DRL for a deposition of radioactive material.

Final

XR_DRL = Exposure Rate Derived Response Level, the external exposure rate, at time t_n , at which the dose from all radionuclides in a deposition mixture would result in a dose equal to the PAG for the time phase under consideration, mR/hr

Intermediate

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

ExXF = External Exposure Factor for each radionuclide in the mixture of interest (mR/hr per $\mu\text{Ci}/\text{m}^2$)

MExXF_Dp = Mixture External Exposure Factor for all radionuclides in the mixture of interest (mR/hr)

Calculation

Calculating the XR_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 TurboFRMAC (SNL 2008), to complete these calculations.

Equation 2.2-1 represents the final form of the XR_DRL calculation.

$$XR_DRL_{E,t_n} = PAG_{E,TP} * \frac{MExXF_Dp_{E,t_n}}{MTDP_Dp_{E,TP}} \quad (\text{Eq. 2.2-1})$$

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

where:

XR_DRL_{E,t_n} = Exposure Rate Derived Response Level, the external exposure rate at time t_n at which the dose from all radionuclides in a deposition mixture would result in a dose to the whole body (E) equal to the PAG for the time phase under consideration, mR/hr;

NOTE: The default value for t_n is the start of the time phase under consideration (t_l), but it may be set to any time (before, during, or after the time phase).

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

$MExXF_Dp_{E,t_n}$ = Mixture External Exposure Factor for Deposition, the external exposure rate received by the whole body (E) at time t_n , from a radionuclide mixture deposited on the ground, mR/hr; and

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

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

$$XR_DRL_{t_n} = PAG * \frac{\sum_i \left\{ \left(Dp_i * e^{-\lambda_i t_n} * WF_{t_n} \right) * \left[\frac{ExDC * GRF}{XDCCF} \right] \right\}}{MTDP_Dp} \quad (\text{Eq. 2.2-2})$$

Described in words, this equation would be:

The Exposure Rate Derived Response Level at time t_n equals:

The appropriate Protective Action Guide multiplied by the sum of:

The products of the time-adjusted Deposition (areal radioactivity) of each radionuclide in the mixture (Dp_i) and the following quantity:

External Dose Coefficient (nuclide-specific) times Ground Roughness Factor divided by Exposure to Dose Conversion Factor

Divided by

The Mixture Total Dose Parameter (From Method 2.1).

Figure 2.2-1 shows the full calculation tree used to develop the XR_DRL and the intermediate outputs of External Exposure Factor ($ExXF$) for individual radionuclides and Mixture External Exposure Factor ($MExXF_Dp$) for the mixture.

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

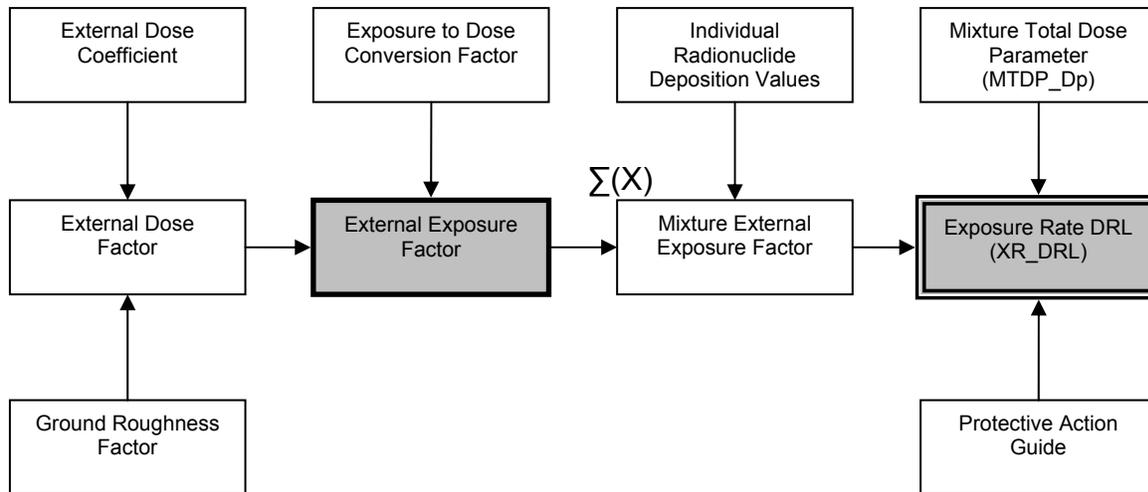


Figure 2.2-1 XR_DRL Calculation Tree

1.0 CALCULATING THE EXPOSURE RATE DERIVED RESPONSE LEVEL

The XR_DRL is a value that is used to relate an exposure rate measurement from a survey instrument to the hazard posed by the deposition of a mixture of radioactive materials over the time phase under consideration relative to the regulatory PAG.

A prime factor in determining the XR_DRL is the External Exposure Factor (ExXF) for each radionuclide present in the mixture. The ExXF is obtained by multiplying a radionuclide-specific External Dose Coefficient (ExDC) by a Ground Roughness Factor (GRF) and then converting the units from dose to exposure.

The ExXF for each radionuclide is then multiplied by the areal activity of that radionuclide present in the mixture (Dp_i) and those products are then summed over all the radionuclides in the mixture. The resulting value, called the Mixture External Exposure Factor (MExXF_Dp), can then be related to the PAG and the Mixture Total Dose Parameter (MTDP_Dp), as shown in Equation 2.2-1, to determine the XR_DRL.

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

The following sections provide step-by-step instructions for the manual calculation of an XR_DRL, beginning with determining the ExXF for each radionuclide, then finding a MExXF_Dp for the mixture, and finally calculating the XR_DRL for the mixture.

1.1 Calculation of the External Exposure Factor

The External Exposure Factor (ExXF) calculation multiplies a radionuclide-specific External Dose Coefficient (ExDC) by a Ground Roughness Factor (*GRF*) and then converts from dose to exposure using an Exposure to Dose Conversion Factor (chronic) (*XDCF_C*) to calculate the effective exposure from groundshine per unit of activity of that radionuclide deposited on the ground.

$$ExXF_{E,i} = \frac{ExDC_{E,i} * GRF * CF}{XDCF_C} \quad (\text{Eq. 2.2-3})$$

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

where:

$ExXF_{E,i}$ = External Exposure Factor for deposition, the external exposure rate to the whole body (*E*) per unit activity deposited on the ground from radionuclide *i* and adjusted for the ground roughness factor, $\text{mR} \cdot \text{m}^2 / \text{hr} \cdot \mu\text{Ci}$;

$ExDC_{E,i}$ = External Dose Coefficient, the effective dose rate to the whole body (*E*) from the external exposure to radionuclide *i* per unit activity deposited on the ground (values from DCFPAK using ICRP 60+ dosimetry models), $\text{Sv} \cdot \text{m}^2 / \text{s} \cdot \text{Bq}$;

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

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; and

CF = Unit Conversion Factor from Sv/(Bq•s) to mrem/(μCi•hr).

$$\frac{\text{mrem}}{\mu\text{Ci} \cdot \text{hr}} = \frac{\text{Sv}}{\text{Bq} \cdot \text{s}} * \frac{10^5 \text{ mrem}}{\text{Sv}} * \frac{3.7\text{E}+04 \text{ Bq}}{\mu\text{Ci}} * \frac{3600\text{s}}{\text{hr}} \Rightarrow 1.33\text{E}+13 \frac{\text{mrem} \cdot \text{Bq} \cdot \text{s}}{\text{Sv} \cdot \mu\text{Ci} \cdot \text{hr}}$$

1.2 Calculating the Mixture External Exposure Factor

The Mixture External Exposure Factor (MExXF_{Dp}) for a given time (*t_n*) based on all the radionuclides in the mixture, is obtained by multiplying the time-adjusted areal activity for each radionuclide by the associated External Exposure Factor (ExXF) and then summing those products for the entire mixture.

$$MExXF_{Dp_{E,t_n}} = WF_{t_n} * \sum_i^{P+D} (Dp_i * e^{-\lambda_i t_n} * ExXF_{E,i}) \quad (\text{Eq. 2.2-4})$$

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

where:

$MExXF_Dp_{E,t_n}$ = Mixture External Exposure Factor for Deposition, the external exposure rate received by the whole body (E) at time t_n , from a radionuclide mixture deposited on the ground, mR/hr;

NOTE: The default value for t_n is the start of the time phase under consideration (t_I), but it may be set to any time (before, during, or after the time phase).

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

λ_i = Decay constant for radionuclide i , s^{-1} ;

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

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

WF_{t_n} = Weathering adjustment from t_0 (deposition) to t_n (time of measurement, prediction, or evaluation), unitless; and

$ExXF_{E,i}$ = External Exposure Factor for deposition, the external exposure rate to the whole body (E) per unit activity deposited on the ground from radionuclide i and adjusted for the ground roughness factor, $\text{mR}\cdot\text{m}^2/\text{hr}\cdot\mu\text{Ci}$.

1.3 Comparing the MExXF_Dp to the PAG

Once the MExXF_Dp for the mixture has been calculated for a specific time, it can be used to determine the XR_DRL by comparing it to the PAG and the Mixture Total Dose Parameter (MTDP_Dp from Method 2.1) value using the following equation.

$$XR_DRL_{E,t_n} = PAG_{E,TP} * \frac{MExXF_Dp_{E,t_n}}{MTDP_Dp_{E,TP}} \quad (\text{Eq. 2.2-5})$$

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

where:

XR_DRL_{E,t_n} = Exposure Rate Derived Response Level, the external exposure rate, at time t_n , at which the dose from all radionuclides in a deposition mixture would result in a dose to the whole body (E) equal to the PAG for the time phase under consideration, mR/hr;

NOTE: The default value for t_n is the start of the time phase under consideration (t_I), but it may be set to any time (before, during, or after the time phase).

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

$MExXF_{Dp_{E,t_n}}$ = Mixture External Exposure Factor for Deposition, the external exposure rate received by the whole body (E) at time t_n from a radionuclide mixture deposited on the ground, mR/hr; and

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

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

EXAMPLE 1

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

Table 2.2-E1

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

To determine the XR_DRL, the intermediate term for the External Exposure Factor (ExXF) must first be calculated for each radionuclide and then combined with the areal activity (Deposition or Dp_i for each radionuclide) and Mixture External Exposure Factor (MExXF_Dp).

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

Table 2.2-E2

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

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

E1.1 Calculating ExXF (Equation 2.2-3)

This calculation requires the External Dose Factor (ExDF) and the Exposure to Dose Conversion Factor (chronic) (XDCF_C).

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

$$ExXF_{241,Am} = \frac{2.33E-17 \frac{\text{Sv}\cdot\text{m}^2}{\text{s}\cdot\text{Bq}} * 0.82 * 1.33E+13 \frac{\text{mrem}\cdot\text{Bq}\cdot\text{s}}{\text{Sv}\cdot\mu\text{Ci}\cdot\text{hr}}}{1.0 \frac{\text{mrem}}{\text{mR}}} = 2.54E-04 \frac{\text{mR}\cdot\text{m}^2}{\mu\text{Ci}\cdot\text{hr}}$$

Table 2.2-E3

Radionuclide	ExDC ^a (Sv•m ²) per (s•Bq)	GRF (unitless)	CF (mrem•Bq•s) per (Sv•μCi•hr)	XDCF _c (mrem/mR)	ExXF (mR•m ²) per (μCi•hr)
²⁴¹ Am	2.33E-17	0.82	1.33E+13	1.0	2.54E-04
⁶⁰ Co	2.30E-15	0.82	1.33E+13	1.0	2.51E-02
⁹⁰ Sr	1.64E-18	0.82	1.33E+13	1.0	1.79E-05
⁹⁰ Y	1.10E-16	0.82	1.33E+13	1.0	1.20E-03

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

E1.2 Calculating MExXF_Dp (Equation 2.2-4)

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

Table 2.2-E4

Radionuclide	Dp _i (μCi/m ²)	e ^{-λt_n}	WF _{t_n}	ExXF (mR•m ²) per (μCi•hr)	Dp _i • ExXF (mR/hr)
²⁴¹ Am	4.15E-02	1	1	2.54E-04	1.05E-05
⁶⁰ Co	2.74E+04	1	1	2.51E-02	688
⁹⁰ Sr	9.25E+04	1	1	1.79E-05	1.66
⁹⁰ Y	9.25E+04	1	1	1.20E-03	111
MExXF_Dp					801

Because the first-year time phase starts at t₀ (deposition), there is no adjustment for radioactive decay or weathering.

E1.3 Calculating XR_DRL (Equation 2.2-1 or 2.2-5)

XR_DRL calculation for the radionuclide mixture for the first-year time phase.

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

$$XR_DRL_E = \frac{2000 \text{ mrem} * 801 \frac{\text{mR}}{\text{hr}}}{6.08E+06 \text{ mrem}} = 0.263 \frac{\text{mR}}{\text{hr}}$$

E1.4 Calculating the XR_DRL for an Individual Organ

The preceding calculations assume that the organ of interest is the whole body. The generic approach can be modified to calculate a Derived Response Level for a specific organ (e.g., skin, thyroid, etc.).

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

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

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

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

Radionuclide	ExDC ^a (Sv•m ²) per (s•Bq)	GRF (unitless)	CF (mrem•Bq•s) per (Sv•μCi•hr)	XDCF _c (mrem/mR)	ExXF (mR•m ²) per (μCi•hr)
²⁴¹ Am	8.32E-17	0.82	1.33E+13	1.0	9.07E-04
⁶⁰ Co	2.76E-15	0.82	1.33E+13	1.0	3.01E-02
⁹⁰ Sr	1.40E-16	0.82	1.33E+13	1.0	1.53E-03
⁹⁰ Y	1.05E-14	0.82	1.33E+13	1.0	0.115

^a Organ of interest is skin. Values from DCFPAK 1.6 Update 1 (ICRP 60+).

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

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

Radionuclide	Dp _i (μCi/m ²)	ExXF (mR•m ²) per (μCi•hr)	Dp _i • ExXF (mR/hr)
²⁴¹ Am	4.15E-02	9.07E-04	3.76E-05
⁶⁰ Co	2.74E+04	3.01E-02	825
⁹⁰ Sr	9.25E+04	1.53E-03	141
⁹⁰ Y	9.25E+04	0.115	1.06E+04
MExXF_Dp			1.16E+04

Finally, to calculate the XR_DRL for the mixture for the first-year time phase:

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

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

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

Table 2.2-5

Radionuclide		²⁴¹ Am	⁶⁰ Co	⁹⁰ Sr	⁹⁰ Y
Dp _i (μCi / m ²)		4.15E-02	2.74E+04	9.25E+04	9.25E+04
ExXF (mR•m ²) per (μCi•hr)	Effective	2.54E-04	2.51E-02	1.79E-05	1.20E-03
	Skin	9.07E-04	3.01E-02	1.53E-03	0.115
MExXF_Dp (mR/hr)	Effective	801			
	Skin	1.16E+04			
MTDP_Dp ^a (mrem)	Effective	6.08E+06			
	Skin	9.16E+07			
XR_DRL (mR/hr)	Effective	0.263			
	Skin	6.31			
^a From Method 2.1.					

EXAMPLE 2

Problem: Calculate Exposure Rate DRL for Second-Year Time Phase for the Following Mixture (deposited at $t=0$).

Table 2.2-E1 (repeated)

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

To determine the XR_DRL, the intermediate term for the External Exposure Factor (ExXF) must first be calculated for each radionuclide and then combined with the areal activity (Deposition or Dp_i for each radionuclide) and Mixture External Exposure Factor (MExXF_Dp).

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

Table 2.2-E2 (repeated)

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

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

E2.1 Calculating ExXF (Equation 2.2-3)

This calculation requires the External Dose Factor (ExDF) and the Exposure to Dose Conversion Factor (chronic) (XDCF_C).

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

$$ExXP_{241Am} = \frac{2.33E-17 \frac{Sv \cdot m^2}{s \cdot Bq} * 0.82 * 1.33E+13 \frac{mrem \cdot Bq \cdot s}{Sv \cdot \mu Ci \cdot hr}}{1.0 \frac{mrem}{mR}} = 2.54E-04 \frac{mR \cdot m^2}{\mu Ci \cdot hr}$$

Table 2.2-E3 (repeated)

Radionuclide	ExDC ^a (Sv·m ²) per (s·Bq)	GRF (unitless)	CF (mrem·Bq·s) per (Sv·μCi·hr)	XDCF _c (mrem/mR)	ExXF (mR·m ²) per (μCi·hr)
²⁴¹ Am	2.33E-17	0.82	1.33E+13	1.0	2.54E-04
⁶⁰ Co	2.30E-15	0.82	1.33E+13	1.0	2.51E-02
⁹⁰ Sr	1.64E-18	0.82	1.33E+13	1.0	1.79E-05
⁹⁰ Y	1.10E-16	0.82	1.33E+13	1.0	1.20E-03

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

E2.2 Calculating MExXF_Dp (Equation 2.2-4)

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

Table 2.2-E6

Radionuclide	Dp _i (μCi/m ²)	e ^{-λt_n}	WF _{tn}	ExXF (mR·m ²) per (μCi·hr)	Dp _i · ExXF (mR/hr)
²⁴¹ Am	4.15E-02	0.998	0.844	2.54E-04	8.88E-06
⁶⁰ Co	2.74E+04	0.877	0.844	2.51E-02	508
⁹⁰ Sr	9.25E+04	0.976	0.844	1.79E-05	1.37
⁹⁰ Y	9.25E+04	0.976	0.844	1.20E-03	91.0
MExXF_Dp					600

Because the second-year time phase starts at t_r = 366 days, there is a need to adjust for radioactive decay and weathering to determine the XR_DRL at the start of the time phase.

E2.3 Calculating XR_DRL (Equation 2.2-1 or 2.2-5)

XR_DRL (effective) calculation for the radionuclide mixture for the second-year time phase.

Organ of Interest: Whole Body
 PAG: 500 mrem
 MTDP_Dp: 4.67E+06 (From Method 2.1)

$$XR_DRL_E = \frac{500 \text{ mrem} * 600 \frac{mR}{hr}}{4.76E+06 \text{ mrem}} = 0.063 \frac{mR}{hr}$$

NOTE: This value is correct for day 366. To calculate a value that can be compared to values for other time phases and plotted on the same data products, see section E2.4 below.

E2.4 Adjusting the XR_DRL to Correspond to the Start of the Other Standard Time Phases ($t_1 = 0$)

This calculation requires the MExXF_Dp value for t_0 (Equation 2.2-4).

Table 2.2-E6

Radionuclide	Dp _i ($\mu\text{Ci}/\text{m}^2$)	$e^{-\lambda t_n}$	WF _{tn}	ExXF ($\text{mR}\cdot\text{m}^2$) per ($\mu\text{Ci}\cdot\text{hr}$)	Dp _i • ExXF (mR/hr)
²⁴¹ Am	4.15E-02	1	1	2.54E-04	1.05E-05
⁶⁰ Co	2.74E+04	1	1	2.51E-02	688
⁹⁰ Sr	9.25E+04	1	1	1.79E-05	1.66
⁹⁰ Y	9.25E+04	1	1	1.20E-03	111
MExXF_Dp					801
Because the other time phases start at $t_i = t_0$ (deposition) there is no adjustment for radioactive decay or weathering to determine the MExXF_Dp at that time.					

E2.5 Calculating XR_DRL (Equation 2.2-1 or 2.2-5)

XR_DRL (effective) calculation for the radionuclide mixture for the second-year time phase.

Organ of Interest: Whole Body
 PAG: 500 mrem
 MTDP_Dp: 4.67E+06 (From Method 2.1)

$$XR_DRL_E = \frac{500 \text{ mrem} * 801 \frac{\text{mR}}{\text{hr}}}{4.76\text{E}+06 \text{ mrem}} = 0.084 \frac{\text{mR}}{\text{hr}}$$

NOTE: This value is correct for day 0. This value represents the Exposure Rate present at t_0 (deposition) which would cause the mixture to produce a dose of 500 mrem (the second-year PAG) over the second year (day 366-730). This value is appropriate for direct comparison with DRLs for other time phases with start times of t_0 . Therefore the DRLs for all time phases can be plotted on the same data product.

METHOD 2.3 ALPHA DERIVED RESPONSE LEVEL

Application

This method has been developed to calculate an Alpha Derived Response Level (α _DRL) for a deposition of radioactive material.

The α _DRL:

- Represents the ground concentration, or areal alpha activity ($\mu\text{Ci}/\text{m}^2$), at a given time (t_n) of a mixture of radionuclides that will be expected to cause the mixture to produce a dose equal to the appropriate Protective Action Guide (PAG) over the time phase under consideration.
- Is derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA92) or the Department of Homeland Security (DHS) (DHS08). A projected or measured deposition value greater than the α _DRL indicates that the PAG has the potential to be exceeded.
- Is used to create data products and define areal alpha activity to assist decision makers in determining where it may be advisable to implement protective actions (e.g., sheltering, evacuation, relocation).
- Is calculated using the Deposition Derived Response Level (Dp_DRL) value calculated in Method 2.1.

Because it is difficult to foresee what instruments will be used by monitoring personnel, it not appropriate for the FRMAC Assessment Division to calculate instrument-specific Alpha DRLs in units of counts per minute (cpm) per a given probe area (e.g., 550 α cpm/100 cm^2) for a given radionuclide mixture. Rather, the value calculated by this method is an intermediate value and must be adjusted for conditions in the field (e.g., instrument efficiency, surface conditions, and environmental conditions).

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

Discussion

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

Calculating an α _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.

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

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

Assumptions

The following assumptions apply in addition to the default assumptions:

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

Inputs

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

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

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

Outputs

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

Final

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

Intermediate

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

None

Calculation

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

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

$$\alpha_DRL_{t_n} = \sum_i^{P+D} (Dp_DRL_{i,t_n} * Y_{\alpha,i}) \quad (\text{Eq. 2.3-1})$$

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

where:

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

\sum_i^{P+D} = Represents the summation of values from all parent (P) and short-lived daughter (D) radionuclide(s);

Dp_DRL_{i,t_n} = Deposition Derived Response Level, the areal activity at time t_n of radionuclide i at which the dose from all radionuclides in mixture would equal the PAG for the time phase under consideration, $\mu\text{Ci}_{\text{nt}}/\text{m}^2$; and

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

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

EXAMPLE 1

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

Table 2.3-E1

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

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

Table 2.3-E2

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

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

E1.1 Calculating α DRL (Equation 2.3-1):

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

Table 2.3-E3

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

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

Applying these values in equation 2.3-1 yields:

$$\begin{aligned}\alpha_DRL_{t_0} &= \left(1.65E+03 \frac{\mu\text{Ci}}{\text{m}^2} * 0.3594 \frac{\mu\text{Ci}_\alpha}{\mu\text{Ci}} \right) + \left(1.06E+03 \frac{\mu\text{Ci}}{\text{m}^2} * 1 \frac{\mu\text{Ci}_\alpha}{\mu\text{Ci}} \right) \\ &= 1.65E+03 \frac{\mu\text{Ci}_\alpha}{\text{m}^2}\end{aligned}$$

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

METHOD 2.4 BETA DERIVED RESPONSE LEVEL

Application

This method has been developed to calculate a Beta Derived Response Level (β^- _DRL) for a deposition of radioactive material.

The β^- _DRL:

- Represents the ground concentration, or areal beta activity ($\mu\text{Ci}/\text{m}^2$), at a given time (t_n) of a mixture of radionuclides that will be expected to cause the mixture to produce a dose equal to the appropriate Protective Action Guide (PAG) over the time phase under consideration.
- Is derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA92) or the Department of Homeland Security (DHS) (DHS08). A projected or measured deposition value greater than the β^- _DRL indicates that the PAG has the potential to be exceeded.
- Is used to create data products and define areal beta activity to assist decision makers in determining where it may be advisable to implement protective actions (e.g., sheltering, evacuation, relocation).
- Is calculated using the Deposition Derived Response Level (Dp_DRL) value calculated in Method 2.1.

Because it is difficult to foresee what instruments will be used by monitoring personnel, it not appropriate for the FRMAC Assessment Division to calculate instrument-specific Beta DRLs in units of counts per minute (cpm) per a given probe area (e.g., 550 β^- cpm/100 cm^2) for a given radionuclide mixture. Rather, the value calculated by this method is an intermediate value and must be adjusted for conditions in the field (e.g., instrument efficiency, surface conditions, and environmental conditions).

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

Discussion

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

Calculating a β^- 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;

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

- Energy variance: varying maximum energies (and corresponding efficiencies) of beta emissions from different radionuclides;
- Detector characteristics: The mass thickness (mg/cm^2) of the detector's window and walls varies between detector types and manufacturers. Therefore the detectable fraction of the beta particle energy spectrum varies with the detector and with the window condition (i.e., open vs. closed);
- Surface characteristics: e.g., soil, pavement, and grass, because these factors affect the fraction of the beta radiation that is shielded or backscattered; and
- Environmental conditions: e.g., rain and dust, due to shielding effects.

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

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

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

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

Assumptions

The following assumptions apply in addition to the default assumptions:

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

Inputs

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

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

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

Outputs

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

Final

β_DRL = Beta Derived Response Level, the areal beta activity at time t_n of the mixture at which the dose from all radionuclides in a deposition mixture would result in a dose equal to the PAG for the time phase under consideration, $\mu\text{Ci}_\beta/\text{m}^2$

Intermediate

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

None

Calculation

The calculation of the β^- DRL determines the areal beta activity of the mixture at which the dose from all radionuclides in the mixture would result in a dose equal to the PAG for the time phase under consideration.

The FRMAC Assessment Division uses the following method to calculate the β^- DRL values. The FRMAC Monitoring & Sampling Division will compare the sampling and monitoring data to the respective DRL to determine if the PAG for the time phase under consideration has been exceeded.

$$\beta^- \text{ DRL}_{t_n} = \sum_i^{P+D} \left(Dp \text{ DRL}_{i,t_n} * Y_{\beta^-,i} \right) \quad (\text{Eq. 2.4-1})$$

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

where:

$\beta^- \text{ DRL}_{t_n}$ = Beta Derived Response Level, the areal beta activity of the mixture, at time t_n (time of measurement, prediction, or evaluation) at which the dose from all radionuclides in the mixture would result in a dose equal to the PAG for the time phase under consideration, $\mu\text{Ci}_{\beta^-}/\text{m}^2$;

\sum_i^{P+D} = Represents the summation of values from all parent (P) and short-lived daughter (D) radionuclide(s);

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

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

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

EXAMPLE 1

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

Table 2.4-E1

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

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

Table 2.4-E2

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

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

E1.1 Calculating β^- DRL (Equation 2.4-1):

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

Table 2.4-E3

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

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

Applying these values in equation 2.4-1 yields:

$$\begin{aligned} \beta^-_{DRL_{t_0}} &= \left(1.65E+03 \frac{\mu\text{Ci}}{\text{m}^2} * 0.6406 \frac{\mu\text{Ci}_{\beta^-}}{\mu\text{Ci}} \right) + \left(5.94E+02 \frac{\mu\text{Ci}}{\text{m}^2} * 1 \frac{\mu\text{Ci}_{\beta^-}}{\mu\text{Ci}} \right) + \left(1.65E+03 \frac{\mu\text{Ci}}{\text{m}^2} * 1 \frac{\mu\text{Ci}_{\beta^-}}{\mu\text{Ci}} \right) \\ &= 3.30E+03 \frac{\mu\text{Ci}_{\beta^-}}{\text{m}^2} \end{aligned}$$

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

METHOD 2.5 PROJECTED PUBLIC DOSE

Application

This method has been developed to calculate the Projected Public Dose (PPD), the dose received by members of the public, from a deposition of radioactive material. The PPD may be calculated from a measured areal activity, Deposition PPD (Dp_PPD) or exposure rate, Exposure Rate PPD (XR_PPD).

The PPD:

- Uses a measured areal activity of a marker radionuclide (or a measured exposure rate) to calculate the dose that a receptor is projected to receive over a specified time phase due to the external dose from material deposited on the ground (i.e., groundshine) and the dose from the inhalation of resuspended material.
- Is compared to Protective Action Guides (PAGs) for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA92) or the Department of Homeland Security (DHS) (DHS08).
- Is used to create data products and define dose levels to assist decision makers in determining where it may be advisable to implement protective actions (e.g., sheltering, evacuation, relocation).
- Is calculated from the Deposition Derived Response Level (Dp_DRL) value calculated in Method 2.1 or the Exposure Rate Derived Response Level (XR_DRL) value calculated in Method 2.2.

Discussion

The PPD is a value obtained by:

- Multiplying the local deposition (areal activity) of a radionuclide at the start of the time phase by the Total Dose Parameter for Deposition for that radionuclide and time phase and summing that product over all the radionuclides in the mixture, or
- Comparing a measured exposure rate (mR/hr) to the calculated XR_DRL for a mixture. Because the XR_DRL are determined using a regulatory PAG, the ratio of the measured value to the appropriate DRL can be used to calculate a projected dose relative to the PAG.

Assumptions

There are no additional assumptions beyond the default assumptions.

Inputs

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

- Total Dose Parameter for Deposition (TDP_Dp) for each radionuclide and Mixture Total Dose Parameter for Deposition (MTDP_Dp) for the mixture – Calculated using Method 2.1.
- Exposure Rate Derived Response Level (XR_DRL) for the mixture – Calculated using Method 2.2.
- Mixture External Exposure Factor for Deposition (MExXF_Dp) for the mixture – Calculated using Method 2.2.

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

Outputs

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

Final

Dp_PPD = Deposition Projected Public Dose over the time phase under consideration, mrem

XR_PPD = Exposure Rate Projected Public Dose over the time phase under consideration, mrem

Intermediate

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

None

Method 2.5.1 ` (Dp_PPD)

Calculation

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

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

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

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

$$Dp_PPD_{E,TP} = \sum_i Dp_{i,t_1} * TDP_Dp_{E,i,TP} \quad (\text{Eq. 2.5-1})$$

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

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

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

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

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

Method 2.5.2 Exposure Rate Projected Public Dose (XR_PPD)

Calculation

Calculate the XR_PPD by comparing a measured exposure rate with the time-adjusted XR_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.

$$\frac{XR_{t_n}}{XR_DRL_{E,t_n}} = \frac{XR_PPD_{E,TP}}{PAG_{E,TP}} \quad (\text{Eq. 2.5-2a})$$

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

$$XR_PPD_{E,TP} = \frac{XR_{t_n} * PAG_{E,TP}}{XR_DRL_{E,t_n}} \quad (\text{Eq. 2.5-2b})$$

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

where:

$XR_PPD_{E,TP}$ = Exposure Rate Projected Public Dose, the projected dose to the whole body (E) over the time phase (TP) under consideration from a measured external exposure rate, mrem;

XR_{t_n} = Measured Exposure Rate at time t_n , mR/hr;

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

NOTE: The default value for t_n is the start of the time phase under consideration (t_l), but it may be set to any time (before, during, or after the time phase).

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

XR_DRL_{E,t_n} = Exposure Rate Derived Response Level to the whole body (E) at time t_n , mR/hr (see Equation 2.2-5 from Method 2.2).

Equation 2.2-5 from Method 2.2 shows that:

$$XR_DRL_{E,t_n} = PAG_{E,TP} * \frac{MExXF_Dp_{E,t_n}}{MTDP_Dp_{E,TP}} \quad (\text{Eq. 2.2-5})$$

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

Substituting for XR_DRL in Eq. 2.5-2b yields:

$$XR_PPD_{E,TP} = XR_{t_n} * \frac{MTDP_Dp_{E,TP}}{MExXF_Dp_{E,t_n}} \quad (\text{Eq. 2.5-3})$$

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

EXAMPLE 1

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

Table 2.5-E1

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

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

Table 2.5-E2

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

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

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

E1.1 Calculating D_p _PPD

This calculation requires the Total Dose Parameter for Deposition (TDP_{Dp}) for each radionuclide in the mixture. Table 2.5-E3 shows the values calculated in Method 2.1 (Table 2.1-E20) for the second-year time phase evaluated at deposition ($t_1=0$).

Table 2.5-E3

Radionuclide	D_{p_i} ($\mu\text{Ci}/\text{m}^2$)	TDP _{Dp} – 2 nd Year ($\text{mrem} \cdot \text{m}^2/\mu\text{Ci}$)	$D_{p_i} \cdot \text{TDP}_{Dp} - 2^{\text{nd}} \text{ Year}$ (mrem)
^{241}Am	4.15E-02	7.23	3.00E-01
^{60}Co	2.74E+04	1.43E+02	3.92E+06
^{90}Sr	9.25E+04	1.28E-01	1.18E+04
^{90}Y	9.25E+04	8.03	7.43E+05
MTDP _{Dp} (Σ)			4.67E+06

Applying the values for D_{p_i} and TDP_{Dp}, Equation 2.5-1 becomes:

$$Dp_PPD_{E,TP} = \left[\begin{array}{l} \left(4.15E-02 \frac{\mu\text{Ci}}{\text{m}^2} * 7.23 \frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}} \right) \\ + \left(2.74E+04 \frac{\mu\text{Ci}}{\text{m}^2} * 1.43E+02 \frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}} \right) \\ + \left(9.25E+04 \frac{\mu\text{Ci}}{\text{m}^2} * 1.28E-01 \frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}} \right) \\ + \left(9.25E+04 \frac{\mu\text{Ci}}{\text{m}^2} * 8.03 \frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}} \right) \end{array} \right] = 4.67E+06 \text{ mrem}$$

NOTE: This value is also the MTDP_Dp for the mixture (see Method 2.1, Example 2, Section E2.4).

E1.2 Calculating a Dp_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 Dp_PPD for a specific organ:

Determine the MTDP_Dp (which is equal to the Dp_PPD) for the sampling location (see Method 2.1, Example 1, Section E1.6 – Table 2.1-E10).

EXAMPLE 2

Problem: Calculate the Exposure Rate Projected Public Dose for the Second-year Time Phase for the following mixture (deposited at $t=0$).

Assume the exposure rate measurement was performed during the time phase on Day 500.

Table 2.5-E1 (repeated)

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

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

Table 2.5-E2 (repeated)

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

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

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

E2.1 Calculating $\text{MExXF}_{\text{Dp}_{\text{tn}}}$

This calculation requires the External Exposure Factors (ExXF) for each radionuclide in the mixture and a time within the time phase at which the measurement (XR_{tn}) was taken.

Table 2.2-E4

Radionuclide	Dp _i (μCi/m ²)	e ^{-λt_n}	WF _{t_n}	ExXF ^a (mR•m ²) per (μCi•hr)	Dp _i • ExXF (mR/hr)
²⁴¹ Am	4.15E-02	0.998	0.801	3.63E-04	1.20E-05
⁶⁰ Co	2.74E+04	0.835	0.801	3.58E-02	656
⁹⁰ Sr	9.25E+04	0.968	0.801	2.56E-05	1.84
⁹⁰ Y	9.25E+04	0.968	0.801	1.71E-03	123
MExXF_Dp _{t_n}					781
Because the measurement was made at t _n = 500 days, adjust for radioactive decay and weathering to determine the MExXF_Dp at the measurement time.					
^a See Method 2.2, Example 1, Section E1.1 for calculation of ExXF values.					

Note how this value differs from the MExXF_Dp calculated for the second-year time phase (t₁=366 days) in Method 2.2, Table 2.2-E6.

E2.2 Calculating XR_PDD_s

Measurement (XR_m) = 0.05 mR/hr at t_n
 t_n = 500 days after deposition
 $MTDP_Dp$ = 4.67E+06 mrem (value from Turbo FRMAC)
 $MExXF_Dp_m$ = 781 mR/hr

Equation 2.5-4 yields:

$$XR_PPD_{E,TP} = 0.05 \frac{\text{mR}}{\text{hr}} * \frac{4.67\text{E}+06 \text{ mrem}}{781 \frac{\text{mR}}{\text{hr}}}$$

$XR_PPD = 299$ mrem for the second year.

E2.3 Calculating an XR_PPD for an Individual Organ

To calculate an XR_PPD for a specific organ, determine the XR_DRL for the organ and compare to the organ-specific PAG as demonstrated above (see Method 2.2, Example 1, Section E1.4).

METHOD 2.6 SKIN DOSE

This method is reserved for future development.

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METHOD 2.7 DETERMINING RETURN TIMES

This method is reserved for future development.

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METHOD 2.8 ASSESSING NUCLEAR DETONATIONS

Application

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

The XR_DRL:

- Represents the exposure rate (mR/hr, measured at 1 m above the ground) at a given time (t_n), from all radionuclides in the mixture that will be expected to produce a dose equal to the appropriate Protective Action Guide (PAG) over the time phase under consideration.
- Is derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA92) or the Department of Homeland Security (DHS) (DHS08). A projected or measured exposure rate value greater than the XR_DRL indicates that the PAG has the potential to be exceeded.
- Is used to create data products and define exposure rates to assist decision makers in determining where implementing protective actions (e.g., sheltering, evacuation, relocation) may be advisable.

Discussion

This application of the XR_DRL relates a measured exposure 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 exposure.

The XR_DRL for nuclear detonation events is based on the exposure rate of the entire fallout mixture, not on concentrations of individual radionuclides. It is important to remember that this calculation only applies to nuclear detonations, for all other application of the XR_DRL, see Method 2.2.

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

Assumptions

- 1) Doses and XR_DRLs are based on external gamma exposure only. Assume one rad external dose is equivalent to one rem.
- 2) During the time from 0.5 to 5,000 hours, the decay of fallout activity at a given location may be approximated by Equation 2.8-1 (G177):

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

where:

XR_t = Exposure rate at time t (hours after detonation), mR/hr;

XR_r = Reference exposure rate at 1 hour after nuclear detonation, mR/hr;

x = Power Function Exponent, the value that represents the decay of fallout radioactivity at a given location. Default value = 1.2, see Section 2.8.3 for instructions on calculating this value if requested.

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

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

Inputs

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

Power Function Exponent (x) – Default of 1.2.

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

Outputs

Final

XR_DRL = Exposure Rate Derived Response Level, the external exposure rate, at time t_n , at which the dose from all radionuclides in a deposition mixture would result in a dose equal to the PAG for the time phase under consideration, mR/hr

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

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

Intermediate

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

- $XR_{r,PAG}$ = Reference exposure rate at 1 hour after nuclear detonation which would produce a dose for the time phase equal to the PAG, mR/hr
- x = Power Function Exponent, the value that represents the decay of fallout radioactivity at a given location. Default value = 1.2, see Method 2.8.4 for instructions on calculating this value if requested.

Method 2.8.1 Nuclear Fallout Dose

Calculation

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

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

$$\text{Dose} = XR_r * \int_{t_1}^{t_2} t^{-x} dt * XDCF_{A \text{ or } C} \quad (\text{Eq. 2.8-2})$$

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

where:

- XR_r = Reference exposure rate at 1 hour after nuclear detonation, mR/hr;
- t_1 = the start of the time phase (integration period) under consideration, hr;
- t_2 = the end of the time phase (integration period) under consideration, hr;
- x = Power Function Exponent, the value that represents the decay of fallout radioactivity at a given location. Default value = 1.2, see Method 2.8.4 for instructions on calculating this value if requested.
- $XDCF_A$ = 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.

Integrating this equation produces:

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

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

The reference exposure rate (XR_r) can be determined using an exposure rate measurement taken at a known time (in hours) after detonation and a modified version of Equation 2.8-1:

$$XR_r = \frac{XR_t}{t^{-x}} \quad (\text{Eq. 2.8-1, Modified})$$

Method 2.8.2 XR_DRL for nuclear fallout

Calculation

Determining the XR_DRL in the case of a nuclear detonation requires knowledge of when the detonation occurred and what time the evaluation of XR_DRL will be made relative to that time and the PAG to be applied.

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

$$\text{PAG} = XR_{r,PAG} * \int_{t_1}^{t_2} t^{-x} dt * XDCF_{A \text{ or } C} \quad (\text{Eq. 2.8-4})$$

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

where:

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

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

Integrating this equation produces:

$$\text{PAG} = XR_{r,PAG} * \left(\frac{t_2^{-x+1} - t_1^{-x+1}}{-x+1} \right) * XDCF_{A \text{ or } C} \quad (\text{Eq. 2.8-5a})$$

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

Solving this equation for XR_r yields:

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

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

This represents the Exposure 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 XR_DRL for a measurement time t_n , apply the power function to the XR_r calculated above.

$$XR_DRL_{t_n} = XR_{t_n} = XR_{r,PAG} * t_n^{-x} \quad (\text{Eq. 2.8-6})$$

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

where:

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

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

$$XR_DRL_{t_n} = \frac{PAG}{XDCF_{A \text{ or } C}} * \left(\frac{-x+1}{t_2^{-x+1} - t_1^{-x+1}} \right) * t_n^{-x} \quad (\text{Eq. 2.8-7a})$$

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

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

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

Method 2.8.3 Nuclear Fallout Stay Time:

Calculation

This calculation uses the reference exposure rate (XR_r) and the exponent of the power function (x) to determine the stay time for an individual in an area of nuclear fallout starting

at a particular time (t_1). This could apply to worker shifts or to members of the public returning to their homes to collect needed items.

This is done by solving the dose equation (Equation 2.8-3) for the end of the time phase (t_2), the time interval from t_1 to t_2 is the “stay time” for that individual in the area that would produce a dose equal to the PAG.

$$\text{Dose} = XR_r * \left(\frac{t_2^{-x+1} - t_1^{-x+1}}{-x+1} \right) * XD CF_{A \text{ or } C} \quad (\text{Eq. 2.8-3})$$

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

Solving for t_2 :

$$t_2^{-x+1} = \frac{\text{Dose} * (-x+1)}{XR_r * XD CF_{A \text{ or } C}} + t_1^{-x+1} \quad (\text{Eq. 2.8-8a})$$

Taking the natural log of both sides:

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

Solving for t_2 :

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

Therefore:

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

To obtain the stay time, subtract t_1 from t_2 .

Method 2.8.4 Calculating the “power function” (t^{-x}):

Calculation

The decay of fission products after a nuclear detonation can be approximated by the power function, t^{-x} . FRMAC uses a default value of 1.2 for the exponent (x) (GL77).

If desired, the exponent of the power function can be calculated using two exposure rate measurements taken at the same location at two different known times after detonation.

Let:

XR_a = exposure rate measured at time t_a , mR/hr;

XR_b = exposure rate measured at time t_b , mR/hr;

XR_r = reference exposure rate at 1 hour after detonation, mR/hr;

By the rule of the power function:

$$XR_a = XR_r * t_a^{-x} \quad \text{and} \quad XR_b = XR_r * t_b^{-x} \quad (\text{Eq. 2.8-9a})$$

Therefore:

$$XR_r = \frac{XR_a}{t_a^{-x}} = \frac{XR_b}{t_b^{-x}} \quad (\text{Eq. 2.8-9b})$$

and,

$$\frac{XR_b}{XR_a} = \frac{t_b^{-x}}{t_a^{-x}} \Rightarrow \left(\frac{t_b}{t_a} \right)^{-x} \quad (\text{Eq. 2.8-9c})$$

Taking the natural log of both sides:

$$\ln \left(\frac{XR_b}{XR_a} \right) = -x \ln \left(\frac{t_b}{t_a} \right) \quad (\text{Eq. 2.8-9d})$$

Solving for $-x$:

$$-x = \frac{\ln \left(\frac{XR_b}{XR_a} \right)}{\ln \left(\frac{t_b}{t_a} \right)} \quad (\text{Eq. 2.8-9e})$$

Method 2.8.5 Handling the case when the “power function” (t^{-x}) exponent is 1:

Calculation

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

Calculating Dose using Equation 2.8-3,

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

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

$$\text{Dose} = XR_r * (\ln t_2 - \ln t_1) * XDCF_{A \text{ or } C}$$

Calculating XR_DRL using Equation 2.8-7a,

$$XR_DRL_{t_n} = \frac{PAG}{XDCF_{A \text{ or } C}} * \left(\frac{-x+1}{t_2^{-x+1} - t_1^{-x+1}} \right) * t_n^{-x} \quad (\text{Eq. 2.8-7a})$$

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

$$XR_DRL_{t_n} = \frac{PAG}{XDCF_{A \text{ or } C} * (\ln t_2 - \ln t_1)} * t_n^{-x}$$

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

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

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

$$t_2 = e^{\left(\frac{\text{Dose}}{XR_r * XDCF_{A \text{ or } C}} + \ln t_1 \right)}$$

EXAMPLE 1

Problem: Calculate the chronic dose XR_DRL for fallout for a time 48 hours after detonation assuming an Early Phase (96 hour) PAG of 100 rad (100 rem) and a start time (t_I) of 1 hour after detonation.

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

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

E1.1 Calculating t^{-x} using Equation 2.8-8e

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

E1.2 Calculating XR_DRL using Equation 2.8-7a

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

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

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

EXAMPLE 2

Problem: Calculate the Acute Dose received from fallout over the 96 hour period beginning 1 hour after detonation.

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

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

The dose is calculated using equation 2.8-3:

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

$x = 1.21$ from Example 1,

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

$$XR_r = \frac{XR_t}{t^{-x}} = \frac{5.1 \frac{\text{R}}{\text{hr}}}{12^{-1.21}} = 103 \frac{\text{R}}{\text{hr}}$$

Then:

$$\text{Dose} = 103 \frac{\text{R}}{\text{hr}} * \left(\frac{97^{-0.21} - 1^{-0.21}}{-0.21} \right) \text{hr} * 0.7 \frac{\text{rem}}{\text{R}} \square 212 \text{ rem}$$

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

$$\text{Dose} = 103 \frac{\text{R}}{\text{hr}} * \left(\frac{108^{-0.21} - 12^{-0.21}}{-0.21} \right) \text{hr} * 0.7 \frac{\text{rem}}{\text{R}} \square 75 \text{ rem}$$

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 exposure rate measurements were taken at a given location:

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

$x = 1.21$ from Example 1,

$XR_r = 103$ R/hr from Example 2,

The end of the work shift is calculated using equation 2.8-9d:

$$e^{\left\{ \frac{\ln \left[\frac{5 \text{ rem} * (-0.21)}{103 \frac{\text{R}}{\text{hr}} * 1 \frac{\text{rem}}{\text{R}}} + 24^{-0.21} \text{ hr} \right]}{-0.21} \right\}} = t_2 = 26.4 \text{ hr}$$

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

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SECTION 3. WORKER PROTECTION METHODS

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 Method 3.1 Basic Worker Protection 3.1-1

 Method 3.2 Advanced Worker Protection Total Dose Calculation 3.2-1

 Method 3.3 Advanced Worker Protection Stay Time Calculation (RESERVED) 3.3-1

 Method 3.4 Worker Skin Dose (RESERVED)..... 3.4-1

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INTRODUCTION TO WORKER PROTECTION METHODS

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

Assumptions

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

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

- 1) The dose projections from this method include contributions from external exposure (groundshine) and the inhalation of resuspended material.
- 2) Inhalation of material from the passage of a plume of radioactive material is not considered in these calculations. The plume is considered to have already passed. Dose consequences from direct inhalation, submersion, and cloud shine are not included in the calculations. (See Section 1 of this Volume for Plume Phase calculations.)
- 3) The effects of radioactive decay, weathering and resuspension are included in the calculations.
- 4) Ingestion is not included in these methods. If ingestion is a significant dose pathway (i.e., >10% of the total dose), it should be addressed separately and included in protective action decisions. (See Ingestion Methods, Section 4.)
- 5) Default calculations assume:
 - a. the receptor is outside in the contaminated area continuously during the time phase under consideration without any protective measures (e.g., shielding, respiratory protection);
 - b. chronic exposure; calculations addressing acute exposures are planned for future methods.
 - c. use of ICRP 60+ dosimetry model;
 - d. adult receptor;
 - e. an Breathing Rate for Light Activity (Adult Male) of 1.5 m³/hr; and
 - f. inhalation of 1-micron Activity Median Aerodynamic Diameter (AMAD) particles in the Maximum lung clearance class.
- 6) Parent – Daughter inclusion rules:

- Daughter radionuclides are included in calculations if:
 - a. Daughter's half-life is less than the half-life of the ultimate parent (i.e., first parent in decay series), and
 - b. Daughter's half-life is less than 1.5 yr.
 - Daughter radionuclides that meet these rules are considered to be in equilibrium (secular, or transient when branching ratio $\neq 1$) at deposition ($t = 0$, i.e., the daughter radionuclides are not grown in to equilibrium activities), and are assigned the parent's half life and decay constants for calculations.
 - Daughter radionuclides that do not meet these rules are excluded from the calculations (as are all subsequent daughter radionuclides, regardless of half life).
 - Optionally, an alternate calculation that models the decay and in-growth of the entire radionuclide decay chain may be used when the using the default Parent – Daughter inclusion rules stated above is not desired. See Appendix F, Supplement 1 for details on the calculation.
- 7) FRMAC's public protection methods generally assume that the organ of interest is the whole body. However, other organs may be evaluated against applicable Protective Action Guides (PAGs) by changing the Dose Coefficients and PAGs used. (See Method 2.1 Example 1, Section E1.6.)

Inputs

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

- Data – This information may come from predictive analysis (models) or field data (monitoring and/or samples):
 - Composition of the deposited radionuclide mixture (radionuclides and areal radioactivity, concentration, activity ratio or mass ratio) and/or external dose (or exposure) rates.
- Other Factors:
 - Ground roughness;
 - Weathering;
 - Resuspension; and
 - Decay of radionuclides during the time period under consideration.
- Constants:
 - Breathing rate;
 - Inhalation dose coefficient;
 - External dose coefficient;
 - Dose limits (e.g., PAGs); and
 - Exposure to Dose conversion factor (1.0 mrem/mR).
- Time Phase:
 - Evaluation Time (t_n) – The point in time, relative to the start of the event, for which the calculation is being performed; and
 - The start (t_1) and end (t_2) time of the worker shift under consideration.

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

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METHOD 3.1 BASIC WORKER PROTECTION

Application

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

The results of this calculation will be used to develop turn-back and stay time guidance for emergency workers based on comparison to the Protective Action Guides (PAGs) for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA92) or the Department of Homeland Security (DHS) (DHS08).

Discussion

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

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

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

Assumptions

The following are exceptions to the default assumptions:

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

NOTE: To include effects from inhalation of resuspended material or a mixture containing radionuclides with short half lives, see Method 3.2.

Inputs

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

Constants – Dose Limits for Workers Performing Emergency Services.

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

Outputs

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

Final

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

Intermediate

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

None

Calculation

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

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

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

where:

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

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

$$ST = \frac{Dose\ Limit}{ExDR} \quad (Eq. 3.1-2)$$

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

where:

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

ExDR = External dose rate in the work area, mrem/hr; and

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

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

EXAMPLE 1

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

Dose Limit: 25000 mrem

Shift Length: 8 hours

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

If the instrument reads out in mR/hr, the *TBL* would be:

XDCF_A: 0.7 mrem/mR

$$TBL = \frac{25000 \text{ mrem}}{8 \text{ hr} * 0.7 \frac{\text{mrem}}{\text{mR}}} = 4464 \frac{\text{mR}}{\text{hr}}$$

Workers should turn back from (avoid) areas with an external dose rate ≥ 125 mrem/hr (125 mR/hr).

EXAMPLE 2

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

Dose Limit: 5000 mrem

Dose Rate: 500 mrem/hr

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

If the Exposure Rate is 500 mR/hr:

XDCF_C: 1.0 mrem/mR

$$ST = \frac{5000 \text{ mrem}}{500 \frac{\text{mR}}{\text{hr}} * 1.0 \frac{\text{mrem}}{\text{mR}}} = 10.0 \text{ hr}$$

Workers may stay in the field for 10 hours.

METHOD 3.2 ADVANCED WORKER PROTECTION

Application

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

The TBL:

- Represents the integrated external dose (or exposure) that will be expected to produce a total dose (external and internal) over a worker's shift equal to the appropriate Protective Action Guide (PAG).
- Is derived from the PAGs for radiological emergency planning established by the Environmental Protection Agency (EPA) (EPA92) or the Department of Homeland Security (DHS) (DHS08) or other dose limits established for worker protection. A projected or measured exposure (or dose) value greater than the TBL indicates that the PAG has the potential to be exceeded.
- Is calculated from the Inhalation Dose Parameter for Deposition (InhDP_Dp) and the External Dose Parameter for Deposition (ExDP_Dp) values calculated in Method 2.1.

Discussion

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

Assumptions

The following is an exception to the default assumptions:

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

Inputs

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

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

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

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

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

Outputs

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

Final

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

Intermediate

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

ExtDCF_{TP} = External to Total Dose Conversion Factor, the ratio of the total dose (external + inhalation) to the external dose for a deposition of radioactive material over the time phase (*TP*) of interest,

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

NOTE: This value is used to convert a measurement from a self-reading dosimeter into a dose that includes the effects of inhalation of resuspended material.

Calculation

1.0 Calculating the Worker Turn-Back Limit

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

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

$$TBL_D_{TP} = \frac{Dose\ Limit}{ExtDCF_{TP}} \quad (Eq. 3.2-1)$$

$$mrem_{external} = \frac{mrem_{inh+external}}{mrem_{inh+external} / mrem_{external}}$$

where:

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

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

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

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

If workers are using dosimeters that read out in units of exposure (mR), divide the TBL_D by the Exposure to Dose Conversion Factor ($XDCF_{A\ or\ C}$) (0.7 $mrem/mR$ for acute dose or 1.0 $mrem/mR$ for chronic dose) to determine the Turn-Back Limit for Integrated External Exposure (TBL_X) in $mR_{external}$.

$$TBL_X_{TP} = \frac{TBL_D_{TP}}{XDCF_{A\ or\ C}} \quad (Eq. 3.2-2)$$

$$mR_{external} = \frac{mrem_{external}}{mrem / mR}$$

1.1 Calculation of the External to Total Dose Conversion Factor

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 3.2-3(a-c).

$ExTDCF_{TP} =$

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

which can be expanded to:

$$= \frac{\sum_i \left(\frac{InhDP_{-} Dp_{i,TP} * Dp_i * e^{-\lambda_i t_1} * WF_{t_1}}{KIPF * RPF} \right)}{\sum_i \left(ExDP_{-} Dp_{i,TP} * Dp_i * e^{-\lambda_i t_1} * WF_{t_1} \right)} + \frac{\sum_i \left(ExDP_{-} Dp_{i,TP} * Dp_i * e^{-\lambda_i t_1} * WF_{t_1} \right)}{\sum_i \left(ExDP_{-} Dp_{i,TP} * Dp_i * e^{-\lambda_i t_1} * WF_{t_1} \right)} \quad (\text{Eq.3.2-3b})$$

which simplifies to:

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

NOTE: Because WF_{t_1} is independent of radionuclide, it may be removed from the summation terms and then cancelled out of the numerator and denominator for the final equation.

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

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

where:

- $ExTDCF_{TP}$ = External to Total Dose Conversion Factor, the ratio of the total dose (external + inhalation) to the external dose for a deposition of radioactive material over the time phase (TP) of interest, $mrem_{inh+external}/mrem_{external}$;
- Dp_i = Deposition, the areal activity of radionuclide i , $\mu Ci/m^2$;
- $InhDP_Dp_{E,i,TP}$ = Inhalation Dose Parameter for Deposition, the committed effective dose received by the whole body (E) over the time phase under consideration (TP), per unit activity of radionuclide i deposited on the ground from the inhalation of the resuspended radionuclide, $mrem \cdot m^2/\mu Ci$;
- λ_i = Decay constant for radionuclide i , s^{-1} ;
- t_1 = start of the time phase (integration period) under consideration, s;
- $e^{-\lambda_i t_1}$ = Radioactive Decay correction for radionuclide i from t_0 (deposition) to t_1 (start of the time phase), unitless;
- WF_{t_1} = Weathering correction from t_0 (deposition) to t_1 (start of the time phase), unitless; and
- $ExDP_Dp_{E,i,TP}$ = External Dose Parameter for Deposition, the groundshine dose received by the whole body (E) over the time phase under consideration (TP), per unit of radioactivity of radionuclide i deposited on the ground and adjusted for the ground roughness factor, $mrem \cdot m^2/\mu Ci$;
- RPF = Respiratory Protection Factor, which defaults to 1 when no respirators are used, unitless; and
- $KIPF$ = Potassium Iodide Protection Factor, which defaults to 1 for all non-iodine isotopes or when no KI is administered, unitless.

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

Typical RPF values are:

Half-face Air-purifying Respirator: 10

Full-face Air-purifying Respirator: 50

Pressure-Demand SCBA: 10,000

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

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

$$TBL - D_{TP} = \frac{Dose\ Limit}{ExTDCF_{TP}} \quad (Eq. 3.2-4)$$

$$mrem_{external} = \frac{mrem_{inh+external}}{mrem_{inh+external} / mrem_{external}}$$

where:

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

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

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

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

1.3 Calculation of Worker Dose

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

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

$$mrem_{inh+external} = mrem_{external} * \frac{mrem_{inh+external}}{mrem_{external}}$$

where:

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

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

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

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

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

$$mrem_{inh+external} = mrem_{external} * \frac{mrem_{external}}{mR_{external}} * \frac{mrem_{inh+external}}{mrem_{external}}$$

where:

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

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

EXAMPLE 1

Problem: Calculate the worker Turn-Back Limit for an 8-hour shift without a respirator starting shortly after Deposition with a worker Dose Limit of 5000 mrem for the following mixture (deposited at $t=0$).

Table 3.2-E1

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

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

Table 3.2-E2

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

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

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

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

Table 3.2-E3

Radionuclide	Dp _i (μCi/m ²)	ExDP_Dp ^a (mrem per μCi/m ²)	InhDP_Dp ^a (mrem per μCi/m ²)	Dp _i • ExDP_Dp (mrem) ^b	Dp _i • InhDP_Dp (mrem) ^b
²⁴¹ Am	4.15E-02	2.04E-03	4.30	8.47E-05	1.79E-01
⁶⁰ Co	2.74E+04	0.201	1.37E-03	5.51E+03	3.75E+01
⁹⁰ Sr	9.25E+04	1.43E-04	7.01E-03	1.32E+01	6.49E+02
⁹⁰ Y	9.25E+04	9.61E-03	6.68E-05	8.89E+02	6.18
Σ				6.41E+03	6.92E+02

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

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

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

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

$$TBL_D_{TP} = \frac{5000 \text{ mrem}_{inh+external}}{1.11 \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}} \square 4500 \text{ mrem}_{external}$$

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

$$XDCC = 1.0 \text{ mrem/mR}$$

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

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

EXAMPLE 2

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

Table 3.2-E4

Radionuclide	Deposition (μCi/m ²)	t _{1/2} (days)
¹³¹ I	712	8.04
²³⁸ Pu	50	3.20E+04

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

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

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

Table 3.2-E5

Radionuclide	Dp _i (μCi/m ²)	ExDP_Dp ^a (mrem per μCi/m ²)	InhDP_Dp ^a (mrem per μCi/m ²)	e ^{-λt₁} ^b	Dp _i • e ^{-λt₁} • ExDP_Dp (mrem)	Dp _i • e ^{-λt₁} • InhDP_Dp (mrem)
¹³¹ I	712	2.22E-02	5.53E-05	0.708	11.2	2.79E-03 ^c
²³⁸ Pu	50	5.46E-05	1.16	1	2.73E-03	57.9
Σ					11.2	57.9

^a Values from TurboFRMAC 2.1 – Breathing Rate for “Light Activity”.

^b Because the time phase starts at t₁ =4 days there is a need to adjust for radioactive decay. (Weathering is also considered, but is not included in the hand calculation because it cancels out of the equation – See Section 1.1.)

^c This value includes a KIPF of 10.

With a respirator:

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

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

Without a respirator:

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

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

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

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

With a respirator:

$$TBL_D_{TP} = \frac{5000 \text{ mrem}_{inh+external}}{1.10 \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}} \square 4550 \text{ mrem}_{external}$$

$$TBL_X_{TP} = \frac{4550 \text{ mrem}_{external}}{1.0 \text{ mrem}/\text{mR}} \square 4550 \text{ mR}_{external}$$

Without a respirator:

$$TBL_D_{TP} = \frac{5000 \text{ mrem}_{inh+external}}{6.18 \frac{\text{mrem}_{inh+external}}{\text{mrem}_{external}}} \square 809 \text{ mrem}_{external}$$

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

METHOD 3.3 ADVANCED WORKER PROTECTION STAY TIME CALCULATION

This method is reserved for future development.

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METHOD 3.4 WORKER SKIN DOSE

This method is reserved for future development.

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SECTION 4. INGESTION PATHWAY METHODS

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INTRODUCTION TO INGESTION PATHWAY METHODS

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

The FDA has established DILs for contamination in food for a list of radionuclides and has specified a method to calculate DILs for all other radionuclides. The DILs are based on PAGs of 0.5 rem Committed Effective Dose (E_{50}) and 5 rem to any specific organ ($H_{T,50}$), whichever is more limiting. FDA Ingestion PAGs are presented in Appendix C, Table 2-2, and DILs for selected radionuclides (including the full FDA list) are presented in Appendix C, Table 8.

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

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

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

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

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

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

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METHOD 4.1 DERIVED INTERVENTION LEVELS

Application

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

The DIL:

- Represents the activity concentration ($\mu\text{Ci}/\text{kg}_{\text{wet}}$ or $\mu\text{Ci}/\text{l}$) of radioactive material found in food that, in the absence of any intervention, could lead to an individual receiving a dose equal to the appropriate Protective Action Guide (PAG) if consumed over 1 year.
- Is derived from the PAG for radiological emergency planning established by the Food and Drug Agency (FDA) (FDA98). A projected or measured value of radioactivity greater than the DIL indicates that the PAG has the potential to be exceeded.
- Applies to the activity concentration in the food “as prepared for consumption” or “wet.”
- Is applied during the first year after an incident and based on the most sensitive population (age group) and target organ to provide a large margin of safety to the public.
- Is used to create data products and define activity concentration levels to assist decision makers in determining where it may be advisable to implement protective actions (e.g., sheltering livestock, embargos, special product handling).

Discussion

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

The FDA established DILs for 9 principle isotopes in 5 groups, 15 secondary isotopes, and provided a method to calculate DILs. The nuclides with FDA-provided DILs are shown in Table 4.1-1 below and in Appendix C, Table 8.

FRMAC does not have the authority to calculate or use different DILs for radionuclides for which the FDA has provided recommended values unless alternate values are requested by

the Advisory Team or local decision makers. FRMAC can calculate DILs for the radionuclides for which the FDA does not provide recommended values, but these values are not automatically approved by the FDA and must receive approval from the Advisory Team or local decision makers before they are used.

Assumptions

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

- 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 ($\text{kg}_{\text{wet}}/\text{yr}$) of all dietary components (e.g., produce, grains, meat, etc.), including tap water used for drinking.
- 4) Annual intake is adjusted for short-lived ($t_{1/2} < 54$ days) radionuclides to account for radioactive decay.
- 5) Annual intake varies by age group (3 month, 1 yr, 5 yr, 10 yr, 15 yr, and adult).
- 6) DILs are applicable to foods as prepared for consumption or “wet”. To compare with analytical results it may be necessary to convert to “dry weight,” see Method 5.2.
- 7) ICRP 26 Ingestion Dose Conversion Factors should not be used to calculate DILs because they only consider the adult receptor (ICRP77).
- 8) The default Ingestion PAGs are:
 - 500 mrem to the whole body or
 - 5000 mrem to an individual organ, whichever is more limiting.
- 9) Inadvertent ingestion of soil is not included in these methods. If ingestion of soil is a significant dose pathway (i.e., >10% of the total dose), it should be addressed separately. (See Method 4.7).
- 10) Default calculations for non-FDA-listed radionuclides use the International Commission on Radiological Protection (ICRP) 60+ dosimetry model.

Inputs

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

Data – Composition of the deposited radionuclide mixture (radionuclides and concentration). This information may come from predictive analysis (models) or field data (monitoring and/or samples).

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

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

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

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

Outputs

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

Final

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

Intermediate

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

None

Method 4.1.1 DILs for FDA-Listed Radionuclides

Table 4.1-1 provides the DILs for the FDA-listed radionuclides. These values must be used when evaluating the radionuclides (and groups of radionuclides) in the table unless an alternate DIL is requested by the Advisory Team or local decision makers. Follow the calculation steps in Method 4.1.2 for all other radionuclides.

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

Radionuclide Group	FDA DIL ^a (Bq/kg _{wet})	FDA DIL ^a (μCi/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	$(^{103}\text{Ru}/6800) + (^{106}\text{Ru}/450) < 1$	$(^{103}\text{Ru}/0.18) + (^{106}\text{Ru}/1.2\text{E}-02) < 1$
¹⁰³ Ru	6800	0.18
¹⁰⁶ Ru	450	1.2E-02
Other Nuclides		
⁸⁹ Sr	1400	3.8E-02
⁹¹ Y	1200	3.2E-02
⁹⁵ Zr	4000	0.11
⁹⁵ Nb	12000	0.32
¹³² Te	4400	0.12
¹²⁹ I	56	1.5E-03
¹³³ I	7000	0.19
¹⁴⁰ Ba	6900	0.19
¹⁴¹ Ce	7200	0.19
¹⁴⁴ Ce	500	1.4E-02
²³⁷ Np	4	1.1E-04
²³⁹ Np	28000	0.76
²⁴¹ Pu	120	3.2E-03
²⁴² Cm	19	5.1E-04
²⁴⁴ Cm	2	5.4E-05
^a A food sample is considered to exceed the DIL if it meets or exceeds the DIL for any individual nuclide. Analysis results are not summed across nuclides except the combinations specifically stated (i.e., ¹³⁴ Cs + ¹³⁷ Cs, ²³⁸ Pu + ²³⁹ Pu + ²⁴¹ Am, and ¹⁰³ Ru + ¹⁰⁶ Ru).		

Method 4.1.2 DILs for Non-FDA-Listed Radionuclides

Calculation

This method uses the FDA approach for all calculations.

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

Equation 4.1-1 shows the DIL calculation.

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

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

where:

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

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

$FDC_{age, i}$ = Fraction of Diet Contaminated, default value of 0.3, (except ^{132}Te , ^{131}I , ^{133}I and ^{239}Np in the diet of an infant (3 months and 1 yr) for which it is 1.0), unitless;

NOTE: If there is convincing local information that the actual FDC is considerably different, local authorities may decide to use a different FDC .

$DFIR_{age}$ = Daily Food Intake Rate, the daily intake rate for the age group under consideration (see Appendix C, Table 10), $\text{kg}_{\text{wet}}/\text{d}$;

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

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

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

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

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

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

EXAMPLE 1

Problem: Calculate the Derived Intervention Level for ¹³⁶Cs.

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

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

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

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

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

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

Table 4.1-E1

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

^a Lower Large Intestine

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

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METHOD 4.2 CROP/PRODUCE INGESTION DERIVED RESPONSE LEVELS

Application

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

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

- Represents the ground concentration, or areal activity ($\mu\text{Ci}/\text{m}^2$), of radionuclide *i* that will be expected to cause the crop/produce growing in that area to exceed the Derived Intervention Level (DIL) for that radionuclide.
- Is indirectly derived (through the DIL) from the PAG for radiological emergency planning established by the Food and Drug Agency (FDA) (FDA98). A projected or measured deposition value greater than the Crop_DRL indicates that the PAG has the potential to be exceeded.
- Is applied during the first year after an incident and based on the most sensitive population (age group) and target organ to provide a large margin of safety to the public.
- Is used to create data products and define contamination levels to assist decision makers in determining where it may be advisable to conduct sampling to evaluate the potential for implementing protective actions (e.g., sheltering livestock, embargos, special product handling).
- Is calculated using the DIL calculated in Method 4.1

Discussion

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

FRMAC does not have the authority to calculate or use different DILs for radionuclides for which the FDA has provided recommended values unless alternate values are requested by the Advisory Team or local decision makers. FRMAC can calculate DILs for the

radionuclides for which the FDA does not provide recommended values, but these values are not automatically approved by the FDA and must receive approval from the Advisory Team or local decision makers before they are used.

Assumptions

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

Crop DRLs:

- 1) Apply to individual radionuclides; there is no sum-of-fraction rule (except for the FDA-listed ^{103}Ru and ^{106}Ru).
- 2) Are based on the most restrictive DIL for each radionuclide based on age group and target organ. See Method 4.1 for DIL calculation assumptions.
- 3) Apply to the plant as a whole and do not predict contamination of only the edible portions (e.g., apples on the tree.)
- 4) Assume a crop yield of $2 \text{ kg}_{\text{wet}}/\text{m}^2$ for fresh produce.
- 5) Assume a soil density of $1600 \text{ kg}_{\text{soil}}/\text{m}^3$.
- 6) Assume a mixing depth of $1.0\text{E}-03 \text{ m}$ for the first growing season and 0.15 after plowing (EPA89).
- 7) Assume a half life of 15 days for material weathering off plant material
- 8) Assume a Time to Market of 1 day for fresh produce.
- 9) Assume, for immature crops, that the crop will remain growing in the contaminated soil for a period of time sufficient to reach equilibrium.
- 10) Are calculated for food as prepared for consumption. To compare with analytical results it may be necessary to convert to “dry weight,” see Method 5.2.
- 11) Use Crop Retention Factors for fresh produce of:
 - 1.0 for radioiodine and
 - 0.2 for all other radionuclides.
- 12) DRLs for FDA grouped radionuclides (e.g., $^{134}\text{Cs} + ^{137}\text{Cs}$) are adjusted for decay during Field Time and Time to Market using the decay constant for the longest-lived group member.

Inputs

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

Data – Composition of the deposited radionuclide mixture (radionuclides and concentration). This information may come from predictive analysis (models) or field data (monitoring and/or samples).

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

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

Appropriate DIL for each radionuclide – Calculated using Method 4.1.

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

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

Outputs

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

Final

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

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

Intermediate

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

None

Method 4.2.1 Crop_DRL for Mature Crop/Produce

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

- Reduction in radioactivity due to weathering.

- Reduction in radioactivity due to biological processes in the crop.
- Increase in radioactivity due to root uptake from contaminated soil.
- Increase in radioactivity due to redeposition of resuspended material.

Calculation

Equation 4.2-1 shows the $Crop_DRL_{mat,i}$ calculation.

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

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

where:

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

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

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

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

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

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

Method 4.2.2 Crop_DRL for Immature Crop/Produce

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

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

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

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

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

The method models processes 1, 2, and 3 independently, while 4, 5, and 6 are combined into an element-dependent Transfer Factor (TF) for a crop type (e.g., leafy vegetable, root vegetable, fruit, or grain). (See PNNL-13421 for details on TFs).

Calculation

Equation 4.2-2 shows the $Crop_DRL_{imm,i}$ calculation.

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

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

where:

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

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

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

NOTE: For crops planted AFTER deposition, the $CRF=0$.

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

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

$$\left(\frac{1 - e^{-\lambda_w t_f}}{\lambda_w * t_f} \right) = \text{Integrated average weathering of radioactive material off plants during the time the crop is growing in the field (the integral of the weathering over the Field Time divided by the Field Time), unitless;}$$

Y = Crop Yield, the mass of crop grown per area of land (default 2.0 for produce), kg_{wet}/m²;

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

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

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

ρ_{soil} = Soil density (default 1600), kg_{soil}/m³;

λ_i = Decay constant for radionuclide i , d⁻¹;

$$\left(\frac{1 - e^{-\lambda_i t_f}}{\lambda_i * t_f} \right) = \text{Integrated average decay of radioactive material during the time the crop is growing in the field (the integral of radioactive decay over the Field Time divided by the Field Time), unitless; and}$$

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

EXAMPLE 1

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

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

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

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

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

Assuming:

$$\begin{aligned} CRF &= 0.2 \\ Y &= 2.0 \text{ kg}_{\text{wet}}/\text{m}^2; \\ \lambda_{Co} &= 3.6\text{E-}04 \text{ d}^{-1}; \text{ and} \\ t_m &= 1 \text{ d.} \end{aligned}$$

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

EXAMPLE 2

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

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

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

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

Assuming:

$$\begin{aligned} \text{CRF} &= 0.2 \\ \lambda_w &= 4.62\text{E-}02 \text{ d}^{-1}; \\ t_f &= 90 \text{ d}; \\ Y &= 2.0 \text{ kg}_{\text{wet}}/\text{m}^2; \\ \text{TF}_{\text{lettuce},i} &= 0.23 \mu\text{Ci}/\text{kg}_{\text{dry}} \text{ per } \mu\text{Ci}/\text{kg}_{\text{soil}}; \\ \text{MCF}_{\text{D-W},f} &= 0.2 \text{ kg}_{\text{dry}}/\text{kg}_{\text{wet}} \text{ for leafy vegetables}; \\ d_m &= 1.0\text{E-}03 \text{ m}; \\ \rho_{\text{soil}} &= 1600 \text{ kg}_{\text{soil}}/\text{m}^3; \\ \lambda_{\text{Co}} &= 3.6\text{E-}04 \text{ d}^{-1}; \text{ and} \\ t_m &= 1 \text{ d}. \end{aligned}$$

$$\begin{aligned} \text{Crop_DRL}_{\text{imm},^{60}\text{Co}} &= \frac{0.02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}}{\left(\frac{0.2 * \frac{1 - e^{-4.62\text{E-}02 \text{d}^{-1} * 90\text{d}}}{4.62\text{E-}02 \text{d}^{-1} * 90\text{d}}}{2.0 \frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \frac{0.23 \left(\frac{\mu\text{Ci}}{\text{kg}_{\text{dry}}} / \frac{\mu\text{Ci}}{\text{kg}_{\text{soil}}} \right) * 0.2 \frac{\text{kg}_{\text{dry}}}{\text{kg}_{\text{wet}}}}{1.0\text{E-}03 \text{ m} * 1600 \frac{\text{kg}_{\text{soil}}}{\text{m}^3}} \right) * \frac{1 - e^{-3.6\text{E-}04 \text{d}^{-1} * 90\text{d}}}{3.6\text{E-}04 \text{d}^{-1} * 90\text{d}} * e^{-3.6\text{E-}04 \text{d}^{-1} * 1\text{d}} \\ &= 0.39 \frac{\mu\text{Ci}}{\text{m}^2} \end{aligned}$$

METHOD 4.3 MILK INGESTION DERIVED RESPONSE LEVEL

Application

This method has been developed to calculate Ingestion Derived Response Levels for radioactive material deposited on animal forage/water for the milk pathway.

The Milk Ingestion Derived Response Level:

- Represents:
 1. Milk_DRL_{area,A,i}: The ground concentration, or areal activity ($\mu\text{Ci}/\text{m}^2$), of radionuclide *i* deposited over a grazing area that would result in a grazing animal's milk exceeding the Derived Intervention Level (DIL) for that radionuclide;
 2. Milk_DRL_{mass,A,i}: The mass concentration ($\mu\text{Ci}/\text{kg}_{\text{wet}}$), of radionuclide *i* in animal feed that would result in the animal's milk exceeding the Derived Intervention Level (DIL) for that radionuclide; or
 3. Milk_DRL_{water,A,i}: The water concentration ($\mu\text{Ci}/\text{l}$), of radionuclide *i* in an animal's drinking water that would result in the animal's milk exceeding the Derived Intervention Level (DIL) for that radionuclide.
- Is indirectly derived (through the DIL) from the PAG for radiological emergency planning established by the Food and Drug Agency (FDA) (FDA98). A projected or measured concentration value greater than the Milk_DRL indicates that the PAG has the potential to be exceeded.
- Is applied during the first year after an incident and based on the most sensitive population (age group) and target organ to provide a large margin of safety to the public.
- Is used to create data products and define contamination levels to assist decision makers in determining where it may be advisable to conduct sampling to evaluate the potential for implementing protective actions (e.g., sheltering livestock, embargos, special product handling).
- Is calculated using the DIL calculated in Method 4.1.

Discussion

The Milk_DRL predicts the amount of radioactivity deposited either on an animal's grazing area ($\mu\text{Ci}/\text{m}^2$) or in an animal's feed or water ($\mu\text{Ci}/\text{kg}_{\text{wet}}$ or $\mu\text{Ci}/\text{l}$) that would cause the animal's milk to exceed the DIL. Sampling efforts should concentrate on the area where the contamination is equal to the Milk_DRL to determine if the DIL has been exceeded in those

areas. Protective actions (e.g., use of stored feed) should be considered in areas where the DIL is exceeded. Milk embargo protective actions should be considered after milk samples indicate that the DIL has actually been exceeded. FDA guidance permits food with radioactivity concentrations below the DIL to move in commerce without restriction. However the FDA and local decision makers have flexibility in whether to apply restrictions in special circumstances.

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

Because milk is obtained from grazing animals daily this method treats milk as a “mature product” and there is no consideration for weathering or radioactive decay during grazing.

Assumptions

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

Milk DRLs:

- 1) Apply to individual radionuclides; there is no sum-of-fraction rule (except for the FDA-listed ^{103}Ru and ^{106}Ru).
- 2) Are based on the most restrictive DIL for each radionuclide based on age group and target organ. See Method 4.1 for DIL calculation assumptions.
- 3) Assume only one intake pathway is present (i.e., if forage/soil is contaminated, drinking water is clean).
- 4) Animal intake rates are assumed to be
 - Cow – 50 $\text{kg}_{\text{wet}}/\text{d}$ for feed, 60 l/d for water, and 0.5 $\text{kg}_{\text{soil}}/\text{d}$ for soil.
 - Goat – 6 $\text{kg}_{\text{wet}}/\text{d}$ for feed, 8 l/d for water, and 0.06 $\text{kg}_{\text{soil}}/\text{d}$ for soil.
- 5) Assume a forage yield of 0.7 $\text{kg}_{\text{wet}}/\text{m}^2$ for pastureland.
- 6) Assume a milk density of 1.0 $\text{kg}_{\text{wet}}/\text{l}$.
- 7) Assume a soil density of 1600 $\text{kg}_{\text{soil}}/\text{m}^3$.
- 8) Assume a mixing depth of 1.0E-03 m for the first growing season and 0.15 after plowing (EPA89).
- 9) Assume a time to market of 2 days.
- 10) Assume the animal consumes the contaminated feed/water over a period of time sufficient for the animal product intended for human consumption to reach equilibrium.

- 11) Assume that 100% of the contaminated pathway (feed or water) is contaminated.
- 12) Are calculated for food (milk or animal feed) as prepared for consumption. To compare with analytical results it may be necessary to convert to “dry weight,” see Method 5.2.
- 13) Use Crop Retention Factors for pastureland of:
 - 1.0 for radioiodine and
 - 0.5 for all other radionuclides.
- 14) DRLs for FDA grouped radionuclides (e.g., $^{134}\text{Cs}+^{137}\text{Cs}$) are adjusted for decay during Time to Market using the decay constant for the longest-lived group member.

Inputs

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

Data – Composition of the deposited radionuclide mixture (radionuclides and concentration). This information may come from predictive analysis (models) or field data (monitoring and/or samples).

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

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

Appropriate DIL for each radionuclide – Calculated using Method 4.1.

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

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

Outputs

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

Final

Milk_DRL_{*i*} = Ingestion Derived Response Level for Milk, expressed as one of the following:

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

- animal’s milk exceeding the Derived Intervention Level (DIL) for that radionuclide;
2. $Milk_DRL_{mass}$: The mass concentration ($\mu\text{Ci}/\text{kg}_{\text{wet}}$) of radionuclide i in animal feed that would result in the animal’s milk exceeding the Derived Intervention Level (DIL) for that radionuclide; or
 3. $Milk_DRL_{\text{water}}$: The water concentration ($\mu\text{Ci}/\text{l}$) of radionuclide i in an animal’s drinking water that would result in the animal’s milk exceeding the Derived Intervention Level (DIL) for that radionuclide.

Intermediate

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

None

Method 4.3.1 Ingestion DRL for Milk based on areal activity ($\mu\text{Ci}/\text{m}^2$) on forage

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

Calculation

Equation 4.3-1 shows this $Milk_DRL_{\text{area}}$ calculation.

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

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

where:

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

- $DIL_{organ, age, i}$ = Derived Intervention Level, the activity concentration level of radionuclide i at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to exceed the applicable ingestion PAG, $\mu\text{Ci}/\text{kg}_{\text{wet}}$;
- ρ_{milk} = Milk density, $\text{kg}_{\text{wet}}/\text{l}$;
- CRF = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop, unitless;
- $AFDIR$ = Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed, $\text{kg}_{\text{wet}}/\text{d}$;
- Y = Crop Yield, the mass of crop grown per area of land, $\text{kg}_{\text{wet}}/\text{m}^2$;
- $ASDIR$ = Animal Soil Daily Ingestion Rate, the daily rate at which an animal consumes soil, $\text{kg}_{\text{soil}}/\text{d}$;
- ρ_{soil} = Soil density, $\text{kg}_{\text{soil}}/\text{m}^3$;
- d_m = Mixing Depth, m;
- FDC_F = Fraction of Diet Contaminated (feed), the fraction of the animal's diet that is from contaminated feed (default 1.0), unitless;
- NOTE:** If there is convincing local information that the actual FDC is considerably different, local authorities may decide to use a different FDC .
- $TF_{\text{Milk}, A, i}$ = Transfer Factor for Milk, the fraction of radionuclide i consumed by an animal (A) that is transferred to the milk produced by the animal, $\mu\text{Ci}/\text{l}$ per $\mu\text{Ci}/\text{d}$;
- λ_i = Decay constant for the radionuclide i , d^{-1} ;
- t_m = Time to Market, the number of days from harvest to consumption (default 2), d; and
- $e^{-\lambda_i t_m}$ = Radioactive Decay adjustment for radionuclide i over time t_m , unitless.

Method 4.3.2 Ingestion DRL for Milk based on mass concentration ($\mu\text{Ci}/\text{kg}_{\text{wet}}$) in forage

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

Calculation

Equation 4.3-2 shows this $Milk_DRL_{\text{mass}}$ calculation.

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

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

where:

$Milk_DRL_{mass,A,i}$ = Ingestion Derived Response Level for Milk, the mass concentration of radionuclide i that will be expected to cause the milk produced by grazing animals (A) to exceed the Derived Intervention Level (DIL) for that radionuclide, $\mu\text{Ci}/\text{kg}_{\text{wet}}$;

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

ρ_{milk} = Milk density, $\text{kg}_{\text{wet}}/\text{l}$;

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

FDC_F = Fraction of Diet Contaminated (feed), the fraction of the animal's diet that is from contaminated feed (default 1.0), unitless;

NOTE: If there is convincing local information that the actual FDC is considerably different, local authorities may decide to use a different FDC .

$TF_{Milk,A,i}$ = Transfer Factor for Milk, the fraction of radionuclide i consumed by an animal (A) that is transferred to the milk produced by the animal, $\mu\text{Ci}/\text{l}$ per $\mu\text{Ci}/\text{d}$;

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

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

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

NOTE: Soil ingestion is not included in this method because any soil (and any radioactivity) included in the fodder being analyzed would inherently be included in the mass and activity values determined by the measurement process.

Method 4.3.3 Ingestion DRL for Milk based on concentration ($\mu\text{Ci}/\text{l}$) in water

This method calculates the concentration level ($\mu\text{Ci}/\text{l}$) of a radionuclide in an animal's drinking water that would result in the animal's milk exceeding the DIL for the radionuclide.

Calculation

Equation 4.3-3 shows this $Milk_DRL_{water}$ calculation.

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

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

where:

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

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

ρ_{milk} = Milk density, $\text{kg}_{\text{wet}}/\text{l}$;

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

FDC_W = Fraction of Diet Contaminated (water), the fraction of an animal's diet that is from contaminated water (default 1.0), unitless;

NOTE: If there is convincing local information that the actual FDC is considerably different, local authorities may decide to use a different FDC .

$TF_{Milk,A,i}$ = Transfer Factor for Milk, the fraction of radionuclide i consumed by an animal (A) that is transferred to the milk produced by the animal, $\mu\text{Ci}/\text{l}$ per $\mu\text{Ci}/\text{d}$;

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

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

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

NOTE: Soil ingestion is not included in this method because any soil (and any radioactivity) included in the water being analyzed would inherently be included in the mass and activity values determined by the measurement process.

EXAMPLE 1

Problem: Calculate the Cow Milk Ingestion DRL for ^{60}Co in units of areal activity ($\mu\text{Ci}/\text{m}^2$)

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

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

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

Assuming:

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

The $Milk_DRL_{area}$ for ^{60}Co for cow milk equals:

$$Milk_DRL_{area,cow,^{60}\text{Co}} = \frac{0.02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * 1.0 \frac{\text{kg}_{\text{wet}}}{\text{l}}}{\left[\left(\frac{0.5 * 50 \frac{\text{kg}_{\text{wet}}}{\text{d}}}{0.7 \frac{\text{kg}_{\text{wet}}}{\text{m}^2}} \right) + \frac{0.5 \frac{\text{kg}_{\text{soil}}}{\text{d}}}{1600 \frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 1.0\text{E}-03 \text{ m}} \right] * 1 * 3.0\text{E}-04 \frac{\mu\text{Ci}}{\mu\text{Ci}/\text{d}} * e^{-3.6\text{E}-04 \text{d}^{-1} * 2\text{d}}} = 1.85 \frac{\mu\text{Ci}}{\text{m}^2}$$

Therefore cows grazing in areas with ^{60}Co contamination on the ground greater than $1.85 \mu\text{Ci}/\text{m}^2$ have the potential to produce milk that would exceed the DIL. Milk that exceeds the DIL could produce a dose that exceeds the PAG when consumed by a 3 month old.

EXAMPLE 2

Problem: Calculate the Cow Milk Ingestion DRL for ^{60}Co in units of mass concentration ($\mu\text{Ci}/\text{kg}_{\text{wet}}$)

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

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

$$\text{Milk_DRL}_{\text{mass},A,i} = \frac{\text{DIL}_{\text{organ,age},i} * \rho_{\text{milk}}}{\text{AFDIR} * \text{FDC}_F * \text{TF}_{\text{Milk},A,i} * e^{-\lambda_i t_m}}$$

Assuming:

$$\begin{aligned} \rho_{\text{milk}} &= 1.0 \text{ kg}_{\text{wet}}/\text{l}, \\ \text{AFDIR}_{\text{cow}} &= 50 \text{ kg}_{\text{wet}}/\text{d}, \\ \text{FDC}_F &= 1.0, \\ \text{TF}_{\text{Milk,cow},^{60}\text{Co}} &= 3.0\text{E-}04 \mu\text{Ci}/\text{l per } \mu\text{Ci}/\text{d}, \\ \lambda_{\text{Co}} &= 3.60\text{E-}04 \text{ d}^{-1}, \text{ and} \\ t_m &= 2 \text{ days}. \end{aligned}$$

The $\text{Milk_DRL}_{\text{mass}}$ for ^{60}Co for cow milk equals:

$$\text{Milk_DRL}_{\text{mass,cow},^{60}\text{Co}} = \frac{0.02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * 1.0 \frac{\text{kg}_{\text{wet}}}{\text{l}}}{50 \frac{\text{kg}_{\text{wet}}}{\text{d}} * 1 * 3.0\text{E-}04 \frac{\mu\text{Ci}}{\mu\text{Ci}} \frac{1}{\text{d}} * e^{-3.6\text{E-}04 * 2}} = 1.33 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

Therefore cows that eat forage with ^{60}Co contamination greater than $1.33 \mu\text{Ci}/\text{kg}_{\text{wet}}$ have the potential to produce milk that would exceed the DIL. Milk that exceeds the DIL could produce a dose that exceeds the PAG when consumed by a 3 month old.

EXAMPLE 3

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

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

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

$$\text{Milk_DRL}_{\text{water},A,i} = \frac{\text{DIL}_{\text{organ,age},i} * \rho_{\text{milk}}}{\text{AWDIR} * \text{FDC}_W * \text{TF}_{\text{Milk},A,i} * e^{-\lambda_i t_m}}$$

Assuming:

$$\begin{aligned} \rho_{\text{milk}} &= 1.0 \text{ kg}_{\text{wet}}/\text{l}, \\ \text{AWDIR}_{\text{cow}} &= 60 \text{ l/d}, \\ \text{FDC}_W &= 1.0, \\ \text{TF}_{\text{Milk,cow},^{60}\text{Co}} &= 3.0\text{E-}04 \mu\text{Ci/l per } \mu\text{Ci/d}, \\ \lambda_{\text{Co}} &= 3.60\text{E-}04 \text{ d}^{-1}, \text{ and} \\ t_m &= 2 \text{ days} \end{aligned}$$

The $\text{Milk_DRL}_{\text{water}}$ for ^{60}Co for cow milk equals:

$$\text{Milk_DRL}_{\text{water,cow},^{60}\text{Co}} = \frac{0.02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * 1.0 \frac{\text{kg}_{\text{wet}}}{\text{l}}}{60 \frac{\text{l}}{\text{d}} * 1 * 3.0\text{E-}04 \frac{\mu\text{Ci}}{\mu\text{Ci/d}} * e^{-3.6\text{E-}04 * 2}} = 1.11 \frac{\mu\text{Ci}}{\text{l}}$$

Therefore cows that drink water with ^{60}Co contamination greater than $1.11 \mu\text{Ci/l}$ have the potential to produce milk that would exceed the DIL. Milk that exceeds the DIL could produce a dose that exceeds the PAG when consumed by a 3 month old.

METHOD 4.4 MEAT INGESTION DERIVED RESPONSE LEVEL

Application

This method has been developed to calculate Ingestion Derived Response Levels for radioactive material deposited on animal forage/water for the meat pathway.

The Meat Ingestion Derived Response Level:

- Represents:
 1. Meat_DRL_{area,A,i}: The ground concentration, or areal activity ($\mu\text{Ci}/\text{m}^2$), of radionuclide *i* deposited over a grazing area that would result in a grazing animal's (*A*) meat exceeding the Derived Intervention Level (DIL) for that radionuclide;
 2. Meat_DRL_{mass,A,i}: The mass concentration ($\mu\text{Ci}/\text{kg}_{\text{wet}}$), of radionuclide *i* in animal feed that would result in the animal's (*A*) meat exceeding the Derived Intervention Level (DIL) for that radionuclide; or
 3. Meat_DRL_{water,A,i}: The water concentration ($\mu\text{Ci}/\text{l}$), of radionuclide *i* in an animal's drinking water that would result in the animal's (*A*) meat exceeding the Derived Intervention Level (DIL) for that radionuclide.
- Is indirectly derived (through the DIL) from the PAG for radiological emergency planning established by the Food and Drug Agency (FDA) (FDA98). A projected or measured concentration value greater than the Meat_DRL indicates that the PAG has the potential to be exceeded.
- Is applied during the first year after an incident and based on the most sensitive population (age group) and target organ to provide a large margin of safety to the public.
- Is used to create data products and define contamination levels to assist decision makers in determining where it may be advisable to conduct sampling to evaluate the potential for implementing protective actions (e.g., sheltering livestock, embargos, special product handling).
- Is calculated using the DIL calculated in Method 4.1

Discussion

The Meat_DRL predicts the amount of radioactivity deposited either on an animal's grazing area ($\mu\text{Ci}/\text{m}^2$) or in an animal's feed or water ($\mu\text{Ci}/\text{kg}_{\text{wet}}$ or $\mu\text{Ci}/\text{l}$) that would cause the animal's meat to exceed the DIL.

Sampling efforts should concentrate on the area where the contamination is equal to the Meat_DRL to determine if the DIL has been exceeded in those areas. Protective actions (e.g., use of stored feed) should be considered in areas where the DIL is exceeded. Meat embargo protective actions should be considered after meat samples indicate that the DIL has actually been exceeded. FDA guidance permits food with radioactivity concentrations below the DIL to move in commerce without restriction. However the FDA and local decision makers have flexibility in whether to apply restrictions in special circumstances.

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

Assumptions

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

Meat DRLs:

- 1) Apply to individual radionuclides; there is no sum-of-fraction rule (except for the FDA-listed ^{103}Ru and ^{106}Ru).
- 2) Are based on the most restrictive DIL for each radionuclide based on age group and target organ. See Method 4.1 for DIL calculation assumptions.
- 3) Assume only one intake pathway is present (i.e., if forage/soil is contaminated, drinking water is clean).
- 4) Animal intake rates are assumed to be
 - Cow – 50 $\text{kg}_{\text{wet}}/\text{d}$ for feed, 60 l/d for water, and 0.5 $\text{kg}_{\text{soil}}/\text{d}$ for soil.
 - Goat – 6 $\text{kg}_{\text{wet}}/\text{d}$ for feed, 8 l/d for water, and 0.06 $\text{kg}_{\text{soil}}/\text{d}$ for soil.
- 5) Assume a forage yield of 0.7 $\text{kg}_{\text{wet}}/\text{m}^2$ for pastureland.
- 6) Assume a soil density of 1600 $\text{kg}_{\text{soil}}/\text{m}^3$.
- 7) Assume a mixing depth of 1.0E-03 m for the first growing season and 0.15 after plowing (EPA89).
- 8) Assume a half life of 15 days for material weathering off plant material.
- 9) Assume a time to market of 20 days.
- 10) Assume the animal consumes the contaminated feed/water over a period of time sufficient for the animal product intended for human consumption to reach equilibrium.
- 11) Assume that 100% of the contaminated pathway (feed or water) is contaminated.

- 12) Are calculated for food (meat or animal feed) as prepared for consumption. To compare with analytical results it may be necessary to convert to “dry weight,” see Method 5.2.
- 13) Uses Crop Retention Factors for pastureland of:
 - 1.0 for radioiodine and
 - 0.5 for all other radionuclides.
- 14) DRLs for FDA grouped radionuclides (e.g., $^{134}\text{Cs}+^{137}\text{Cs}$) are adjusted for decay during Grazing Time and Time to Market using the decay constant for the longest-lived group member.

Inputs

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

Data – Composition of the deposited radionuclide mixture (radionuclides and concentration). This information may come from predictive analysis (models) or field data (monitoring and/or samples).

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

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

Appropriate DIL for each radionuclide – Calculated using Method 4.1.

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

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

Outputs

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

Final

Meat_DRL_{*i*} = Ingestion Derived Response Level for Meat, expressed as one of the following:

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

2. Meat_DRL_{mass,A,i}: The mass concentration (μCi/kg_{wet}) of radionuclide *i* in animal feed that would result in the animal's (*A*) meat exceeding the Derived Intervention Level (DIL) for that radionuclide; or
3. Meat_DRL_{water,A,i}: The water concentration (μCi/l) of radionuclide *i* in an animal's drinking water that would result in the animal's (*A*) meat exceeding the Derived Intervention Level (DIL) for that radionuclide.

Intermediate

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

None

Method 4.4.1 Ingestion DRL for Meat based on areal activity (μCi/m²) on forage

This method calculates the areal activity level (μCi/m²) of a radionuclide deposited over a grazing area that would result in a grazing animal's meat exceeding the DIL for the radionuclide.

Calculation

Equation 4.4-1 shows this Meat_DRL_{area} calculation.

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

(Eq. 4.4-1)

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

where:

Meat_DRL_{area,A,i} = Ingestion Derived Response Level for Meat, the ground concentration, or areal activity, of radionuclide *i* that will be expected to cause the

meat from grazing animals (*A*) to exceed the Derived Intervention Level (DIL) for that radionuclide, $\mu\text{Ci}/\text{m}^2$;

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

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

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

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

$\left(\frac{1 - e^{-\lambda_w t_g}}{\lambda_w * t_g} \right)$ = Integrated average weathering of radioactive material off plants during

the time the animal is grazing in the field (the integral of the weathering over the Grazing Time divided by the Grazing Time), unitless;

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

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

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

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

d_m = Mixing Depth, m;

FDC_F = Fraction of Diet Contaminated (feed), the fraction of the animal's diet that is from contaminated feed (default 1.0), unitless;

NOTE: If there is convincing local information that the actual FDC is considerably different, local authorities may decide to use a different FDC .

$TF_{Meat, A, i}$ = Transfer Factor for Meat, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the meat of the animal, $\mu\text{Ci}/\text{kg}_{\text{wet}}$ per $\mu\text{Ci}/\text{d}$;

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

$\left(\frac{1 - e^{-\lambda_i t_g}}{\lambda_i * t_g} \right)$ = Integrated average decay of radioactive material during the time the

animal is grazing in the field (the integral of radioactive decay over the Grazing Time divided by the Grazing Time), unitless;

t_m = Time to Market, the number of days from harvest to consumption (default 20), d; and

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

Method 4.4.2 Ingestion DRL for Meat based on mass concentration ($\mu\text{Ci}/\text{kg}_{\text{wet}}$) in forage

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

Calculation

Equation 4.4-2 shows this *Meat_DRL_{mass}* calculation.

$$Meat_DRL_{mass,A,i} = \frac{DIL_{organ,age,i}}{AFDIR * FDC_F * TF_{Meat,A,i} * \left(\frac{1 - e^{-\lambda_w t_g}}{\lambda_w * t_g} \right) * \left(\frac{1 - e^{-\lambda_i t_g}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m}} \quad (\text{Eq. 4.4-2})$$

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

where:

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

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

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

FDC_F = Fraction of Diet Contaminated (feed), the fraction of an animal's diet that is from contaminated feed (default 1.0), unitless;

NOTE: If there is convincing local information that the actual *FDC* is considerably different, local authorities may decide to use a different *FDC*.

TF_{Meat,A,i} = Transfer Factor for Meat, the fraction of radionuclide *i* consumed by an animal (*A*) that is transferred to the meat of the animal, $\mu\text{Ci}/\text{kg}_{\text{wet}}$ per $\mu\text{Ci}/\text{d}$;

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

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

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

$\left(\frac{1 - e^{-\lambda_w t_g}}{\lambda_w * t_g} \right)$ = Integrated average weathering of radioactive material off plants during the time the animal is grazing in the field (the integral of the weathering over the Grazing Time divided by the Grazing Time), unitless;

$\left(\frac{1 - e^{-\lambda_i t_g}}{\lambda_i * t_g} \right)$ = Integrated average decay of radioactive material during the time the animal is grazing in the field (the integral of radioactive decay over the Grazing Time divided by the Grazing Time), unitless;

t_m = Time to Market, the number of days from harvest to consumption (default 20), d; and

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

NOTE: Soil ingestion is not included in this method because any soil (and any radioactivity) included in the fodder being analyzed would inherently be included in the mass and activity values determined by the measurement process.

Method 4.4.3 Ingestion DRL for Meat based on concentration ($\mu\text{Ci/l}$) in water

This method calculates the concentration level ($\mu\text{Ci/l}$) of a radionuclide in an animal's drinking water that would result in the animal's meat exceeding the DIL for the radionuclide.

NOTE: Because any form of "weathering" that could be applied to this calculation could vary by such a large amount (dependent on water source), and because not including weathering is the conservative approach, no consideration of physical removal of contamination from the drinking water is addressed in this method.

Calculation

Equation 4.4-3 shows this $Meat_DRL_{water}$ calculation.

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

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

where:

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

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

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

FDC_W = Fraction of Diet Contaminated (water), the fraction of an animal's diet that is from contaminated water (default 1.0), unitless;

NOTE: If there is convincing local information that the actual FDC is considerably different, local authorities may decide to use a different FDC .

$TF_{Meat,A,i}$ = Transfer Factor for Meat, the fraction of radionuclide i consumed by an animal (A) that is transferred to the meat of the animal, $\mu\text{Ci/kg}_{\text{wet}}$ per $\mu\text{Ci/d}$;

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

t_g = Grazing Time, time from deposition or sampling to the end of the grazing period, 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 (default 20), d ; and

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

NOTE: Soil ingestion is not included in this method because any soil (and any radioactivity) included in the water being analyzed would inherently be included in the mass and activity values determined by the measurement process.

EXAMPLE 1

Problem: Calculate the Meat (Beef) Ingestion DRL for ^{60}Co in units of areal activity ($\mu\text{Ci}/\text{m}^2$)

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

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

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

Assuming:

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

The $Meat_DRL_{area}$ for ^{60}Co for Beef equals:

$$\begin{aligned} Meat_DRL_{area,cow,^{60}\text{Co}} &= \frac{0.02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}}{\left[\frac{\left(0.5 * \frac{1-e^{-4.62\text{E-}02\text{d}^{-1} * 90\text{d}}}{4.62\text{E-}02\text{d}^{-1} * 90\text{d}} * 50 \frac{\text{kg}_{\text{wet}}}{\text{d}} \right)}{0.7 \frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \frac{0.5 \frac{\text{kg}_{\text{soil}}}{\text{d}}}{1600 \frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 1.0\text{E-}03 \text{ m}} \right] * 1 * 1.0\text{E-}02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} * \frac{1-e^{-3.6\text{E-}04\text{d}^{-1} * 90\text{d}}}{3.6\text{E-}04\text{d}^{-1} * 90\text{d}} * e^{-3.6\text{E-}04 * 20}} \\ &= 0.232 \frac{\mu\text{Ci}}{\text{m}^2} \end{aligned}$$

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

EXAMPLE 2

Problem: Calculate the Meat (Beef) Ingestion DRL for ^{60}Co in units of mass concentration ($\mu\text{Ci}/\text{kg}_{\text{wet}}$)

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

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

$$\text{Meat_DRL}_{\text{mass},A,i} = \frac{\text{DIL}_{\text{organ,age},i}}{\text{AFDIR} * \text{FDC}_F * \text{TF}_{\text{Meat},A,i} * \left(\frac{1 - e^{-\lambda_w t_g}}{\lambda_w * t_g} \right) * \left(\frac{1 - e^{-\lambda_i t_g}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m}}$$

Assuming:

$$\begin{aligned} \text{AFDIR}_{\text{cow}} &= 50 \text{ kg}_{\text{wet}}/\text{d}, \\ \text{FDC}_F &= 1.0, \\ \text{TF}_{\text{Meat,cow},^{60}\text{Co}} &= 1.0\text{E-}02 \mu\text{Ci}/\text{kg}_{\text{wet}} \text{ per } \mu\text{Ci}/\text{d}, \\ \lambda_w &= 4.62\text{E-}02 \text{ d}^{-1}, \\ t_g &= 90 \text{ d}, \\ \lambda_{\text{Co}} &= 3.60\text{E-}04 \text{ d}^{-1}, \text{ and} \\ t_m &= 20 \text{ days} \end{aligned}$$

The $\text{Meat_DRL}_{\text{mass}}$ for ^{60}Co for Beef equals:

$$\begin{aligned} \text{Meat_DRL}_{\text{mass,cow},^{60}\text{Co}} &= \frac{0.02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}}{50 \frac{\text{kg}_{\text{wet}}}{\text{d}} * 1 * 1.0\text{E-}02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}/\text{d}} * \frac{1 - e^{-4.62\text{E-}02 \text{d}^{-1} * 90\text{d}}}{4.62\text{E-}02 \text{d}^{-1} * 90\text{d}} * \frac{1 - e^{-3.6\text{E-}04 \text{d}^{-1} * 90\text{d}}}{3.6\text{E-}04 \text{d}^{-1} * 90\text{d}} * e^{-3.6\text{E-}04 * 20}} \\ &= 0.172 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} \end{aligned}$$

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

EXAMPLE 3

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

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

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

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

Assuming:

$$\begin{aligned} AWDIR_{\text{cow}} &= 60 \text{ l/d,} \\ FDC_W &= 1.0, \\ TF_{\text{Meat,cow},^{60}\text{Co}} &= 1.0\text{E-}02 \mu\text{Ci/kg}_{\text{wet}} \text{ per } \mu\text{Ci/d,} \\ \lambda_{\text{Co}} &= 3.60\text{E-}04 \text{ d}^{-1}, \\ t_g &= 90 \text{ d, and} \\ t_m &= 20 \text{ days} \end{aligned}$$

The $\text{Meat_DRL}_{\text{water}}$ for ^{60}Co for Beef equals:

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

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

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METHOD 4.5 INGESTION DOSE

Application

This method has been developed to calculate the Ingestion Dose from the consumption of radioactive material, either in food, milk or water.

The Ingestion Dose:

- Can be applied to the whole body (E_{50}) or to a specific organ ($H_{T,50}$)
- Uses sample results for various food types to calculate the dose that a receptor is projected to receive over a specified time phase (generally 1 year) due to ingestion of the contaminated food.
- Is used to define dose levels to assist decision makers in determining where it may be advisable to implement protective actions (e.g. sheltering livestock, embargos, special product handling).

Discussion

The Ingestion Dose method calculates the expected dose from consuming foods contaminated by radioactive material and is obtained by combining sample results ($\mu\text{Ci}/\text{kg}$ or $\mu\text{Ci}/\text{l}$) for various food types to produce a total projected dose from the entire diet. Food types generally fall into 4 groups (shown with subgroups):

- Meat/Fish (Beef, Pork, Poultry, Fin Fish, Shell Fish, Other Meat);
- Crop/Produce (Leafy, Exposed, Protected, Other Produce, Breads, Cereals, Other Grains);
- Milk (Fresh Cow's Milk, Other Dairy, Eggs); and
- Beverages (Tap Water, Water Based Drinks, Soups, Other Beverages).

Assumptions

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

- 1) Annual intake for each group and subgroup of foods varies by age group (3 month, 1 yr, 5 yr, 10 yr, 15 yr and adult) (FDA98). If specific intake rates are known, use those instead of defaults.

- 2) Dose calculations are based on samples of foods as prepared for consumption and assume a consumption period of 1 year. To compare with analytical results it may be necessary to convert to “dry weight,” see Method 5.2.
- 3) Inadvertent ingestion of soil is not included in these methods. Activity contained in any soil present in the food would be accounted for in the sample analysis process. Inadvertent Soil Ingestion is discussed in Method 4.7.
- 4) Default calculations utilize the International Commission on Radiological Protection (ICRP) 60+ dosimetry model.

Inputs

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

- Data – Activity concentration ($\mu\text{Ci}/\text{kg}$ or $\mu\text{Ci}/\text{l}$) from sample analysis data.
- Constants – Fraction of food contaminated, daily food intake rate, ingestion dose coefficient.
- Other Factors – Decay of radionuclides from sampling time to consumption time (hold time) and over the duration of consumption (default consumption period is 1 year).

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

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

Outputs

The final output of this method is the Ingestion Dose for a diet including food sources that have been contaminated by a deposition of radioactive material.

Final

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

$H_{T,50}$ = Committed Equivalent Dose, the dose to organ “t”, received by the receptor under consideration over the commitment period, from the ingestion of all radionuclides in contaminated food, mrem

Intermediate

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

IngDP = Ingestion Dose Parameter for a specific food type for the age group under consideration (mrem·d/kg_{wet})

Method 4.5.1 Calculation of Committed Effective Dose

The Ingestion Dose calculation includes contributions from each type of contaminated food at its individual contamination level and appropriate intake rates (averaged over each subgroup). Food contamination levels are decay adjusted for:

- the time between sample evaluation and consumption (hold time) and
- the duration of consumption (default of 1 year).

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

Equation 4.5-1 represents the final form of the Ingestion Dose calculation:

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

$$mrem = \sum_{Subgroup} \left(\frac{kg_{wet}}{d} * \frac{mrem \cdot d}{kg_{wet}} \right)$$

where:

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

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

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

4.5.1.1 Calculation of IngDP

Equation 4.5-2 shows the calculation of the individual $IngDP_{E,f,age}$ for each type of contaminated food. These values should be averaged with all other food types in a subgroup to determine the $IngDP_{avg,age}$ for each food subgroup. For example, if the diet includes 3 food types from the “protected” subgroup of the crop/produce group (e.g., corn, carrots, oranges) then sum the IngDPs for each food type and divide by 3 to determine the average Ingestion Dose Parameter for the subgroup.

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

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

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

where:

- $IngDP_{E,f,age}$ = Ingestion Dose Parameter, the committed effective dose received by the whole body (E) over the commitment period, from ingestion of all radionuclides in a specific food type (f) by a specific age group, mrem·d/kg_{wet};
- $C_{f,i}$ = Food Contamination, the level of contamination of radionuclide i in a specific food type (f), $\mu\text{Ci}/\text{kg}_{\text{wet}}$ or $\mu\text{Ci}/\text{l}$;
- $FFC_{f,i}$ = Fraction of Food Type Contaminated, (default 1.0), unitless;
NOTE: If there is convincing local information that the actual FFC is considerably different, local authorities may decide to use a different FFC .
- $IngDC_{E,age,i}$ = Ingestion Dose Coefficient, the ingestion pathway dose coefficient for the whole body (E) for the age group under consideration for radionuclide i , mrem/ μCi ;
- 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 from sample measurement to the beginning of the consumption period, unitless;
- t_c = Consumption Time, the length of the consumption period (default 365 days), d;
- $\frac{1 - e^{-\lambda_i t_c}}{\lambda_i}$ = Integrated decay over the length of consumption period, d.

Method 4.5.2 Calculation of Equivalent Dose to an Organ

The preceding calculations assume that the organ of interest is the whole body. The generic approach can be modified to calculate a dose for a specific organ (e.g., skin, thyroid, etc.).

To calculate the dose to a specific organ, replace the $IngDC$ for the whole body with the $IngDC$ for the specific organ when calculating the $IngDP$.

EXAMPLE 1

Problem: Calculate the Whole Body Ingestion Dose received by an adult from consuming food contaminated with ¹³⁷Cs and ⁶⁰Co for 1 year beginning 100 days after sampling.

Assume food samples were collected for several food types with results as shown below:

Table 4.5-E1

Food Type	⁶⁰ Co (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 4.5-2

Table 4.5-E2 shows the values needed to calculate the individual IngDP for each food type.

Table 4.5-E2

Radionuclide	IngDC (mrem/μCi)	λ (days ⁻¹)	e ^{-λt_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
 Fraction of Food Contaminated (FFC): 1.0 (default)

Example IngDP calculation for Beef and IngDP values for the other contaminated food types (Table 4.5-E3):

$$\begin{aligned}
 IngDP_{E,Beef,Adult} &= 2.5E-03 \frac{\mu Ci}{kg_{wet}} * 1.0 * 1.0 * 12.7 \frac{mrem}{\mu Ci} * 0.965 * 342 \text{ d} \\
 &\quad + 4.0E-03 \frac{\mu Ci}{kg_{wet}} * 1.0 * 1.0 * 50.3 \frac{mrem}{\mu Ci} * 0.993 * 361 \text{ d} \\
 &= 82.6 \frac{mrem \cdot d}{kg_{wet}}
 \end{aligned}$$

Table 4.5-E3

Food Type	Sub-group	IngDP (mrem·d/kg _{wet})
Beef	Beef	82.6
Corn	Protected Crop	20.7
Lettuce	Leafy Crop	189
Milk	Cow's Milk	62.3
Oranges	Protected Crop	3.45
Water	Tap Water	23.7

E1.2 Calculating Ingestion Dose using Equation 4.5-1

Obtain the Ingestion Dose for each subgroup by multiplying the IngDP for the subgroup by the associated Daily Food Intake Rate (DFIR), and then add up the subgroup doses to obtain the Committed Effective Dose (E_{50}) as shown in Table 4.5-E4.

Table 4.5-E4

Food Type	Sub-group	IngDP (mrem·d/kg _{wet})	Daily Food Intake Rate (kg _{wet} /d) ^a	Subgroup Ingestion Dose (mrem)
Beef	Beef	82.6	0.098	8.09
Corn/Oranges	Protected Crop	12.1 ^b	0.155	1.88
Lettuce	Leafy Crop	189	0.042	7.94
Milk	Cow's Milk	62.3	0.238	14.8
Water	Tap Water	23.7	0.679	16.1
E_{50} (Σ)				48.8
^a Assumes a density of 1.04 kg/l for milk and 1.0 kg/l for water. ^b Average value for all the food types in the subgroup. NOTE: When individual food-type DFIRs are known, they may be used and multiplied by the individual food-type IngDP.				

E1.3 Calculating an Ingestion Dose for an individual organ or for a different age group

To calculate a Committed Equivalent Dose ($H_{T,50}$) for a specific organ and/or different age group, use the appropriate IngDC for the organ/age group and calculate as demonstrated above.

METHOD 4.6 PROJECTING CONTAMINATION LEVELS IN FOOD

Application

This method has been developed to project potential contamination levels in food (C_f) based on a measured or projected deposition of radioactive material on the ground.

The contamination levels in food:

- Can be used to determine potential doses to individuals consuming the food when results from direct sampling of the food are not available.
- Uses deposition data to project potential contamination levels in crops, milk and meat.
- Is used to define dose levels to assist decision makers in determining where it may be advisable to implement protective actions (e.g. sheltering livestock, embargos, special product handling).

Discussion

This method projects the potential contamination levels in food using projected or measured deposition (areal activity) values ($\mu\text{Ci}/\text{m}^2$). Calculations will be shown for food crops harvested from contaminated ground and for milk and meat from animals grazing on contaminated forage.

Assumptions

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

- 1) All deposition values used are for the time of deposition ($t=0$).
- 2) A time to market of 1 day for fresh produce, 2 days for milk and 20 days for meat.
- 3) A crop yield of $2 \text{ kg}_{\text{wet}}/\text{m}^2$ for fresh produce.
- 4) Calculations are for food (crops, meat, milk, or animal feed) as prepared for consumption. To compare with analytical results it may be necessary to convert to “dry weight,” see Method 5.2.
- 5) Crop Retention Factors for fresh produce of:
 - 1.0 for radioiodine and
 - 0.2 for all other radionuclides.
- 6) Animal intake rates:

- Cow – 50 kg_{wet}/d for feed, 60 l/d for water, and 0.5 kg_{soil}/d for soil.
 - Goat – 6 kg_{wet}/d for feed, 8 l/d for water, and 0.06 kg_{soil}/d for soil.
- 7) A forage yield of 0.7 kg_{wet}/m² for pastureland.
 - 8) Crop Retention Factors for pastureland of:
 - 1.0 for radioiodine and
 - 0.5 for all other radionuclides.
 - 9) Assume a soil density of 1600 kg_{soil}/m³.
 - 10) Assume a mixing depth of 1.0E-03 m for the first growing season and 0.15 after plowing (EPA89).
 - 11) The animal consumes the contaminated feed/water over a period of time sufficient for the animal product intended for human consumption to reach equilibrium.

Inputs

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

- Data – Composition of the deposited radionuclide mixture (radionuclides and concentration). This information may come from predictive analysis (models) or field data (monitoring and/or samples).
- Constants – Crop Retention Factor, Crop Yield, Animal Daily Intake Rates (Feed, Water, Soil), Transfer Factor for milk for each radionuclide, Transfer Factor for meat for each radionuclide.
- Other Factors – Decay of radionuclides during the time period under consideration, fraction of animals' diet contaminated, soil mixing depth.

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

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

Outputs

The final output of this method is the projected contamination levels in foods that have been affected by a deposition of radioactive material.

Final

C_{crop} = Projected Contamination level in a food Crop (fresh produce), the level of activity per mass in a food type harvested from contaminated ground, $\mu\text{Ci}/\text{kg}_{\text{wet}}$;

- C_{milk} = Projected Contamination level in Milk, the level of activity per volume in milk produced from consuming radioactive material, $\mu\text{Ci/l}$; and
- C_{meat} = Projected Contamination level in Meat, the level of activity per mass in meat produced from consuming radioactive material, $\mu\text{Ci/kg}_{\text{wet}}$.

Intermediate

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

Values calculated by this method may be used in Method 4.5 to calculate ingestion dose when food samples are not available.

Method 4.6.1 Calculation of Contamination in Crops

NOTE: Weathering Factor is not included in this calculation because the food supply is constantly being added to from available sources, using the initial (unweathered) deposition provides a conservative evaluation of the potential contamination in food types regardless of when they are placed into the supply.

Equation 4.6-1 shows the calculation for determining the amount of contamination that would be expected in a crop based on the deposition (areal activity) on the ground:

$$C_{crop,i} = \frac{Dp_i * CRF}{Y} * e^{-\lambda_i t_m} \quad (\text{Eq. 4.6-1})$$

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

where:

- $C_{crop,i}$ = Projected Contamination level in a food Crop (fresh produce), the level of activity of radionuclide i per mass in a food type harvested from contaminated ground, $\mu\text{Ci/kg}_{\text{wet}}$;
- $Dp_{i(m)}$ = Deposition, the areal activity of a marker radionuclide $i(m)$ per unit area of ground at t_0 (deposition), $\mu\text{Ci/m}^2$;
- CRF = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop, unitless; and
- Y = Crop Yield, the mass of crop grown per area of land, $\text{kg}_{\text{wet}}/\text{m}^2$; and
- λ_i = Decay constant for the radionuclide i , d^{-1} ;
- t_m = Time to Market, the number of days from harvest to consumption (default 1), d; and
- $e^{-\lambda_i t_m}$ = Radioactive Decay adjustment for radionuclide i over time t_m , unitless.

Method 4.6.2 Calculation of Contamination in Milk

Equation 4.6-2a shows the calculation for determining the amount of contamination that would be expected in milk based on areal contamination of pastureland and contamination in the drinking water of the animal.

$$C_{milk,i} = \left\{ \begin{aligned} & Dp_i * \left[\frac{(CRF * AFDIR)}{Y} + \frac{ASDIR}{\rho_{soil} * d_m} \right] * FDC_F \\ & + [AWDIR * FDC_W * C_W] \end{aligned} \right\} * TF_{Milk,A,i} * e^{-\lambda_i t_m} \quad (\text{Eq. 4.6-2a})$$

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

where:

- $C_{milk,i}$ = Projected Contamination level in Milk, the level of activity of radionuclide i per volume in milk produced from animals consuming radioactive material, $\mu\text{Ci}/\text{l}$;
- CRF = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop (default 0.5 for pastureland), unitless;
- $AFDIR$ = Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed, $\text{kg}_{\text{wet}}/\text{d}$;
- Y = Crop Yield, the mass of crop grown per area of land, $\text{kg}_{\text{wet}}/\text{m}^2$;
- $ASDIR$ = Animal Soil Daily Ingestion Rate, the daily rate at which an animal consumes soil, $\text{kg}_{\text{soil}}/\text{d}$;
- ρ_{soil} = Soil density, $\text{kg}_{\text{soil}}/\text{m}^3$;
- d_m = Mixing Depth, m;
- FDC_F = Fraction of the animals' Diet Contaminated (feed), unitless;
- Dp_i = Deposition, the areal radioactivity of radionuclide i per unit area of ground, $\mu\text{Ci}/\text{m}^2$;
- $AWDIR$ = Animal Water Daily Ingestion Rate, the daily rate at which an animal consumes water, l/d;
- FDC_W = Fraction of the animals' Diet Contaminated (water), unitless;
- C_W = Contamination level in drinking water, $\mu\text{Ci}/\text{l}$;
- $TF_{Milk,A,i}$ = Transfer Factor for milk, the fraction of radionuclide i consumed by an animal (A) that is transferred to the milk produced by the animal, $\mu\text{Ci}/\text{l}$ per $\mu\text{Ci}/\text{d}$;
- λ_i = Decay constant for the radionuclide i , d^{-1} ;

t_m = Time to Market, the number of days from harvest to consumption (default 2), d; and
 $e^{-\lambda_i t_m}$ = Radioactive Decay adjustment for radionuclide i over time t_m , unitless.

If the contamination level in the soil is known ($\mu\text{Ci}/\text{kg}_{\text{soil}}$) the equation can be rewritten as shown in Equation 4.6-2b.

$$C_{\text{milk},i} = \left\{ \frac{(Dp_i * CRF * AFDIR * FDC_F) + (ASDIR * C_S)}{Y} + (AWDIR * FDC_W * C_W) \right\} * TF_{\text{Milk},A,i} * e^{-\lambda_i t_m} \quad (\text{Eq. 4.6-2b})$$

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

where:

C_S = Contamination level in soil, $\mu\text{Ci}/\text{kg}_{\text{soil}}$;

Method 4.6.3 Calculation of Contamination in Meat

Equation 4.6-3a shows the calculation for determining the amount of contamination that would be expected in meat based on areal contamination of pastureland and contamination in the drinking water of the animal.

$$C_{\text{meat},i} = \left\{ Dp_i * \left[\frac{\left(CRF * \left(\frac{1 - e^{-\lambda_w t_g}}{\lambda_w * t_g} \right) * AFDIR \right)}{Y} + \frac{ASDIR}{\rho_{\text{soil}} * d_m} \right] * FDC_F \right\} * TF_{\text{Meat},A,i} * \left(\frac{1 - e^{-\lambda_i t_g}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m} \quad (\text{Eq. 4.6-3a})$$

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

where:

- $C_{meat,i}$ = Projected Contamination level in Meat, the level of activity of radionuclide i per mass in an animal's meat from consuming radioactive material, $\mu\text{Ci}/\text{kg}_{\text{wet}}$;
- CRF = Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop (default 0.5 for pastureland), unitless;
- t_g = Grazing Time, time from deposition or sampling to the end of the grazing period, d;
- λ_w = Decay constant for weathering radioactive material off plants (default 4.62E-02, corresponds to a 15 day half life), d^{-1} ;
- $\left(\frac{1-e^{-\lambda_w t_g}}{\lambda_w * t_g}\right)$ = Integrated average weathering of radioactive material off plants during the time the animal is grazing in the field (the integral of the weathering over the Grazing Time divided by the Grazing Time), unitless;
- $AFDIR$ = Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed, $\text{kg}_{\text{wet}}/\text{d}$;
- Y = Crop Yield, the mass of crop grown per area of land, $\text{kg}_{\text{wet}}/\text{m}^2$;
- $ASDIR$ = Animal Soil Daily Ingestion Rate, the daily rate at which an animal consumes soil, $\text{kg}_{\text{soil}}/\text{d}$;
- ρ_{soil} = Soil density, $\text{kg}_{\text{soil}}/\text{m}^3$;
- d_m = Mixing Depth, m;
- FDC_F = Fraction of the animals' Diet Contaminated (feed), unitless;
- Dp_i = Deposition, the areal radioactivity of radionuclide i per unit area of ground, $\mu\text{Ci}/\text{m}^2$;
- $AWDIR$ = Animal Water Daily Ingestion Rate, the daily rate at which an animal consumes water, l/d;
- FDC_W = Fraction of the animals' Diet Contaminated (water), unitless;
- C_W = Contamination level in drinking water, $\mu\text{Ci}/\text{l}$;
- $TF_{Meat,A,i}$ = Transfer Factor for meat, the fraction of radionuclide i consumed by an animal (A) that is transferred to the meat of the animal, $\mu\text{Ci}/\text{kg}_{\text{wet}}$ per $\mu\text{Ci}/\text{d}$;
- λ_i = Decay constant for the radionuclide i , d^{-1} ;
- $\left(\frac{1-e^{-\lambda_i t_g}}{\lambda_i * t_g}\right)$ = Integrated average decay of radioactive material during the time the animal is grazing in the field (the integral of radioactive decay over the Grazing Time divided by the Grazing Time), unitless;
- t_m = Time to Market, the number of days from harvest to consumption, d; and
- $e^{-\lambda_i t_m}$ = Radioactive Decay adjustment for radionuclide i over time t_m , unitless.

If the contamination level in the soil is known ($\mu\text{Ci}/\text{kg}_{\text{soil}}$) the equation can be rewritten as shown in Equation 4.6-3b.

$$C_{meat,i} = \left\{ \frac{\left(Dp_i * CRF * \left(\frac{1 - e^{-\lambda_w t_g}}{\lambda_w * t_g} \right) * AFDIR * FDC_F \right)}{Y} + (ASDIR * C_S) \right\} * TF_{Meat,A,i} * \left(\frac{1 - e^{-\lambda_i t_m}}{\lambda_i * t_g} \right) * e^{-\lambda_i t_m}$$

(Eq. 4.6-3b)

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

$$+ \left(\frac{1}{d} * \text{unitless} * \frac{\mu Ci}{l} \right)$$

where:

C_S = Contamination level in soil, $\mu Ci/kg_{soil}$;

EXAMPLE 1

Problem: Calculate the projected contamination levels for a lettuce crop from an area with a deposition of ^{60}Co .

Assuming a deposition (areal activity) of ^{60}Co of $4.0\text{E-}03 \mu\text{Ci}/\text{m}^2$, Equation 4.6-1 can be used to predict the contamination level in the lettuce crop.

$$C_{crop,i} = \frac{Dp_i * CRF}{Y} * e^{-\lambda_i t_m}$$

Assuming:

$$\begin{aligned} CRF &= 0.2 \text{ (fresh produce),} \\ Y &= 2.0 \text{ kg}_{\text{wet}}/\text{m}^2 \text{ (fresh produce),} \\ \lambda_{Co} &= 3.60\text{E-}04 \text{ d}^{-1}, \text{ and} \\ t_m &= 1 \text{ day.} \end{aligned}$$

$$C_{\text{lettuce},^{60}\text{Co}} = \frac{4.0\text{E-}03 \frac{\mu\text{Ci}}{\text{m}^2} * 0.2}{2.0 \frac{\text{kg}_{\text{wet}}}{\text{m}^2}} * e^{-3.6\text{E-}04 * 1} = 4.0\text{E-}04 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

EXAMPLE 2

Problem: Calculate the projected contamination levels for cow's milk from an area with a deposition of ^{60}Co .

Assume a deposition (areal activity) of ^{60}Co of $4.0\text{E-}03 \mu\text{Ci}/\text{m}^2$ and a water concentration value of $3.0\text{E-}05 \mu\text{Ci}/\text{l}$.

Equation 4.6-2 can be used to calculate the contamination level in the cow's milk.

$$C_{\text{milk},i} = \left\{ \begin{aligned} & Dp_i * \left[\frac{(CRF * AFDIR)}{Y} + \frac{ASDIR}{\rho_{\text{soil}} * d_m} \right] * FDC_F \\ & + [AWDIR * FDC_W * C_W] \end{aligned} \right\} * TF_{\text{Milk},A,i} * e^{-\lambda_i t_m}$$

Assuming:

$$\begin{aligned} CRF &= 0.5 \text{ (pasture),} \\ AFDIR_{\text{cow}} &= 50 \text{ kg}_{\text{wet}}/\text{d}, \\ Y &= 0.7 \text{ kg}_{\text{wet}}/\text{m}^2 \text{ (pasture),} \\ ASDIR_{\text{cow}} &= 0.5 \text{ kg}_{\text{soil}}/\text{d}, \\ \rho_{\text{soil}} &= 1600 \text{ kg}_{\text{soil}}/\text{m}^3, \\ d_m &= 1.0\text{E-}03 \text{ m}, \\ FDC_F &= 1.0, \\ AWDIR_{\text{cow}} &= 60 \text{ l/d}, \\ FDC_W &= 1.0, \\ TF_{\text{Milk},\text{cow},^{60}\text{Co}} &= 3.0\text{E-}04 \mu\text{Ci}/\text{l per } \mu\text{Ci}/\text{d}, \\ \lambda_{\text{Co}} &= 3.60\text{E-}04 \text{ d}^{-1}, \text{ and} \\ t_m &= 2 \text{ days.} \end{aligned}$$

$$\begin{aligned} C_{\text{milk},^{60}\text{Co}} &= \left\{ \begin{aligned} & \left[\frac{\left(\frac{0.5 * 50 \text{ kg}_{\text{wet}}}{\text{d}} \right)}{0.7 \frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \frac{0.5 \frac{\text{kg}_{\text{soil}}}{\text{d}}}{1600 \frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 1.0\text{E-}03\text{m}} \right] * 1 * 4.0\text{E-}03 \frac{\mu\text{Ci}}{\text{m}^2} \\ & + \left[60 \frac{\text{l}}{\text{d}} * 1 * 3.0\text{E-}05 \frac{\mu\text{Ci}}{\text{l}} \right] \end{aligned} \right\} * 3.0\text{E-}04 \frac{\mu\text{Ci}}{\mu\text{Ci}/\text{d}} * e^{-3.6\text{E-}04 * 2} \\ &= 4.4\text{E-}05 \frac{\mu\text{Ci}}{\text{l}} \end{aligned}$$

EXAMPLE 3

Problem: Calculate the projected contamination levels for beef from an area with a deposition of ^{60}Co .

Assume a deposition (areal activity) of ^{60}Co of $4.0\text{E-}03 \mu\text{Ci/m}^2$ and a water concentration value of $3.0\text{E-}05 \mu\text{Ci/l}$.

Assuming that the cow will continue to graze on the contaminated field for 90 days after deposition, Equation 4.6-3 can be used to calculate the contamination level in the cow's meat.

$$C_{meat,i} = \left\{ Dp_i * \left[\frac{\left(CRF * \left(\frac{1 - e^{-\lambda_w t_g}}{\lambda_w * t_g} \right) * AFDIR \right)}{Y} + \frac{ASDIR}{\rho_{soil} * d_m} \right] * FDC_F \right\} * TF_{Meat,A,i} * \left(\frac{1 - e^{-\lambda_i t_m}}{\lambda_i * t_m} \right) * e^{-\lambda_i t_m} + [AWDIR * FDC_W * C_W]$$

Assuming:

$$\begin{aligned} CRF &= 0.5 \text{ (pasture)}, \\ \lambda_w &= 4.62\text{E-}02 \text{ d}^{-1}, \\ t_g &= 90 \text{ d}, \\ AFDIR_{cow} &= 50 \text{ kg}_{wet}/\text{d}, \\ Y &= 0.7 \text{ kg}_{wet}/\text{m}^2 \text{ (pasture)}, \\ ASDIR_{cow} &= 0.5 \text{ kg}_{soil}/\text{d}, \\ \rho_{soil} &= 1600 \text{ kg}_{soil}/\text{m}^3, \\ d_m &= 1.0\text{E-}03 \text{ m}, \\ FDC_F &= 1.0, \\ AWDIR_{cow} &= 60 \text{ l/d}, \\ FDC_W &= 1.0, \\ TF_{Meat,cow,60Co} &= 1.0\text{E-}02 \mu\text{Ci}/\text{kg}_{wet} \text{ per } \mu\text{Ci}/\text{d}, \\ \lambda_{Co} &= 3.60\text{E-}04 \text{ d}^{-1}, \text{ and} \\ t_m &= 20 \text{ days}. \end{aligned}$$

$$\begin{aligned}
 C_{beef, {}^{60}\text{Co}} &= \left\{ \left[\frac{\left(0.5 * \frac{1 - e^{-4.62E-02d^{-1} * 90d}}{4.62E-02d^{-1} * 90d} * 50 \frac{\text{kg}_{\text{wet}}}{\text{d}} \right)}{0.7 \frac{\text{kg}_{\text{wet}}}{\text{m}^2}} + \frac{0.5 \frac{\text{kg}_{\text{soil}}}{\text{d}}}{1600 \frac{\text{kg}_{\text{soil}}}{\text{m}^3} * 1.0E-03\text{m}} \right] * 1 * 4.0E-03 \frac{\mu\text{Ci}}{\text{m}^2} \right. \\
 &\quad \left. + \left[60 \frac{1}{\text{d}} * 1 * 3.0E-05 \frac{\mu\text{Ci}}{1} \right] \right. \\
 &\quad \left. * 1.0E-02 \frac{\mu\text{Ci}}{\mu\text{Ci}/\text{d}} * \frac{1 - e^{-3.6E-04d^{-1} * 90d}}{3.6E-04d^{-1} * 90d} * e^{-3.6E-04 * 20} \right. \\
 &= 3.6E-04 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}
 \end{aligned}$$

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METHOD 4.7 DOSE FROM INADVERTENT SOIL INGESTION

Application

This method calculates the Ingestion Dose from the inadvertent consumption of soil that has been contaminated with radioactive material.

The Ingestion Dose Method:

- Can be applied to the whole body (E_{50}) or to a specific organ ($H_{T,50}$)
- Uses monitoring results of areal activity to calculate the dose that a receptor is projected to receive over a specified time phase (generally 1 year) due to ingestion of the contaminated soil.
- Is used to define dose levels to assist decision makers in determining where it may be advisable to implement protective actions.

Discussion

This method calculates the projected dose from the inadvertent ingestion of soil contaminated by radioactive material and is calculated by evaluating ground monitoring results ($\mu\text{Ci}/\text{m}^2$). Ingestion of contaminated dirt can occur when surface contamination is transferred from a surface to hands, toys, cigarettes, etc.

Generally the contribution of this pathway is minor. However, it can become significant and even dominant in certain special cases. One such case is for long-term residence or outdoor work in areas contaminated with aged plutonium in surface soil.

If the dose from this pathway exceeds 10% of the appropriate EPA PAG for the Time Phase, it should be included in a decision for protective actions.

Assumptions

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

- 1) Default soil intake rates are $5.0\text{E-}05 \text{ kg}_{\text{soil}}/\text{day}$ for adults and $1.0\text{E-}04 \text{ kg}_{\text{soil}}/\text{day}$ for children (EPA97a). This method uses the conservative value of $1.0\text{E-}04 \text{ kg}_{\text{soil}}/\text{day}$ for all calculations. If specific intake rates are known, use those instead of defaults.
- 2) Soil density of $1600 \text{ kg}_{\text{soil}}/\text{m}^3$.

- 3) Mixing depth of 1.0E-03 m for the surface layer of contaminated soil and 1.0E-04 m for the layer of dust over pavement (EPA89). This method uses the conservative value of 1.0E-04 m for all calculations.
- 4) Default calculations utilize the International Commission on Radiological Protection (ICRP) 60+ dosimetry model.

Inputs

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

- Data – Areal concentration ($\mu\text{Ci}/\text{m}^2$) from monitoring data.
- Constants – Daily Soil Intake Rate, Ingestion Dose Coefficient.
- Other Factors – Start and end time of period (duration of consumption) under consideration, decay and weathering of radionuclides over the duration of consumption (default consumption period is 1 year).

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

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

Outputs

The final output of this method is the Ingestion Dose for soils that have been contaminated by a deposition of radioactive material.

Final

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

$H_{T,50,\text{soil}}$ = Committed Equivalent Dose, the dose to organ “t”, received by the receptor under consideration over the commitment period, from the ingestion of all radionuclides in contaminated soil, mrem

Intermediate

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

None

Method 4.7.1 Calculation of Committed Effective Dose from Inadvertent Soil Ingestion

Equation 4.7-1 shows the Ingestion Dose calculation:

$$E_{50,soil,age} = \frac{DSIR}{\rho_{soil} * d_m} * \sum_i \left(Dp_{i,t_0} * e^{-\lambda t_1} * WF_{t_1} * IngDC_{E,age,i} * CRP_{i,TP} \right) \quad (\text{Eq. 4.7-1})$$

$$\text{mrem} = \frac{\frac{\text{kg}_{soil}}{\text{d}}}{\frac{\text{kg}_{soil}}{\text{m}^3} * \text{m}} * \sum_i \left(\frac{\mu\text{Ci}}{\text{m}^2} * \text{unitless} * \text{unitless} * \frac{\text{mrem}}{\mu\text{Ci}} * \text{d} \right)$$

where:

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

$DSIR$ = Daily Soil Intake Rate, $\text{kg}_{soil}/\text{d}$;

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

d_m = Mixing Depth, m;

Dp_{i,t_0} = Deposition, the measured or predicted areal activity of radionuclide i per unit area of ground at the time of deposition (t_0), $\mu\text{Ci}/\text{m}^2$;

$e^{-\lambda t_1}$ = Radioactive Decay adjustment from t_0 (deposition) to t_1 (start of the time phase), unitless;

WF_{t_1} = Weathering adjustment from t_0 (deposition) to t_1 (start of the time phase), unitless;

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

$CRP_{i,TP}$ = Combined Removal Parameter, value that adjusts for radioactive decay and weathering effects that decrease the amount of radionuclide i available to cause direct exposure or to be ingested over the time phase (TP , t_1 to t_2) under consideration, d; (See Method 2.1 for derivation.)

Method 4.7.2 Calculation of Equivalent Dose to an Organ

The preceding calculations assume that the organ of interest is the whole body. The generic approach can be modified to calculate a dose for a specific organ (e.g., skin, thyroid, etc.).

To calculate the dose to a specific organ, replace the $IngDC$ for the whole body with the $IngDC$ for the specific organ when calculating the $IngDP$.

EXAMPLE 1

Problem: Calculate the Whole Body Ingestion Dose received by an adult from inadvertent consumption of soil contaminated with ^{60}Co and ^{137}Cs for 1 year, beginning 100 days after deposition.

Assume monitoring results (at deposition) as shown below:

$$\begin{aligned} Dp_{i,Co} &= 2.5\text{E-}03 \mu\text{Ci}/\text{m}^2 \\ Dp_{i,Cs} &= 4.0\text{E-}03 \mu\text{Ci}/\text{m}^2 \end{aligned}$$

Equation 4.7-1 can be used to calculate the dose:

$$E_{50,soil,age} = \frac{DSIR}{\rho_{soil} * d_m} * \sum_i \left(Dp_{i,t_0} * e^{-\lambda t_1} * WF_{t_1} * IngDC_{E,age,i} * CRP_{i,TP} \right)$$

Given:

$$\begin{aligned} IngDC_{Co} &= 12.7 \text{ mrem}/\mu\text{Ci} \\ \lambda_{Co} &= 3.6\text{E-}04 \text{ d}^{-1} \\ IngDC_{Cs} &= 50.3 \text{ mrem}/\mu\text{Ci} \\ \lambda_{Cs} &= 6.33\text{E-}05 \text{ d}^{-1} \\ t_1 &= 100 \text{ d (Start of Time Phase – used in CRP calculation)} \\ t_2 &= 465 \text{ d (End of Time Phase – used in CRP calculation)} \\ WF_{100d} &= 0.950 \end{aligned}$$

Assuming:

$$\begin{aligned} DSIR &= 1.0\text{E-}04 \text{ kg}_{soil}/\text{d} \\ \rho_{soil} &= 1600 \text{ kg}_{soil}/\text{m}^3 \\ d_m &= 1.0\text{E-}04 \text{ m} \end{aligned}$$

Calculating CRP using Equation 2.1-9c from Method 2.1 yields:

$$\begin{aligned} CRP_{Co} &= 290 \text{ d} \\ CRP_{Cs} &= 314 \text{ d} \end{aligned}$$

$$\begin{aligned} E_{50,soil,Adult} &= \frac{1.0\text{E-}04 \frac{\text{kg}_{soil}}{\text{d}}}{1600 \frac{\text{kg}_{soil}}{\text{m}^3} * 1.0\text{E-}04 \text{ m}} * \left(\begin{aligned} &2.5\text{E-}03 \frac{\mu\text{Ci}}{\text{m}^2} * 0.965 * 0.950 * 12.7 \frac{\text{mrem}}{\mu\text{Ci}} * 290 \text{ d} \\ &+ 4.0\text{E-}03 \frac{\mu\text{Ci}}{\text{m}^2} * 0.994 * 0.950 * 50.3 \frac{\text{mrem}}{\mu\text{Ci}} * 314 \text{ d} \end{aligned} \right) \\ &= 4.26\text{E-}02 \text{ mrem} \end{aligned}$$

To calculate an Committed Equivalent Dose ($H_{T,50}$) for a specific organ and/or different age group, use the appropriate IngDC for the organ/age group and calculate as demonstrated above.

SECTION 5. SAMPLE MANAGEMENT METHODS

Introduction to Sample Management Methods..... 5.0-3

 Method 5.1 Determining Resuspension from Samples..... 5.1-1

 Method 5.2 Comparing Sample Results to Ingestion Pathway Thresholds..... 5.2-1

 Method 5.3 Normalizing Samples (RESERVED) 5.3-1

 Method 5.4 Determining Laboratory Analysis MDA Requirements (RESERVED) 5.4-1

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INTRODUCTION TO SAMPLE MANAGEMENT METHODS

These methods describe how to use sample data to perform various assessment activities. The results of these methods may be used to determine alternate (non default) input factors that may be used to calculate values that are more applicable to the incident being assessed. These methods may also be used to normalize sample data for comparison to values calculated by other methods.

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METHOD 5.1 DETERMINING RESUSPENSION FROM SAMPLES

Application

This method has been developed to calculate a Resuspension Factor based on air and deposition samples.

The Resuspension Factor (K):

- Represents the ratio of activity in the air at a particular location to the activity on the ground at that location for a particular radionuclide.

NOTE: Resuspension Factors may be different for each radionuclide in a mixture because some chemical/physical forms may be more likely to become airborne than others. Local decision makers should be consulted to determine if radionuclide-specific Resuspension Factors should be used instead of one factor for the entire mixture.

- Is used to calculate the Resuspension Parameter (KP) and Inhalation Dose Parameter for Deposition ($InhDP_{Dp}$) for each radionuclide in a deposition mixture.

Discussion

This calculation is presented as an alternative to the default, time dependent, formula from NCRP 129 used in Method 2.1 – Deposition DRL, Section 1.1.2 and may be used only with approval from local decision makers.

In contrast to direct measurements of air concentration (usually made at occupied locations), air and ground measurements used for determining resuspension factors must be made at or near source locations – i.e., areas of contaminated ground from which activity is being resuspended *into* occupied areas. Although it is possible that such source areas may be near (or may be the same as) occupied areas, it is also possible that the source contamination area is some distance away from the occupied area of interest.

Therefore, the location of resuspension measurements must take into account the geography and weather factors that affect the transfer of activity from the ground to the air that will end up in the occupied areas of interest. In general, resuspension measurements should be made at locations in contaminated areas that are upwind (or may be expected to be upwind) of the occupied areas of interest.

Several ground samples should be taken upwind of each air sampler in order to obtain an average value for the ground in the area covered by the air sampler. The purpose of these

measurements is to obtain the general level of ground activity for comparison to the measured activity on the air filter.

There are several pitfalls to consider when deciding to use a sample based resuspension value:

- It may be difficult to obtain accurate/representative sample-based values.
- Hot particles may significantly skew the air sample activity results.
- Samples are only representative of the resuspension factor for a specific point in time and space.
- Resuspension may change over the time phase of interest as the land use changes.
- Weathering processes and alpha-recoil energy can break apart contaminated particles creating smaller particle sizes over time potentially changing resuspension.
- Sample based resuspension values are sensitive to many factors, including:
 - Air sampler location,
 - Wind direction relative to the air sample location, and
 - Activities being conducted in the sampling area.

Assumptions

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

None

Inputs

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

Data – Sampling Results from air and ground monitoring.

Outputs

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

Final

K_i = Resuspension Factor, the ratio of the activity level in the air to the level on the ground of radionuclide i , m^{-1} .

Intermediate

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

None

Calculation

Equation 5.1-1 shows the Resuspension Factor calculation.

$$K_i = \frac{C_{air,i}}{C_{ground,i}} \quad (\text{Eq. 5.1-1})$$

$$m^{-1} = \frac{\mu\text{Ci}/m^3}{\mu\text{Ci}/m^2}$$

where:

K_i = Resuspension Factor for radionuclide i , m^{-1} ;
 $C_{air,i}$ = Air Concentration of radionuclide i , $\mu\text{Ci}/m^3$; and
 $C_{ground,i}$ = Ground Concentration of radionuclide i , $\mu\text{Ci}/m^2$.

EXAMPLE 1**Problem: Calculate the Resuspension Factor from sample results**At a particular sampling location, the average results for ^{137}Cs are:Air Sampling: $2.74\text{E-}03 \mu\text{Ci}/\text{m}^3$ Ground Sampling: $2.74\text{E+}04 \mu\text{Ci}/\text{m}^2$

$$K = \frac{2.74\text{E-}03 \frac{\mu\text{Ci}}{\text{m}^3}}{2.74\text{E+}04 \frac{\mu\text{Ci}}{\text{m}^2}} = 1.00\text{E-}07 \text{ m}^{-1}$$

METHOD 5.2 COMPARING SAMPLE RESULTS TO INGESTION PATHWAY THRESHOLDS

Application

This method provides instructions on how to compare analytical sample results of food and fodder to DILs.

Discussion

DILs are based on the level of radioactive material in food “as prepared for consumption.” The default assumption for this method is that food products are intended to be eaten in a fresh or “wet” condition.

Because many methods of sample analysis require drying the sample material it may be necessary to apply a dry-to-wet conversion factor to the sample results before a direct comparison may be made to the appropriate DIL. Assessment Scientists must determine when it is appropriate to apply the dry-to-wet conversion factor to sample results for comparison to the DIL.

Assumptions

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

- Food products are intended to be eaten in a fresh or “wet” condition. This does not apply to fodder that is to be fed to livestock in a dry form.

Inputs

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

Data – Sampling Results from food products/fodder in terms of dry mass ($\mu\text{Ci}/\text{kg}_{\text{dry}}$).

Constants – Mass Conversion Factor for the food product/fodder.

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

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

Outputs

The final output of this method is a sample analysis result in “wet mass” that may be directly compared to a DIL.

Final

$C_{sample,i,wet}$ = Sample Contamination, the level of contamination of radionuclide i in a analytical sample in terms of wet mass, $\mu\text{Ci}/\text{kg}_{wet}$.

Intermediate

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

None.

Calculation

Equation 5.2-1 shows the wet mass Contamination calculation.

$$C_{sample,i,wet} = C_{sample,i,dry} * MCF_{D-W,subgroup} \quad (\text{Eq. 5.2-1})$$

$$\frac{\mu\text{Ci}}{\text{kg}_{wet}} = \frac{\mu\text{Ci}}{\text{kg}_{dry}} * \frac{\text{kg}_{dry}}{\text{kg}_{wet}}$$

where:

$C_{sample,i,wet}$ = Sample Contamination, the level of contamination of radionuclide i in an analytical sample in terms of wet mass, $\mu\text{Ci}/\text{kg}_{wet}$;

$C_{sample,i,dry}$ = Sample Contamination, the level of contamination of radionuclide i in an analytical sample in terms of dry mass, $\mu\text{Ci}/\text{kg}_{dry}$; and

$MCF_{D-W,subgroup}$ = Mass Conversion Factor (dry to wet) – the ratio of dry mass to wet mass for a food subgroup (See Appendix C, Table 9), $\text{kg}_{dry}/\text{kg}_{wet}$.

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 $6.0\text{E-}02$ $\mu\text{Ci}/\text{kg}$ 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 $3.7\text{E-}02$ $\mu\text{Ci}/\text{kg}$; does the sample exceed the DIL?

Because this apple crop's "as prepared for consumption" form will be wet mass, Equation 5.2-1 should be used to calculate the wet mass Concentration.

$$C_{\text{sample},i,\text{wet}} = C_{\text{sample},i,\text{dry}} * MCF_{D-W,\text{subgroup}}$$

Given:

$$MCF_{D-W,\text{apples}} = 0.18 \text{ kg}_{\text{dry}}/\text{kg}_{\text{wet}}$$

$$C_{\text{sample},i,\text{wet}} = 6.0\text{E-}02 \frac{\mu\text{Ci}}{\text{kg}_{\text{dry}}} * 0.18 \frac{\text{kg}_{\text{dry}}}{\text{kg}_{\text{wet}}} = 1.08\text{E-}02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

Since:

$$1.08\text{E-}02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} < 3.7\text{E-}02 \frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$$

The sample does not exceed the DIL when the apples are evaluated in the "as prepared for consumption" form.

This demonstrates the importance of comparing "wet apples to wet apples" when making decisions about whether a particular food product exceeds the DIL.

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METHOD 5.3 NORMALIZING SAMPLES

This method is reserved for future development.

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METHOD 5.4 DETERMINING MDA REQUIREMENTS

This method is reserved for future development.

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GLOSSARY

Acute Health Effects	See Early Health Effects.
Cloud Shine	Gamma radiation from radioactive materials in the air (plume).
Committed Effective Dose (E_{50})	The sum of the committed equivalent doses for 50 years following intake (inhalation or ingestion) of a radionuclide to each organ multiplied by a tissue weighting factor.
Committed Equivalent Dose ($H_{T,50}$)	The equivalent dose to a specific organ for 50 years following intake (inhalation or ingestion). It does not include contributions from external dose.
Delayed Health Effects	A wide range of cancers and hereditary effects that usually occur many years after exposure. In contrast to early health effects, it is assumed there are no dose thresholds below which these effects do not occur.
Deposition	The contamination found on the surface of the ground.
Derived Intervention Level (DIL)	The concentration of a radionuclide in food derived from the protective action guide and at which introduction of protective measures should be considered.
Derived Response Level (DRL)	A calculated value (<i>e.g.</i> , exposure 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.
Dose Conversion Factor (DCF)	The equivalent dose per unit intake of a radionuclide (mrem/ μ Ci).
Early Health Effects	Health effects that are likely to occur shortly after exposure (hours, weeks) resulting from high doses over a short period (acute doses) to specific organs and involve thresholds below which these health effects are not expected to occur.
Early Phase	The period of time that extends from the time the threat of a major release is identified until the release or threat of major release has ended and areas of major deposition have been identified.
Effective Dose (E)	The sum of the equivalent dose from each organ multiplied by a tissue weighting factor.
Equivalent Dose (H_T)	The dose to an organ multiplied by the radiation weighting factor.
Emergency Worker Guidance	Guidance on the external dose and Committed Effective Dose incurred by workers (other than a pregnant woman) while performing emergency services.
External Dose	The dose of radiation received by an individual from a source of ionizing radiation outside the body.
Facility Operator	The organization that operates the facility.
Groundshine	Gamma radiation from radioactive materials deposited on the ground.

ICRP 60+	ICRP Publication 60 and the collection of ICRP documents relating to the ICRP 60 dosimetry model published subsequently.
Submersion	To be surrounded or engulfed by the radioactive cloud.
Intermediate Phase	The period beginning after the release and potential for further major release is over and reliable environmental data are available for use as a basis for relocation and ingestion protective actions. Usually one year of deposition and 30 days of ingestion calculation.
Light-Water Reactor (LWR)	A nuclear reactor that uses natural water as a coolant and moderator. All U.S. commercial power reactors in the United States are LWRs, as are the Russian-constructed VVERs.
Marker Radionuclide	A nuclide contained in deposition or samples that is easily identified in the field or laboratory. It is used to determine areas of concern before performing a comprehensive nuclide analysis.
Mixture	The nuclide ratio (relative abundance) of the radionuclides in a sample or deposition.
Pathways	The paths radionuclides follow from the source through the environment, including vegetation and animals, to reach an individual or a population.
Protective Action Guide (PAG)	The projected dose, from an accidental release of radioactive material, where specific actions to reduce or avoid dose are warranted.
Quality Factor (QF)	The principal modifying factor that represents the biological effectiveness of different radiation types with respect to induction of stochastic effects. It is used to calculate the dose equivalent from the absorbed dose. The absorbed dose, expressed in rad or Gy, is multiplied by the appropriate quality factor to obtain the dose equivalent.
Relative Biological Effectiveness (RBE)	The RBE of a given type of ionizing radiation is a factor used to compare the biological effectiveness of absorbed radiation doses (i.e., rads) due to one type of ionizing radiation with that of other types of ionizing radiation; more specifically, it is the experimentally determined ratio of an absorbed dose of a radiation in question to the absorbed dose of a reference radiation required to produce an identical biological effect in a particular experimental organism or tissue.
Resuspension	Reintroduction to the atmosphere of material originally deposited onto surfaces.
Stability Class	A class that describes conditions of atmospheric turbulence. Classes are generally grouped into six classes ranging from class A, very unstable, through class F, very stable.
Total Effective Dose (TED)	The sum of the effective dose (for external exposures) and the committed effective dose.
Total Equivalent Dose – Organ (TEDO)	The sum of the equivalent dose (for external exposure) and the committed equivalent dose to a specific organ.
Transfer Factor	The ratio of the concentration of an element in a 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 ($H_{\text{remainder}}$) is normally calculated as the mass-weighted mean dose to the preceding ten organs and tissues. In those cases in which the most highly irradiated remainder tissue or organ receives the highest equivalent dose of all the organs, a weighting factor of 0.025 (half of remainder) is applied to that tissue or organ and 0.025 (half of remainder) to the mass-weighted equivalent dose in the rest of the remainder tissues and organs to give the remainder equivalent dose.

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
α_DRL_m	$\frac{\mu Ci_\alpha}{m^2}$	Alpha Derived Response Level, the areal alpha activity of the mixture, at time t_n (time of measurement, prediction or evaluation), at which the dose from all radionuclides in the mixture would result in a dose equal to the PAG for the time phase under consideration.	2.3
$AFDIR$	$\frac{kg_{wet}}{d}$	Animal Feed Daily Ingestion Rate, the daily rate at which an animal consumes feed (forage or stored): (Cow default 50, Goat default 6).	4.3, 4.4, 4.6, Table 10
$ASDIR$	$\frac{kg_{soil}}{d}$	Animal Soil Daily Ingestion Rate, the daily rate at which an animal consumes soil: (Cow default 0.5, Goat default 0.06).	4.3, 4.4, 4.6, Table 10
$AvCRP$		(RESERVED)	
$AWDIR$	$\frac{L}{d}$	Animal Water Daily Ingestion Rate, the daily rate at which an animal consumes water: (Cow default 60, Goat default 8).	4.3, 4.4, 4.6, Table 10
β_DRL_m	$\frac{\mu Ci_\beta}{m^2}$	Beta Derived Response Level, the areal beta activity of the mixture, at time t_n (time of measurement, prediction or evaluation), at which the dose from all radionuclides in the mixture would result in a dose equal to the PAG for the time phase under consideration.	2.4
BR	$\frac{m^3}{s}$	Breathing Rate, the activity-weighted average volume of air breathed per unit time by an adult male (ICRP94, Table B.16B), 2.56E-04.	2.1
$C_{air,i}$	$\frac{\mu Ci}{m^3}$	Air concentration of radionuclide i.	5.1
$C_{crop,i}$	$\frac{\mu Ci}{kg_{wet}}$	Projected Contamination level in a food crop (fresh produce), the level of activity of radionuclide i per mass in a food type harvested from contaminated ground.	4.6
$C_{f,i}$	$\frac{\mu Ci}{kg_{wet}}$ or $\frac{\mu Ci}{L}$	Food Contamination, the level of contamination of radionuclide i in a specific food type (f).	4.5

TERM	UNITS	DEFINITION	METHODS
$C_{ground,i}$	$\frac{\mu\text{Ci}}{\text{m}^2}$	Ground concentration of radionuclide i.	5.1
$C_{meat,i}$	$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$	Projected Contamination level in meat, the level of activity of radionuclide i per mass in an animal’s meat from consuming radioactive material.	4.6
$C_{milk,i}$	$\frac{\mu\text{Ci}}{\text{L}}$	Projected Contamination level in milk, the level of activity of radionuclide i per volume in milk produced from animals consuming radioactive material.	4.6
$C_{S,i}$	$\frac{\mu\text{Ci}}{\text{kg}_{\text{soil}}}$	Measured Contamination level of radionuclide i in soil.	4.6
$C_{sample,i,dry}$	$\frac{\mu\text{Ci}}{\text{kg}_{\text{dry}}}$	Sample Contamination, the level of contamination of radionuclide i in an analytical sample in terms of dry mass.	5.2
$C_{sample,i,wet}$	$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$	Sample Contamination, the level of contamination of radionuclide i in an analytical sample in terms of wet mass.	5.2
$C_{W,i}$	$\frac{\mu\text{Ci}}{\text{L}}$	Measured Contamination level of radionuclide i in drinking water.	4.6
CRF	unitless	Crop Retention Factor, the fraction of deposited material that is retained by the edible portion of the crop (default 0.5 for pastureland and 0.2 (1.0 for iodine) for fresh produce).	4.2, 4.3, 4.4, 4.6, Table 10
$Crop_DRL_{mat,i}$	$\frac{\mu\text{Ci}}{\text{m}^2}$	Ingestion Derived Response Level for mature Crop/Produce, the ground concentration, or areal activity, of radionuclide i that will be expected to cause the crop/produce growing in that area to exceed the applicable Derived Intervention Level (DIL).	4.2
$Crop_DRL_{imm,i}$	$\frac{\mu\text{Ci}}{\text{m}^2}$	Ingestion Derived Response Level for immature Crop/Produce, the ground concentration, or areal activity, of radionuclide i that will be expected to cause the crop/produce growing in that area to exceed the applicable Derived Intervention Level (DIL).	4.2
$CRP_{i,TP}$	s, d	Combined Removal Parameter, value that adjusts for radioactive decay and weathering effects that decrease the amount of radionuclide i available to cause direct exposure or to be ingested over the time phase (TP) under consideration.	2.1, 4.7

TERM	UNITS	DEFINITION	METHODS
$DFIR_{age}$	$\frac{kg_{wet}}{d}$	Daily Food Intake Rate, the daily intake rate (as prepared for consumption, i.e. wet mass) for the age group under consideration.	4.1
$DFIR_{subgroup,age}$	$\frac{kg_{wet}}{d}$	Daily Food Intake Rate for a food subgroup (as prepared for consumption, i.e. wet mass) for the age group under consideration.	4.5
$DIL_{organ,age,i}$	$\frac{\mu Ci}{kg_{wet}}$	Derived Intervention Level, the activity concentration level of radionuclide i at which the ingestion dose to the most sensitive population (age group) and target organ has the potential to exceed the applicable ingestion PAG.	4.1, 4.2, 4.3, 4.4
d_m	m	Mixing Depth (default 1.0E-03 for the first growing season and 0.15 after plowing).	4.2, 4.3, 4.4, 4.6,
Dp_DRL_{organ,i,t_n}	$\frac{\mu Ci}{m^2}$	Deposition Derived Response Level, the areal activity (radioactivity per unit area) at time t_n of radionuclide i, at which the dose to the organ of interest from all radionuclides in mixture would result in a dose equal to the PAG for the time phase under consideration.	2.1, 2.3, 2.4
$Dp_PPD_{E,TP}$	mrem	Deposition Projected Public Dose, the projected dose to the whole body (E), over the time phase (TP) under consideration from a deposition of radioactive material.	2.5
Dp_{i,t_n}	$\frac{\mu Ci}{m^2}$	Deposition, the measured or predicted areal activity of radionuclide i per unit area of ground at time t_n .	2.1, 2.5, 3.2, 4.6
$Dp_{i(m)}$	$\frac{\mu Ci}{m^2}$	Deposition of the marker radionuclide.	2.1, 4.6
$DRCF_{skin,i,TP}$		(RESERVED)	
$DSIR$	$\frac{kg_{soil}}{d}$	Daily Soil Intake Rate, the amount of soil inadvertently ingested by humans in a day (default of 1.0E-04).	4.7
$E_{50,Ing,age}$	mrem	Committed Effective Dose from ingestion, the dose to the whole body, received by the age group under consideration over the commitment period, from ingestion of all radionuclides in all contaminated food types.	4.5
$E_{50,soil}$	mrem	Committed Effective Dose from ingestion of soil.	4.7

TERM	UNITS	DEFINITION	METHODS
EDI_i	d	Effective Days of Intake, the number of days required for the radionuclide to decay to <1% of its initial activity (set to 365 if value is greater).	4.1
$ExDC_{E,i}$	$\frac{Sv \cdot m^2}{s \cdot Bq}$	External Dose Coefficient, the effective dose rate to the whole body (E) from the external exposure to radionuclide i per unit activity deposited on the ground, (values using DCFPAK from ICRP 60+ dosimetry models).	2.1, 2.2
$ExDF_{E,i}$	$\frac{mrem \cdot m^2}{s \cdot \mu Ci}$	External Dose Factor for Deposition, the effective dose rate to the whole body (E) from the external exposure to radionuclide i per unit activity deposited on the surface and adjusted for the ground roughness factor.	2.1
$ExDP_{Dp_{E,i,TP}}$	$\frac{mrem \cdot m^2}{\mu Ci}$	External Dose Parameter for Deposition, the groundshine dose received by the whole body (E), over the time phase under consideration (TP), per unit of radioactivity of radionuclide i deposited on the ground and adjusted for the ground roughness factor.	2.1, 3.2
$ExDR$	$\frac{mrem}{hr}$	External dose rate, the external dose rate from materials deposited on the ground.	3.1
$ExTDCF_{TP}$	$\frac{mrem_{inh+external}}{mrem_{external}}$	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 (TP) of interest NOTE: This value is used to convert a measurement from a self reading dosimeter into a dose which includes the effects of inhalation of resuspended material.	3.2
$ExXF_{E,i}$	$\frac{mR \cdot m^2}{hr \cdot \mu Ci}$	External Exposure Factor for Deposition, the external exposure rate to the whole body (E) per unit activity deposited on the ground from radionuclide i and adjusted for the ground roughness factor.	2.2
$FDC_{age,i}$	unitless	Fraction of Diet Contaminated, the fraction of a human’s diet that is contaminated; default value of 0.3 (except for ¹³² Te, ¹³¹ I, ¹³³ I and ²³⁹ Np in the diet of an infant where it is 1.0). NOTE: If there is convincing local information that the actual FDC is considerably different, local authorities may decide to use a different FDC.	4.1
FDC_F	unitless	Fraction of Diet Contaminated (feed), the fraction of the animal’s diet that is from contaminated feed (default 1.0). NOTE: If there is convincing local information that the actual FDC is considerably different, local authorities may decide to use a different FDC.	4.3, 4.4, 4.6

TERM	UNITS	DEFINITION	METHODS
FDC_W	unitless	Fraction of Diet Contaminated (water), the fraction of an animal’s diet that is from contaminated water (default 1.0). NOTE: If there is convincing local information that the actual FDC is considerably different, local authorities may decide to use a different FDC.	4.3, 4.4, 4.6
$FFC_{f,i}$	unitless	Fraction of Food Type Contaminated, (default 1.0). NOTE: If there is convincing local information that the actual FFC is considerably different, local authorities may decide to use a different FFC.	4.5
GRF	unitless	Ground Roughness Factor, a unitless constant (0.82) that compensates for the fact that the external exposure is not coming from an infinite flat plane (An02).	2.1, 2.2
$H_{Skin,TP}$		(RESERVED)	
$H_{T,50}$	mrem	Committed Equivalent Dose, the dose to organ “T”, received by the receptor under consideration over the commitment period, from the ingestion of all radionuclides in contaminated food.	4.5
$H_{T,50,soil}$	mrem	Committed Equivalent Dose, the dose to organ “T” from the ingestion of soil.	4.7
$ICRF$		(RESERVED)	
$IngDC_{organ, age, i}$	$\frac{\text{mrem}}{\mu\text{Ci}}$	Ingestion Dose Coefficient, the ingestion pathway dose coefficient for the target organ for a specific age group for radionuclide i.	4.1, 4.5
$IngDP_{avg,age}$	$\frac{\text{mrem}\cdot\text{d}}{\text{kg}_{\text{wet}}}$	Average Ingestion Dose Parameter for a subgroup, the average of the individual $IngDP_{E,f,age}$ for each type of contaminated food in a subgroup for the age group under consideration.	4.5
$IngDP_{E,f,age}$	$\frac{\text{mrem}\cdot\text{d}}{\text{kg}_{\text{wet}}}$	Ingestion Dose Parameter, the committed effective dose received by the whole body (E) over the commitment period, from ingestion of all radionuclides in a specific food type (f) by a specific age group.	4.5
$InhDC_{E,i}$	$\frac{\text{Sv}}{\text{Bq}}$	Inhalation Dose Coefficient, the committed effective dose coefficient for the whole body (E), for radionuclide i (values from ICRP 60+ dosimetry models, DCFPAK).	2.1
$InhDF_{E,i}$	$\frac{\text{mrem}\cdot\text{m}^3}{\text{s}\cdot\mu\text{Ci}}$	Inhalation Dose Factor, the committed effective dose rate from breathing (at a specified rate) air contaminated with a unit activity of radionuclide i, to the whole body (E).	2.1

TERM	UNITS	DEFINITION	METHODS
$InhDP_{Dp_{E,i,TP}}$	$\frac{\text{mrem}\cdot\text{m}^2}{\mu\text{Ci}}$	Inhalation Dose Parameter for Deposition, the committed effective dose received by the whole body (E), over the time phase under consideration (TP), per unit activity of radionuclide i deposited on the ground from the inhalation of the resuspended radionuclide.	2.1, 3.2
K	m^{-1}	Resuspension Factor, value based on the time-varying formula from NCRP Report No. 129, (NCRP99).	2.1, 5.1
$KIPF$	unitless	Potassium Iodide Protection Factor, which defaults to 1 for all non-iodine isotopes or when no KI is administered. NOTE: Consult Health and Safety personnel for appropriate values for KIPF.	3.2
$KP_{i,TP}$	s/m	Resuspension Parameter, value that adjusts the airborne radioactivity level of radionuclide i over the time phase (TP) under consideration for radioactive decay and the time-dependent resuspension factor (K) (value obtained via numerical integration from Turbo FRMAC).	2.1
λ_i	s^{-1}	Decay constant for radionuclide i.	2.1, 2.2, 3.2, 4.2, 4.3, 4.4, 4.5, 4.6
λ_w	d^{-1}	Decay constant for weathering radioactive material off plants. (Corresponds to a 15 day half life, default 4.62E-02).	4.2, 4.4, 4.6
$MCF_{D-W,subgroup}$	$\frac{\text{kg}_{\text{dry}}}{\text{kg}_{\text{wet}}}$	Mass Conversion Factor (dry to wet) – the ratio of dry mass to wet mass for a food subgroup (See Appendix C, Table 9).	4.2, 4.5, 5.2
$Meat_DRL_{area,i}$	$\frac{\mu\text{Ci}}{\text{m}^2}$	Ingestion Derived Response Level for meat, the ground concentration, or areal activity, of radionuclide i that will be expected to cause the meat from grazing animals (A) to exceed the Derived Intervention Level (DIL) for that radionuclide.	4.4
$Meat_DRL_{mass,A,i}$	$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$	Ingestion Derived Response Level for meat, the mass concentration of radionuclide i that will be expected to cause the meat from grazing animals (A) to exceed the Derived Intervention Level (DIL) for that radionuclide.	4.4
$Meat_DRL_{water,A,i}$	$\frac{\mu\text{Ci}}{\text{L}}$	Ingestion Derived Response Level for meat, the water concentration of radionuclide i that will be expected to cause the meat from drinking animals (A) to exceed the Derived Intervention Level (DIL) for that radionuclide.	4.4

TERM	UNITS	DEFINITION	METHODS
<i>MExXF_{DpE,tn}</i>	$\frac{\text{mR}}{\text{hr}}$	Mixture External Exposure Factor for Deposition, the external exposure rate received by the whole body (E) at time t_n , from a radionuclide mixture deposited on the ground.	2.2, 2.5
<i>Milk_{DRL_{area,A,i}}</i>	$\frac{\mu\text{Ci}}{\text{m}^2}$	Ingestion Derived Response Level for milk, the ground concentration, or areal activity, of radionuclide i that will be expected to cause the milk produced by grazing animals (A) to exceed the Derived Intervention Level (DIL) for that radionuclide.	4.3
<i>Milk_{DRL_{mass,A,i}}</i>	$\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}}$	Ingestion Derived Response Level for milk, the mass concentration in feed of radionuclide i that will be expected to cause the milk produced by grazing animals (A) to exceed the Derived Intervention Level (DIL) for that radionuclide.	4.3
<i>Milk_{DRL_{water,A,i}}</i>	$\frac{\mu\text{Ci}}{\text{L}}$	Ingestion Derived Response Level for Milk, the water concentration of radionuclide i that will be expected to cause the milk produced by drinking animals (A) to exceed the Derived Intervention Level (DIL) for that radionuclide.	4.3
<i>MTDP_{DpE TP}</i>	mrem	Mixture Total Dose Parameter for Deposition, the sum of the external dose from groundshine and the internal dose from inhalation of resuspended material received by the whole body (E), over the time phase under consideration (TP), from the areal activity level of the mixture.	2.1, 2.2, 2.5
<i>PAG</i>	mrem	Protective Action Guide, the dose limits specified by federal or local authorities at which protective actions may be warranted.	2.1, 2.2, 2.5, 2.8, 4.1
ρ_{milk}	$\frac{\text{kg}_{\text{wet}}}{\text{L}}$	Milk density (default 1.0).	4.3
ρ_{soil}	$\frac{\text{kg}_{\text{soil}}}{\text{m}^3}$	Soil Density (default 1600).	4.2, 4.3, 4.4, 4.6
<i>RPF</i>	unitless	Respiratory Protection Factor, which defaults to 1 when no respirators are used. NOTE: Consult Health and Safety personnel for appropriate values for RPF.	3.2
<i>SF</i>		(RESERVED)	
<i>SSF</i>		(RESERVED)	
<i>SkinDP</i>		(RESERVED)	
<i>ST</i>	hr	Stay Time	3.1
t_0	NA	Time of Deposition	2.1

TERM	UNITS	DEFINITION	METHODS
t_1	s	The start of the time phase (integration period) under consideration.	2.1, 2.8
t_2	s	The end of the time phase (integration period) under consideration.	2.1, 2.8
t_a, t_b	hr	Time after a nuclear detonation at which an exposure rate measurement is made.	2.8
t_c	d	Consumption Time, the length of the consumption period (default 365 days).	4.5
t_f	d	Field Time, the time the crop spends growing in the field from deposition or sampling to harvest, d;	4.2
t_g	d	Grazing Time, time from deposition or sampling to the end of the grazing period.	4.4, 4.6
t_h	d	Hold Time, the time elapsed from sample measurement to the beginning of the consumption period.	4.5
t_{In}		(RESERVED)	
t_m	d	Time to Market, the number of days from harvest to consumption (Default 1 for crops, 2 for milk and 20 for meat).	4.2, 4.3, 4.4, 4.6, Table 10
t_n	s	Evaluation Time, the point in time, relative to the start of the event, at which the measurement, prediction or evaluation is performed.	2.1, 2.2, 2.5, 2.8 (in hours)
t_{Out}		(RESERVED)	
TBL	$\frac{mrem}{hr}$ or $\frac{mR}{hr}$	Worker Turn-Back Limit, the Integrated Turn-Back Limit divided by the Stay Time in the contaminated area.	3.1
$TBL_{D_{TP}}$	$mrem_{external}$	Turn-Back Limit for Integrated External Dose, the integrated external dose, as recorded by the self-reading dosimeter, received from a radionuclide mixture deposited on the ground over the time phase under consideration (TP) that would result in the worker receiving their dose limit.	3.2
$TBL_{X_{TP}}$	mR	Worker Turn-Back Limit for Integrated External Exposure, the integrated external exposure, as recorded by a self-reading exposure meter, received from a radionuclide mixture deposited on the ground over the time phase under consideration (TP) that would result in the worker receiving their dose limit.	3.2
$TDP_{D_{pE, i, TP}}$	$\frac{mrem \cdot m^2}{\mu Ci}$	Total Dose Parameter for Deposition, the sum of the external dose from groundshine and the internal (committed effective) dose from inhalation of resuspended material received, by the whole body (E), over the time phase under consideration (TP), per unit of areal activity of radionuclide i deposited on the ground.	2.1, 2.5

TERM	UNITS	DEFINITION	METHODS
$TF_{crop,i}$	$\frac{\mu\text{Ci}/\text{kg}_{\text{dry}}}{\mu\text{Ci}/\text{kg}_{\text{soil}}}$	Transfer Factor for a food crop, the fraction of radionuclide i deposited on the growing medium that is transferred to the plant during the growing season. Transfer Factors for plants are in terms of edible dry plants (PNNL03).	4.2
$TF_{Meat,A,i}$	$\frac{\mu\text{Ci}/\text{kg}_{\text{wet}}}{\mu\text{Ci}/\text{d}}$	Transfer Factor for meat, the fraction of radionuclide i consumed by an animal (A) that is transferred to the meat of the animal.	4.4, 4.6
$TF_{Milk,A,i}$	$\frac{\mu\text{Ci}/\text{L}}{\mu\text{Ci}/\text{d}}$	Transfer Factor for milk, the fraction of radionuclide i consumed by an animal (A) that is transferred to the milk produced by the animal.	4.3, 4.6
WF	unitless	Weathering Factor, value that adjusts the groundshine dose for weathering forces that reduce the radionuclide activity near the surface and thereby decrease the external dose rate (An02).	2.1, 2.2, 3.2
WF_{tn}	unitless	Weathering adjustment from t_0 (deposition) to t_n (time of measurement, prediction or evaluation).	2.1, 2.2, 3.2
x	unitless	Power function exponent, the value that represents the decay of fallout radioactivity at a given location. Default =1.2.	2.8
$XDCF_A$	$\frac{\text{mrem}}{\text{mR}}$	Exposure to Dose Conversion Factor (acute), the constant used to convert external exposure (mR) to midline (bone marrow) dose (mrem), 0.7.	2.8, 3.2
$XDCF_C$	$\frac{\text{mrem}}{\text{mR}}$	Exposure to Dose Conversion Factor (chronic), the constant used to convert external exposure (mR) to deep tissue (1 cm) dose (mrem), 1.0.	2.2, 2.8, 3.2
XR_a	$\frac{\text{mR}}{\text{hr}}$	Exposure rate at time t_a (hours after detonation).	2.8
XR_b	$\frac{\text{mR}}{\text{hr}}$	Exposure rate at time t_b (hours after detonation).	2.8

TERM	UNITS	DEFINITION	METHODS
XR_r	$\frac{mR}{hr}$	Reference exposure rate at 1 hour after nuclear detonation.	2.8
$XR_{r,PAG}$	$\frac{mR}{hr}$	Reference exposure rate at 1 hour after nuclear detonation which would produce a dose for the time phase equal to the PAG.	2.8
XR_t	$\frac{mR}{hr}$	Exposure rate at time t (hours after detonation).	2.8
$XR_DRL_{E,m}$	$\frac{mR}{hr}$	Exposure Rate Derived Response Level, the external exposure rate at time t_n at which the dose from all radionuclides in a deposition mixture would result in a dose to the whole body (E) equal to the PAG for the time phase under consideration.	2.2, 2.5, 2.8
$XR_PPD_{E,TP}$	mrem	Exposure Rate Projected Public Dose, the projected dose to the whole body (E), over the time phase under consideration (TP) based on a measured exposure rate.	2.5
XR_{m}	$\frac{mR}{hr}$	Measured Exposure Rate at time t_n .	2.5
Y	$\frac{kg_{wet}}{m^2}$	Crop Yield, the mass of crop grown per area of land (default 2.0 for produce and 0.7 for pastureland).	4.2, 4.3, 4.4, 4.6, Table 10
$Y_{\alpha i}$	$\frac{\mu Ci_{\alpha}}{\mu Ci_{nt}}$	Yield, the alpha activity per total (nuclear transformation) activity of radionuclide i.	2.3
$Y_{\beta i}$	$\frac{\mu Ci_{\beta}}{\mu Ci_{nt}}$	Yield, the beta activity per total (nuclear transformation) activity of radionuclide i.	2.4

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#	Radionuclide	t _{1/2} (d)	λ (d ⁻¹)	Branching Ratio
1	Am-241	1.58E+05	4.36E-06	NA
2	Ba-140/La-140			
	Ba-140	1.27E+01	5.44E-02	1
	La-140	1.68E+00	4.13E-01	1
3	Ce-141	3.25E+01	2.13E-02	NA
4	Ce-144/Pr-144/Pr-144m			
	Ce-144	2.84E+02	2.44E-03	1
	Pr-144	1.20E-02	5.78E+01	0.982
	Pr-144m	5.00E-03	1.39E+02	1.78E-02
	Pr-144	1.20E-02	5.78E+01	0.999
5	Cf-252	9.64E+02	7.19E-04	NA
6	Cm-242	1.63E+02	4.26E-03	NA
7	Cm-244	6.61E+03	1.05E-04	NA
8	Co-60	1.93E+03	3.60E-04	NA
9	Cs-134	7.53E+02	9.20E-04	NA
10	Cs-136	1.31E+01	5.29E-02	NA
11	Cs-137/Ba-137m			
	Cs-137	1.10E+04	6.33E-05	1
	Ba-137m	1.77E-03	3.91E+02	0.946
12	Gd-153	2.42E+02	2.86E-03	NA
13	I-129	5.73E+09	1.21E-10	NA
14	I-131	8.04E+00	8.62E-02	NA
15	I-132	9.58E-02	7.23E+00	NA
16	I-133	8.67E-01	8.00E-01	NA
17	I-134	3.65E-02	1.90E+01	NA
18	I-135/Xe-135m			
	I-135	2.75E-01	2.52E+00	1
	Xe-135m	1.06E-02	6.53E+01	0.154
19	Ir-192	7.40E+01	9.36E-03	NA
20	Kr-87	5.30E-02	1.31E+01	NA
21	Kr-88/Rb-88			
	Kr-88	1.18E-01	5.86E+00	1
	Rb-88	1.24E-02	5.61E+01	1
22	La-140	1.68E+00	4.13E-01	NA
23	Mo-99/Tc-99m			
	Mo-99	2.75E+00	2.52E-01	1
	Tc-99m	2.51E-01	2.76E+00	0.876
24	Nb-95	3.52E+01	1.97E-02	NA
25	Np-237/Pa-233			
	Np-237	7.82E+08	8.87E-10	1
	Pa-233	2.70E+01	2.57E-02	1
26	Np-239	2.36E+00	2.94E-01	NA
27	Pm-147	9.58E+02	7.23E-04	NA
28	Pu-238	3.20E+04	2.16E-05	NA
29	Pu-239	8.79E+06	7.89E-08	NA
30	Pu-241/U-237			
	Pu-241	5.26E+03	1.32E-04	1
	U-237	6.75E+00	1.03E-01	2.45E-05

#	Radionuclide	t _{1/2} (d)	λ (d ⁻¹)	Branching Ratio
31	Ra-226/Rn-222...			
	Ra-226	5.84E+05	1.19E-06	1
	Rn-222	3.82E+00	1.81E-01	1
	Po-218	2.12E-03	3.27E+02	1
	At-218	2.31E-05	2.99E+04	2.00E-04
	Bi-214	1.38E-02	5.02E+01	1
	Po-214	1.90E-09	3.65E+08	1
	Pb-214	1.86E-02	3.72E+01	1
	Bi-214	1.38E-02	5.02E+01	1
	Po-214	1.90E-09	3.64E+08	1
32	Ru-103/Rh-103m			
	Ru-103	3.93E+01	1.76E-02	1
	Rh-103m	3.90E-02	1.78E+01	0.997
33	Ru-106/Rh-106			
	Ru-106	3.68E+02	1.88E-03	1
	Rh-106	3.46E-04	2.00E+03	1
34	Sb-127/Te-127			
	Sb-127	3.85E+00	1.80E-01	1
	Te-127	3.90E-01	1.78E+00	0.824
35	Sb-129/Te-129			
	Sb-129	1.80E-01	3.85E+00	1
	Te-129	4.83E-02	1.43E+01	0.775
36	Se-75	1.20E+02	5.79E-03	NA
37	Sr-89	5.05E+01	1.37E-02	NA
38	Sr-90/Y-90			
	Sr-90	1.06E+04	6.52E-05	1
	Y-90	2.67E+00	2.60E-01	1
39	Sr-91/Y-91m			
	Sr-91	3.96E-01	1.75E+00	1
	Y-91m	3.45E-02	2.01E+01	0.578
40	Te-129m/Te-129			
	Te-129m	3.36E+01	2.06E-02	1
	Te-129	4.83E-02	1.43E+01	0.65
41	Te-131m/Te-131			
	Te-131m	1.25E+00	5.55E-01	1
	Te-131	1.74E-02	3.99E+01	0.222
42	Te-132/I-132			
	Te-132	3.26E+00	2.13E-01	1
	I-132	9.58E-02	7.23E+00	1
43	Tm-170	1.29E+02	5.39E-03	NA
44	Xe-133	5.24E+00	1.32E-01	NA
45	Xe-135	3.79E-01	1.83E+00	NA
46	Xe-138	9.84E-03	7.04E+01	NA
47	Y-91	5.85E+01	1.18E-02	NA
48	Yb-169	3.20E+01	2.16E-02	NA
49	Zr-95/Nb-95m/Nb-95			
	Zr-95	6.40E+01	1.08E-02	1
	Nb-95m	3.61E+00	1.92E-01	6.98E-03
	Nb-95	3.52E+01	1.97E-02	1
	Nb-95	3.52E+01	1.97E-02	0.993

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Table 2-1 Dose Limits for Workers Performing Emergency Services

TED ^a (rem)	Lens of Eye (rem)	Other Organ, Thyroid, Skin (rem)	Activity	Condition
5	15	50	All.	
10	30	100	Protecting valuable property.	Lower dose not practicable.
25	75	250	Life saving or protection of large populations.	Lower dose not practicable.
>25	>75	>250	Life saving or protection of large populations.	Only on a voluntary basis by persons fully aware of the risks involved (see Table 3).

Source: EPA92, Table 2-2

^a Sum of external Effective Dose and Committed Effective Dose to non-pregnant adults from exposure and intake during an emergency situation. These limits apply to all doses from an incident, except those received in unrestricted areas as members of the public during the Intermediate Phase of the incident.

Table 2-2 PAGs

Time Phase	Protective Action	Limit (rem)	Comments
Early	Evacuation or Sheltering	TED 1-5 ^a Thyroid 5-25 Skin 50-250	Evacuation should normally be initiated at 1 rem. Sheltering may be the preferred protective action when it provides protection equal to or greater than evacuation.
	Administration of stable iodine	25	Equivalent Dose to the thyroid from radioiodine. Requires approval of state medical officials.
1 st Year	Relocation ^b	2 ^a	Or 100 rem skin dose.
	Apply dose reduction techniques	<2	Should be taken to reduce doses to ALARA. (Scrubbing and/or flushing hard surfaces, soaking or plowing soil, minor removal of soil from areas of concentration, limiting outdoor time, etc.)
2 nd Year	Relocation ^b	0.5 ^a	Any single year after the 1 st .
50 Years	Relocation ^b	5 ^a	Total for 50 years.
Ingestion	See Table 2-3	0.5 CED 5 H _T	Due to ingestion of contaminated food in one year. Whichever is more limiting (Whole Body or Organ).

Source: EPA92, FDA98

^a The sum of the Effective Dose resulting from exposure to external sources and the Committed Effective Dose incurred from all significant inhalation pathways during the time phase.

^b Persons previously evacuated from areas outside the relocation zone defined by this PAG may return to occupy their residences. Cases involving relocation of persons at high risk from such action (e.g., patients under intensive care) should be evaluated individually.

Table 2-3 Ingestion Protective Actions

Animals	Move to shelter and/or corral, provide protected feed and water.
All foods	Isolate by temporary embargo until survey and initial sampling is completed. Determine whether condemnation or other disposition is appropriate.
Milk	Hold for decay or divert to other products involving adequate decay during processing (e.g., cheese, butter, dry milk solids, or evaporated milk).
Fruits and Vegetables	Wash, brush, scrub or peel to remove surface contamination. Preserve by canning, freezing, dehydration, or storage to permit decay.
Grains	Process by milling and polishing to remove surface contamination.

No actions are to be implemented that place personnel in jeopardy from an imminent release, or that may interfere with them taking shelter, or cause them to leave shelter during a release.

The blending of contaminated food with uncontaminated food is not permitted.

The FDA has developed guidance (FDA98) on the protective actions that should be considered if the ingestion of contaminated food may result in doses that meet or exceed the PAG. Specific protective actions to be implemented following an accident are not provided in these recommendations because there is such a wide variety of actions that could be taken. The protective actions would be determined by state and local officials with assistance from the growers, producers, and manufacturers.

Table 3-1 Whole-Body

Whole-Body Absorbed Dose (rad)	Early Fatalities ^{a, b} (percent)	Whole-Body Absorbed Dose (rad)	Prodromal Effects ^{a, c} (percent affected)
140	5	50	2
200	15	100	15
300	50	150	50
400	85	200	85
460	95	250	98

Source: EPA92, Table 2-3

^a Risks will be lower for protracted exposure periods.

^b Supportive medical treatment may increase the dose where these frequencies occur by approximately 50 percent.

^c Forewarning symptoms of more serious health effects associated with large doses of radiation.

Table 3-2 Organs

Organ	Dose Threshold (rad)	Early Health Effects
Bone Marrow (hematopoietic syndrome)	50	Marrow depression
Small Intestine (gastrointestinal syndrome)	50 100 800	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 LET (alpha) dose conversion factors.

Table 3-3 Cancer Risk to Average Individuals from 25 rem Effective Dose

Age at Exposure (years)	Approximate Risk of Premature Death (deaths per 1,000 persons exposed)	Average Years of Life Lost if Premature Death Occurs (years)
20 to 30	9.1	24
30 to 40	7.2	19
40 to 50	5.3	15
50 to 60	3.5	11

Source: EPA92, Table 2-4

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This Table contains the Deposition and Exposure Rate DRLs and the intermediate products necessary to calculate the DRLs for the Assessment Working Group’s list of radionuclides. Values are provided for the 4 standard Time Phases (Early, 1st Year, 2nd Year and 50 Year.)

These values are **only appropriate** when the start of the Time Phase (t_1) and the time of interest (t_n) are both equal to the time of Deposition (t_0).

The terms contained in this table are defined below:

DRLs		
Dp_DRL_{organ,i,t_n}	$\frac{\mu Ci}{m^2}$	Deposition Derived Response Level, the areal activity (radioactivity per unit area) at time t_n of radionuclide i , at which the dose to the organ of interest from all radionuclides in mixture would result in a dose equal to the PAG for the time phase under consideration.
XR_DRL_{E,t_n}	$\frac{mR}{hr}$	Exposure Rate Derived Response Level, the external exposure rate, at time t_n , at which the dose from all radionuclides in a deposition mixture would result in a dose to the whole body (E) equal to the PAG for the time phase under consideration.
Intermediate Values		
$ExDP_Dp_{E,i,TP}$	$\frac{mrem \cdot m^2}{\mu Ci}$	External Dose Parameter for Deposition, the groundshine dose received by the whole body (E), over the time phase under consideration (TP), per unit of radioactivity of radionuclide i deposited on the ground and adjusted for the ground roughness factor.
$ExXF_{E,i}$	$\frac{mR \cdot m^2}{hr \cdot \mu Ci}$	External Exposure Factor for deposition, the external exposure rate to the whole body (E) per unit activity deposited on the ground from radionuclide i and adjusted for the ground roughness factor.
$InhDP_Dp_{E,i,TP}$	$\frac{mrem \cdot m^2}{\mu Ci}$	Inhalation Dose Parameter for Deposition, the committed effective dose received by the whole body (E), over the time phase under consideration (TP), per unit activity of radionuclide i deposited on the ground from the inhalation of the resuspended radionuclide.
$TDP_Dp_{E,i,TP}$	$\frac{mrem \cdot m^2}{\mu Ci}$	Total Dose Parameter for Deposition, the sum of the external dose from groundshine and the internal (committed effective) dose from inhalation of resuspended material received, by the whole body (E), over the time phase under consideration (TP), per unit of areal activity of radionuclide i deposited on the ground.

Notes:

Dp_DRLs apply to individual (marker) radionuclides. If a radionuclide is formed from multiple pathways in a chain (e.g., ^{144}Pr is formed by two separate branches from the decay of ^{144}Ce), the Dp_DRL values have been summed to indicate the total contribution from that radionuclide for all branches.

XR_DRLs apply to the mixture of radionuclides. (In this case, a single parent and the included daughters.)

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#	Radionuclide	ExDP_Dp (mrem·m ²)/μCi	InhDP_Dp (mrem·m ²)/μCi	TDP_Dp (mrem·m ²)/μCi	ExXF (mR·m ²)/(hr·μCi)	Dp_DRL μCi/m ²	XR_DRL mR/hr
1	Am-241	2.28E-02	1.89E+01	1.89E+01	2.38E-04	5.29E+01	1.26E-02
2	Ba-140/La-140	2.20E+00	1.27E-03	2.20E+00	2.56E-02	-	1.16E-02
	Ba-140	1.80E-01	1.06E-03	1.81E-01	2.09E-03	4.53E+02	-
	La-140	2.02E+00	2.07E-04	2.02E+00	2.35E-02	4.53E+02	-
3	Ce-141	7.00E-02	7.12E-04	7.07E-02	7.63E-04	1.41E+04	1.08E-02
4	Ce-144/Pr-144/Pr-144m	1.86E-01	1.03E-02	1.96E-01	1.95E-03	-	9.94E+00
	Ce-144	1.80E-02	1.03E-02	2.83E-02	1.89E-04	5.09E+03	-
	Pr-144m	1.14E-02	NA	1.14E-02	1.19E-04	9.06E+01	-
	Pr-144	1.68E-01	3.57E-06	1.68E-01	1.76E-03	5.09E+03	-
5	Cf-252	4.52E-01	7.24E+00	7.69E+00	4.72E-03	1.30E+02	6.13E-01
6	Cm-242	6.94E-04	1.15E+00	1.15E+00	7.28E-06	8.67E+02	6.33E-03
7	Cm-244	6.14E-04	1.12E+01	1.12E+01	6.39E-06	8.96E+01	5.73E-04
8	Co-60	2.41E+00	6.01E-03	2.41E+00	2.51E-02	4.14E+02	1.04E+01
9	Cs-134	1.55E+00	3.99E-03	1.55E+00	1.62E-02	6.44E+02	1.04E+01
10	Cs-136	1.88E+00	5.05E-04	1.88E+00	2.18E-02	5.32E+02	1.16E+01
11	Cs-137/Ba-137m	5.75E-01	7.68E-03	5.82E-01	6.00E-03	-	1.03E+01
	Cs-137	3.28E-03	7.68E-03	1.10E-02	3.42E-05	1.72E+03	-
	Ba-137m	6.04E-01	NA	6.04E-01	6.31E-03	1.62E+03	-
12	Gd-153	9.59E-02	4.68E-04	9.64E-02	1.01E-03	1.04E+04	1.04E+01
13	I-129	2.08E-02	7.03E-03	2.79E-02	2.18E-04	3.59E+04	7.77E+00
14	I-131	3.23E-01	1.28E-03	3.25E-01	3.99E-03	3.08E+03	1.23E+01
15	I-132	7.90E-02	1.29E-06	7.90E-02	2.38E-02	1.27E+04	3.02E+02
16	I-133	1.95E-01	1.19E-04	1.96E-01	6.80E-03	5.11E+03	3.47E+01
17	I-134	3.44E-02	2.42E-07	3.44E-02	2.72E-02	2.91E+04	7.91E+02
18	I-135/Xe-135m	1.60E-01	1.03E-05	1.60E-01	1.67E-02	-	1.05E+02
	I-135	1.53E-01	1.03E-05	1.53E-01	1.60E-02	6.26E+03	-
	Xe-135m	4.32E-02	NA	4.32E-02	4.54E-03	9.65E+02	-
19	Ir-192	7.97E-01	1.28E-03	7.98E-01	8.47E-03	1.25E+03	1.06E+01
20	Kr-87	1.68E-02	NA	1.68E-02	9.17E-03	5.95E+04	5.45E+02
21	Kr-88/Rb-88	1.11E-01	3.87E-07	1.11E-01	2.70E-02	-	2.44E+02
	Kr-88	7.70E-02	NA	7.70E-02	1.88E-02	9.05E+03	-
	Rb-88	3.35E-02	3.87E-07	3.35E-02	8.19E-03	9.05E+03	-
22	La-140	1.10E+00	1.33E-04	1.10E+00	2.35E-02	9.07E+02	2.35E-02
23	Mo-99/Tc-99m	1.83E-01	1.41E-04	1.83E-01	3.02E-03	-	1.65E+01
	Mo-99	1.17E-01	1.39E-04	1.17E-01	1.93E-03	5.47E+03	-
	Tc-99m	7.53E-02	2.81E-06	7.53E-02	1.25E-03	4.79E+03	-
24	Nb-95	7.31E-01	3.33E-04	7.32E-01	7.91E-03	1.37E+03	1.09E+01
25	Np-237/Pa-233	2.38E-01	9.74E+00	9.97E+00	2.47E-03	-	2.48E-01
	Np-237	2.56E-02	9.74E+00	9.76E+00	2.67E-04	1.00E+02	-
	Pa-233	2.12E-01	7.56E-04	2.12E-01	2.21E-03	1.00E+02	-
26	Np-239	9.98E-02	1.37E-04	9.99E-02	1.77E-03	1.00E+04	1.77E+01
27	Pm-147	2.94E-05	1.37E-03	1.40E-03	3.07E-07	7.17E+05	2.20E-01
28	Pu-238	6.28E-04	2.12E+01	2.12E+01	6.55E-06	4.73E+01	3.09E-04
29	Pu-239	3.21E-04	2.33E+01	2.33E+01	3.35E-06	4.29E+01	1.44E-04
30	Pu-241/U-237	4.66E-06	4.49E-01	4.49E-01	4.85E-08	-	1.09E-04
	Pu-241	1.50E-06	4.49E-01	4.49E-01	1.56E-08	2.23E+03	-
	U-237	1.29E-01	3.68E-04	1.29E-01	1.34E-03	5.46E-02	-

#	Radionuclide	ExDP_Dp (mrem·m ²)/μCi	InhDP_Dp (mrem·m ²)/μCi	TDP_Dp (mrem·m ²)/μCi	ExXF (mR·m ²)/(hr·μCi)	Dp_DRL μCi/m ²	XR_DRL mR/hr
31	Ra-226/Rn-222...	1.75E+00	1.87E+00	3.62E+00	1.83E-02	-	5.04E+00
	Ra-226	7.00E-03	1.86E+00	1.87E+00	7.28E-05	2.76E+02	-
	Rn-222	3.90E-04	NA	3.90E-04	4.07E-06	2.76E+02	-
	Po-218	6.97E-09	NA	6.97E-09	7.28E-11	2.76E+02	-
	At-218	1.31E-04	NA	1.31E-04	1.37E-06	5.53E-02	-
	Pb-214	2.55E-01	2.88E-03	2.57E-01	2.65E-03	2.76E+02	-
	Bi-214	1.49E+00	3.02E-03	1.49E+00	1.55E-02	2.76E+02	-
	Po-214	8.25E-05	NA	8.25E-05	8.61E-07	2.76E+02	-
32	Ru-103/Rh-103m	4.81E-01	5.64E-04	4.81E-01	5.19E-03	-	1.08E+01
	Ru-103	4.80E-01	5.63E-04	4.80E-01	5.18E-03	2.08E+03	-
	Rh-103m	8.36E-04	5.21E-07	8.36E-04	9.03E-06	2.07E+03	-
33	Ru-106/Rh-106	3.61E-01	1.29E-02	3.74E-01	3.78E-03	-	1.01E+01
	Ru-106	NA	1.29E-02	1.29E-02	0.00E+00	2.67E+03	-
	Rh-106	3.61E-01	NA	3.61E-01	3.78E-03	2.67E+03	-
34	Sb-127/Te-127	5.14E-01	3.06E-04	5.14E-01	7.51E-03	-	1.46E+01
	Sb-127	5.08E-01	2.88E-04	5.08E-01	7.42E-03	1.94E+03	-
	Te-127	7.84E-03	2.14E-05	7.86E-03	1.15E-04	1.60E+03	-
35	Sb-129/Te-129	1.01E-01	5.96E-06	1.01E-01	1.62E-02	-	1.60E+02
	Sb-129	9.46E-02	5.31E-06	9.46E-02	1.52E-02	9.92E+03	-
	Te-129	7.90E-03	8.35E-07	7.90E-03	1.27E-03	7.69E+03	-
36	Se-75	3.69E-01	2.60E-04	3.69E-01	3.89E-03	2.71E+03	1.06E+01
37	Sr-89	7.01E-02	1.52E-03	7.17E-02	7.49E-04	1.40E+04	1.05E+01
38	Sr-90/Y-90	1.17E-01	3.11E-02	1.49E-01	1.22E-03	-	8.26E+00
	Sr-90	1.72E-03	3.08E-02	3.25E-02	1.79E-05	6.76E+03	-
	Y-90	1.15E-01	2.94E-04	1.16E-01	1.20E-03	6.76E+03	-
39	Sr-91/Y-91m	1.54E-01	1.84E-05	1.54E-01	1.13E-02	-	7.28E+01
	Sr-91	1.10E-01	1.81E-05	1.10E-01	8.05E-03	6.50E+03	-
	Y-91m	7.60E-02	5.06E-07	7.60E-02	5.55E-03	3.76E+03	-
40	Te-129m/Te-129	1.35E-01	1.51E-03	1.36E-01	1.46E-03	-	1.07E+01
	Te-129m	5.86E-02	1.51E-03	6.01E-02	6.37E-04	7.35E+03	-
	Te-129	1.17E-01	7.47E-06	1.17E-01	1.27E-03	4.78E+03	-
41	Te-131m/Te-131	6.17E-01	1.09E-04	6.17E-01	1.60E-02	-	2.60E+01
	Te-131m	5.73E-01	1.08E-04	5.73E-01	1.48E-02	1.62E+03	-
	Te-131	1.99E-01	2.88E-06	1.99E-01	5.16E-03	3.60E+02	-
42	Te-132/I-132	1.69E+00	3.18E-04	1.69E+00	2.61E-02	-	1.55E+01
	Te-132	1.50E-01	3.01E-04	1.51E-01	2.32E-03	5.92E+02	-
	I-132	1.54E+00	1.67E-05	1.54E+00	2.38E-02	5.92E+02	-
43	Tm-170	2.58E-02	1.81E-03	2.76E-02	2.72E-04	3.62E+04	9.87E+00
44	Xe-133	3.30E-02	NA	3.30E-02	4.44E-04	3.03E+04	1.34E+01
45	Xe-135	3.58E-02	NA	3.58E-02	2.73E-03	2.79E+04	7.63E+01
46	Xe-138	3.98E-03	NA	3.98E-03	1.17E-02	2.51E+05	2.93E+03
47	Y-91	7.60E-02	1.72E-03	7.77E-02	8.12E-04	1.29E+04	1.04E+01
48	Yb-169	2.96E-01	5.66E-04	2.97E-01	3.22E-03	3.37E+03	1.09E+01
49	Zr-95/Nb-95m/Nb-95	1.46E+00	1.47E-03	1.46E+00	1.55E-02	-	1.06E+01
	Zr-95	7.14E-01	1.13E-03	7.15E-01	7.63E-03	6.85E+02	-
	Nb-95m	6.41E-02	1.70E-04	6.43E-02	6.83E-04	4.78E+00	-
	Nb-95	7.44E-01	3.37E-04	7.45E-01	7.91E-03	6.85E+02	-

#	Radionuclide	ExDP_Dp (mrem·m ²)/μCi	InhDP_Dp (mrem·m ²)/μCi	TDP_Dp (mrem·m ²)/μCi	ExXF (mR·m ²)/(hr·μCi)	Dp_DRL μCi/m ²	XR_DRL mR/hr
1	Am-241	1.91E+00	5.46E+01	5.65E+01	2.38E-04	3.54E+01	8.40E-03
2	Ba-140/La-140	1.12E+01	1.93E-03	1.12E+01	2.56E-02	-	2.29E-03
	Ba-140	9.12E-01	1.61E-03	9.13E-01	2.09E-03	1.79E+02	-
	La-140	1.03E+01	3.15E-04	1.03E+01	2.35E-02	1.79E+02	-
3	Ce-141	8.37E-01	1.32E-03	8.38E-01	7.63E-04	2.39E+03	9.10E-04
4	Ce-144/Pr-144/Pr-144m	1.05E+01	2.67E-02	1.05E+01	1.95E-03	-	3.70E-01
	Ce-144	1.02E+00	2.67E-02	1.04E+00	1.89E-04	1.90E+02	-
	Pr-144m	6.41E-01	0.00E+00	6.41E-01	1.19E-04	3.38E+00	-
	Pr-144	9.47E+00	9.28E-06	9.47E+00	1.76E-03	1.90E+02	-
5	Cf-252	3.34E+01	2.02E+01	5.37E+01	4.72E-03	3.73E+01	1.76E-01
6	Cm-242	3.04E-02	2.81E+00	2.85E+00	7.28E-06	7.03E+02	5.13E-03
7	Cm-244	5.04E-02	3.21E+01	3.22E+01	6.39E-06	6.22E+01	3.98E-04
8	Co-60	1.89E+02	1.71E-02	1.89E+02	2.51E-02	1.06E+01	2.65E-01
9	Cs-134	1.11E+02	1.10E-02	1.11E+02	1.62E-02	1.81E+01	2.92E-01
10	Cs-136	9.77E+00	7.73E-04	9.77E+00	2.18E-02	2.05E+02	4.45E+00
11	Cs-137/Ba-137m	4.76E+01	2.21E-02	4.76E+01	6.00E-03	-	2.52E-01
	Cs-137	2.71E-01	2.21E-02	2.94E-01	3.42E-05	4.20E+01	-
	Ba-137m	5.00E+01	0.00E+00	5.00E+01	6.31E-03	3.97E+01	-
12	Gd-153	5.08E+00	1.20E-03	5.08E+00	1.01E-03	3.93E+02	3.96E-01
13	I-129	1.75E+00	2.03E-02	1.77E+00	2.18E-04	1.13E+03	2.46E-01
14	I-131	1.10E+00	1.77E-03	1.11E+00	3.99E-03	1.81E+03	7.21E+00
15	I-132	7.90E-02	1.29E-06	7.90E-02	2.38E-02	2.53E+04	6.03E+02
16	I-133	2.04E-01	1.21E-04	2.04E-01	6.80E-03	9.81E+03	6.66E+01
17	I-134	3.44E-02	2.42E-07	3.44E-02	2.72E-02	5.81E+04	1.58E+03
18	I-135/Xe-135m	1.60E-01	1.03E-05	1.60E-01	1.67E-02	-	2.10E+02
	I-135	1.53E-01	1.03E-05	1.53E-01	1.60E-02	1.25E+04	-
	Xe-135m	4.32E-02	0.00E+00	4.32E-02	4.54E-03	1.93E+03	-
19	Ir-192	2.00E+01	2.77E-03	2.00E+01	8.47E-03	9.98E+01	8.47E-01
20	Kr-87	1.68E-02	0.00E+00	1.68E-02	9.17E-03	1.19E+04	1.09E+03
21	Kr-88/Rb-88	1.11E-01	3.87E-07	1.11E-01	2.70E-02	-	4.88E+02
	Kr-88	7.70E-02	0.00E+00	7.70E-02	1.88E-02	1.81E+04	-
	Rb-88	3.35E-02	3.87E-07	3.35E-02	8.19E-03	1.81E+04	-
22	La-140	1.36E+00	1.40E-04	1.36E+00	2.35E-02	1.47E+03	2.35E-02
23	Mo-99/Tc-99m	2.87E-01	1.60E-04	2.87E-01	3.02E-03	-	2.11E+01
	Mo-99	1.84E-01	1.57E-04	1.84E-01	1.93E-03	6.95E+03	-
	Tc-99m	1.18E-01	3.17E-06	1.18E-01	1.25E-03	6.09E+03	-
24	Nb-95	9.40E+00	6.26E-04	9.40E+00	7.91E-03	2.13E+02	1.69E+00
25	Np-237/Pa-233	1.98E+01	2.82E+01	4.80E+01	2.47E-03	8.34E+01	1.03E-01
	Np-237	2.14E+00	2.82E+01	3.03E+01	2.67E-04	4.17E+01	-
	Pa-233	1.77E+01	2.19E-03	1.77E+01	2.21E-03	4.17E+01	-
26	Np-239	1.44E-01	1.51E-04	1.44E-01	1.77E-03	1.39E+04	2.46E+01
27	Pm-147	2.17E-03	3.81E-03	5.99E-03	3.07E-07	3.34E+05	1.03E-01
28	Pu-238	5.32E-02	6.11E+01	6.12E+01	6.55E-06	3.27E+01	2.14E-04
29	Pu-239	2.68E-02	6.74E+01	6.74E+01	3.35E-06	2.97E+01	9.94E-05
30	Pu-241/U-237	3.81E-04	1.29E+00	1.29E+00	4.85E-08	-	7.59E-05
	Pu-241	1.24E-04	1.29E+00	1.29E+00	1.56E-08	1.55E+03	-
	U-237	1.05E+01	1.06E-03	1.05E+01	1.34E-03	3.80E-02	-

#	Radionuclide	ExDP_Dp (mrem·m ²)/μCi	InhDP_Dp (mrem·m ²)/μCi	TDP_Dp (mrem·m ²)/μCi	ExXF (mR·m ²)/(hr·μCi)	Dp_DRL μCi/m ²	XR_DRL mR/hr
31	Ra-226/Rn-222...	1.47E+02	5.41E+00	1.52E+02	1.83E-02	-	2.40E-01
	Ra-226	5.86E-01	5.39E+00	5.97E+00	7.28E-05	1.32E+01	-
	Rn-222	3.26E-02	0.00E+00	3.26E-02	4.07E-06	1.32E+01	-
	Po-218	5.83E-07	0.00E+00	5.83E-07	7.28E-11	1.32E+01	-
	At-218	1.10E-02	0.00E+00	1.10E-02	1.37E-06	2.63E-03	-
	Pb-214	2.13E+01	8.33E-03	2.13E+01	2.65E-03	1.32E+01	-
	Bi-214	1.25E+02	8.72E-03	1.25E+02	1.55E-02	1.32E+01	-
Po-214	6.90E-03	0.00E+00	6.90E-03	8.61E-07	1.32E+01	-	
32	Ru-103/Rh-103m	6.85E+00	1.08E-03	6.85E+00	5.19E-03	-	1.51E+00
	Ru-103	6.84E+00	1.08E-03	6.84E+00	5.18E-03	2.92E+02	-
	Rh-103m	1.19E-02	1.00E-06	1.19E-02	9.03E-06	2.91E+02	-
33	Ru-106/Rh-106	2.22E+01	3.42E-02	2.22E+01	3.78E-03	-	3.41E-01
	Ru-106	0.00E+00	3.42E-02	3.42E-02	0.00E+00	9.01E+01	-
	Rh-106	2.22E+01	0.00E+00	2.22E+01	3.78E-03	9.01E+01	-
34	Sb-127/Te-127	1.00E+00	3.64E-04	1.00E+00	7.51E-03	-	1.51E+01
	Sb-127	9.87E-01	3.43E-04	9.88E-01	7.42E-03	2.00E+03	-
	Te-127	1.52E-02	2.56E-05	1.53E-02	1.15E-04	1.65E+03	-
35	Sb-129/Te-129	1.01E-01	5.96E-06	1.01E-01	1.62E-02	-	3.21E+02
	Sb-129	9.46E-02	5.31E-06	9.46E-02	1.52E-02	1.98E+04	-
	Te-129	7.90E-03	8.35E-07	7.90E-03	1.27E-03	1.54E+04	-
36	Se-75	1.34E+01	6.09E-04	1.34E+01	3.89E-03	1.50E+02	5.82E-01
37	Sr-89	1.26E+00	3.07E-03	1.26E+00	7.49E-04	1.58E+03	1.19E+00
38	Sr-90/Y-90	9.68E+00	8.94E-02	9.77E+00	1.22E-03	-	2.50E-01
	Sr-90	1.42E-01	8.86E-02	2.31E-01	1.79E-05	2.05E+02	-
	Y-90	9.54E+00	8.47E-04	9.54E+00	1.20E-03	2.05E+02	-
39	Sr-91/Y-91m	1.54E-01	1.84E-05	1.54E-01	1.13E-02	-	1.46E+02
	Sr-91	1.10E-01	1.81E-05	1.10E-01	8.05E-03	1.30E+04	-
	Y-91m	7.60E-02	5.07E-07	7.60E-02	5.55E-03	7.51E+03	-
40	Te-129m/Te-129	1.66E+00	2.81E-03	1.66E+00	1.46E-03	-	1.76E+00
	Te-129m	7.23E-01	2.80E-03	7.26E-01	6.37E-04	1.20E+03	-
	Te-129	1.44E+00	1.39E-05	1.44E+00	1.27E-03	7.83E+02	-
41	Te-131m/Te-131	6.92E-01	1.12E-04	6.93E-01	1.60E-02	-	4.63E+01
	Te-131m	6.42E-01	1.11E-04	6.43E-01	1.48E-02	2.89E+03	-
	Te-131	2.23E-01	2.96E-06	2.23E-01	5.16E-03	6.42E+02	-
42	Te-132/I-132	2.94E+00	3.68E-04	2.94E+00	2.61E-02	-	1.78E+01
	Te-132	2.62E-01	3.49E-04	2.62E-01	2.32E-03	6.80E+02	-
	I-132	2.68E+00	1.94E-05	2.68E+00	2.38E-02	6.80E+02	-
43	Tm-170	9.80E-01	4.27E-03	9.84E-01	2.72E-04	2.03E+03	5.53E-01
44	Xe-133	8.02E-02	0.00E+00	8.02E-02	4.44E-04	2.49E+04	1.11E+01
45	Xe-135	3.58E-02	0.00E+00	3.58E-02	2.73E-03	5.59E+04	1.53E+02
46	Xe-138	3.98E-03	0.00E+00	3.98E-03	1.17E-02	5.02E+05	5.87E+03
47	Y-91	1.56E+00	3.56E-03	1.56E+00	8.12E-04	1.28E+03	1.04E+00
48	Yb-169	3.49E+00	1.04E-03	3.49E+00	3.22E-03	5.73E+02	1.85E+00
49	Zr-95/Nb-95m/Nb-95	3.23E+01	3.08E-03	3.23E+01	1.55E-02	-	9.59E-01
	Zr-95	1.58E+01	2.37E-03	1.58E+01	7.63E-03	6.18E+01	-
	Nb-95m	1.42E+00	3.58E-04	1.42E+00	6.83E-04	4.31E-01	-
	Nb-95	1.65E+01	7.11E-04	1.65E+01	7.91E-03	6.18E+01	-

#	Radionuclide	ExDP_Dp (mrem·m ²)/μCi	InhDP_Dp (mrem·m ²)/μCi	TDP_Dp (mrem·m ²)/μCi	ExXF (mR·m ²)/(hr·μCi)	Dp_DRL μCi/m ²	XR_DRL mR/hr
1	Am-241	1.64E+00	5.47E+00	7.12E+00	2.38E-04	7.02E+01	1.67E-02
2	Ba-140/La-140	2.24E-08	6.54E-14	2.24E-08	2.56E-02	-	5.70E+08
	Ba-140	1.83E-09	5.47E-14	1.83E-09	2.09E-03	2.23E+10	-
	La-140	2.06E-08	1.07E-14	2.06E-08	2.35E-02	2.23E+10	-
3	Ce-141	2.96E-04	1.47E-08	2.96E-04	7.63E-04	1.69E+06	1.29E+03
4	Ce-144/Pr-144/Pr-144m	3.70E+00	8.57E-04	3.70E+00	1.95E-03	-	2.63E-01
	Ce-144	3.59E-01	8.57E-04	3.60E-01	1.89E-04	1.39E+03	-
	Pr-144m	2.26E-01	0.00E+00	2.26E-01	1.19E-04	2.47E+01	-
	Pr-144	3.34E+00	2.98E-07	3.34E+00	1.76E-03	1.39E+03	-
5	Cf-252	2.22E+01	1.45E+00	2.36E+01	4.72E-03	2.12E+01	1.00E-01
6	Cm-242	5.50E-03	3.93E-02	4.48E-02	7.28E-06	1.12E+04	8.13E-02
7	Cm-244	4.18E-02	3.07E+00	3.11E+00	6.39E-06	1.61E+02	1.03E-03
8	Co-60	1.43E+02	1.45E-03	1.43E+02	2.51E-02	3.50E+00	8.79E-02
9	Cs-134	6.82E+01	7.18E-04	6.82E+01	1.62E-02	7.33E+00	1.19E-01
10	Cs-136	3.39E-08	4.61E-14	3.39E-08	2.18E-02	1.47E+10	3.21E+08
11	Cs-137/Ba-137m	4.01E+01	2.16E-03	4.01E+01	6.00E-03	-	7.48E-02
	Cs-137	2.29E-01	2.16E-03	2.31E-01	3.42E-05	1.25E+01	-
	Ba-137m	4.21E+01	0.00E+00	4.21E+01	6.31E-03	1.18E+01	-
12	Gd-153	1.53E+00	3.16E-05	1.54E+00	1.01E-03	3.25E+02	3.27E-01
13	I-129	1.50E+00	2.04E-03	1.51E+00	2.18E-04	3.31E+02	7.21E-02
14	I-131	2.01E-14	4.03E-19	2.01E-14	3.99E-03	2.49E+16	9.93E+13
15	I-132	0.00E+00	0.00E+00	0.00E+00	2.38E-02	NA	NA
16	I-133	2.86E-128	6.84E-134	2.86E-128	6.80E-03	1.75E+130	1.19E+128
17	I-134	0.00E+00	0.00E+00	0.00E+00	2.72E-02	NA	NA
18	I-135/Xe-135m	0.00E+00	0.00E+00	0.00E+00	1.67E-02	-	NA
	I-135	0.00E+00	0.00E+00	0.00E+00	1.60E-02	NA	-
	Xe-135m	0.00E+00	0.00E+00	0.00E+00	4.54E-03	NA	-
19	Ir-192	5.61E-01	4.12E-06	5.61E-01	8.47E-03	8.91E+02	7.55E+00
20	Kr-87	0.00E+00	0.00E+00	0.00E+00	9.17E-03	NA	NA
21	Kr-88/Rb-88	0.00E+00	0.00E+00	0.00E+00	2.70E-02	-	NA
	Kr-88	0.00E+00	0.00E+00	0.00E+00	1.88E-02	NA	-
	Rb-88	0.00E+00	0.00E+00	0.00E+00	8.19E-03	NA	-
22	La-140	3.81E-66	2.04E-72	3.81E-66	2.35E-02	1.31E+68	3.09E+66
23	Mo-99/Tc-99m	1.14E-41	9.89E-47	2.69E-41	3.02E-03	-	5.62E+40
	Mo-99	1.72E-42	9.72E-47	1.72E-41	1.93E-03	1.86E+43	-
	Tc-99m	1.11E-41	1.98E-48	1.11E-41	1.25E-03	1.63E+43	-
24	Nb-95	5.98E-03	1.33E-08	5.98E-03	7.91E-03	8.36E+04	6.61E+02
25	Np-237/Pa-233	1.71E+01	2.83E+00	2.00E+01	2.47E-03	-	6.21E-02
	Np-237	1.84E+00	2.83E+00	4.67E+00	2.67E-04	2.51E+01	-
	Pa-233	1.53E+01	2.20E-04	1.53E+01	2.21E-03	2.51E+01	-
26	Np-239	2.68E-48	1.72E-53	2.68E-48	1.77E-03	1.87E+50	3.30E+47
27	Pm-147	1.44E-03	2.72E-04	1.71E-03	3.07E-07	2.92E+05	8.99E-02
28	Pu-238	4.48E-02	6.08E+00	6.12E+00	6.55E-06	8.17E+01	5.35E-04
29	Pu-239	2.31E-02	6.77E+00	6.79E+00	3.35E-06	7.36E+01	2.46E-04
30	Pu-241/U-237	3.13E-04	1.22E-01	1.22E-01	4.85E-08	-	1.99E-04
	Pu-241	1.01E-04	1.22E-01	1.22E-01	1.56E-08	4.10E+03	-
	U-237	8.66E+00	9.98E-05	8.66E+00	1.34E-03	1.00E-01	-

#	Radionuclide	ExDP_Dp (mrem·m ²)/μCi	InhDP_Dp (mrem·m ²)/μCi	TDP_Dp (mrem·m ²)/μCi	ExXF (mR·m ²)/(hr·μCi)	Dp_DRL μCi/m ²	XR_DRL mR/hr
31	Ra-226/Rn-222...	1.26E+02	5.43E-01	1.27E+02	1.83E-02	-	7.19E-02
	Ra-226	5.05E-01	5.41E-01	1.05E+00	7.28E-05	3.94E+00	-
	Rn-222	2.81E-02	0.00E+00	2.81E-02	4.07E-06	3.94E+00	-
	Po-218	5.02E-07	0.00E+00	5.02E-07	7.28E-11	3.94E+00	-
	At-218	9.44E-03	0.00E+00	9.44E-03	1.37E-06	7.87E-04	-
	Pb-214	1.84E+01	8.36E-04	1.84E+01	2.65E-03	3.94E+00	-
	Bi-214	1.07E+02	8.76E-04	1.07E+02	1.55E-02	3.94E+00	-
Po-214	5.95E-03	0.00E+00	5.95E-03	8.61E-07	3.94E+00	-	
32	Ru-103/Rh-103m	9.29E-03	5.26E-08	9.29E-03	5.19E-03	-	2.79E+02
	Ru-103	9.27E-03	5.26E-08	9.27E-03	5.18E-03	5.39E+04	-
	Rh-103m	1.61E-05	4.87E-11	1.61E-05	9.03E-06	5.37E+04	-
33	Ru-106/Rh-106	9.59E+00	1.42E-03	9.59E+00	3.78E-03	-	1.97E-01
	Ru-106	0.00E+00	1.42E-03	1.42E-03	0.00E+00	5.21E+01	-
	Rh-106	9.59E+00	0.00E+00	9.59E+00	3.78E-03	5.21E+01	-
34	Sb-127/Te-127	2.44E-29	7.10E-35	2.44E-29	7.51E-03	-	1.53E+29
	Sb-127	2.41E-29	6.69E-35	2.41E-29	7.42E-03	2.05E+31	-
	Te-127	3.72E-31	4.98E-36	3.72E-31	1.15E-04	1.69E+31	-
35	Sb-129/Te-129	0.00E+00	0.00E+00	0.00E+00	1.62E-02	-	NA
	Sb-129	0.00E+00	0.00E+00	0.00E+00	1.52E-02	NA	-
	Te-129	0.00E+00	0.00E+00	0.00E+00	1.27E-03	NA	-
36	Se-75	1.38E+00	4.30E-06	1.38E+00	3.89E-03	3.62E+02	1.41E+00
37	Sr-89	7.16E-03	7.37E-07	7.16E-03	7.49E-04	6.98E+04	5.23E+01
38	Sr-90/Y-90	8.15E+00	8.71E-03	8.16E+00	1.22E-03	-	7.46E-02
	Sr-90	1.20E-01	8.63E-03	1.28E-01	1.79E-05	6.13E+01	-
	Y-90	8.03E+00	8.25E-05	8.03E+00	1.20E-03	6.13E+01	-
39	Sr-91/Y-91m	3.41E-279	1.39E-285	3.41E-279	1.13E-02	-	1.65E+279
	Sr-91	2.44E-279	1.37E-285	2.44E-279	8.05E-03	1.47E+281	-
	Y-91m	1.68E-279	3.83E-287	1.68E-279	5.55E-03	8.48E+280	-
40	Te-129m/Te-129	7.55E-04	4.15E-08	7.56E-04	1.46E-03	-	9.68E+02
	Te-129m	3.29E-04	4.14E-08	3.30E-04	6.37E-04	6.61E+05	-
	Te-129	6.56E-04	2.05E-10	6.56E-04	1.27E-03	4.30E+05	-
41	Te-131m/Te-131	7.35E-89	5.46E-95	7.35E-89	1.60E-02	-	1.09E+89
	Te-131m	6.82E-89	5.43E-95	6.82E-89	1.48E-02	6.81E+90	-
	Te-131	2.37E-89	1.45E-96	2.37E-89	5.16E-03	1.51E+90	-
42	Te-132/I-132	4.72E-34	4.29E-40	4.72E-34	2.61E-02	-	2.77E+34
	Te-132	4.20E-35	4.06E-40	4.20E-35	2.32E-03	1.06E+36	-
	I-132	4.30E-34	2.26E-41	4.30E-34	2.38E-02	1.06E+36	-
43	Tm-170	1.17E-01	3.59E-05	1.17E-01	2.72E-04	4.27E+03	1.16E+00
44	Xe-133	7.63E-23	0.00E+00	7.63E-23	4.44E-04	6.55E+24	2.91E+21
45	Xe-135	2.39E-292	0.00E+00	2.39E-292	2.73E-03	2.09E+294	5.71E+291
46	Xe-138	0.00E+00	0.00E+00	0.00E+00	1.17E-02	NA	NA
47	Y-91	1.76E-02	1.86E-06	1.76E-02	8.12E-04	2.84E+04	2.31E+01
48	Yb-169	1.09E-03	1.03E-08	1.09E-03	3.22E-03	4.59E+05	1.48E+03
49	Zr-95/Nb-95m/Nb-95	5.29E-01	2.47E-06	5.29E-01	1.55E-02	-	1.47E+01
	Zr-95	2.59E-01	1.90E-06	2.59E-01	7.63E-03	9.45E+02	-
	Nb-95m	2.33E-02	2.86E-07	2.33E-02	6.83E-04	6.60E+00	-
	Nb-95	2.70E-01	5.68E-07	2.70E-01	7.91E-03	9.45E+02	-

#	Radionuclide	ExDP_Dp (mrem·m ²)/μCi	InhDP_Dp (mrem·m ²)/μCi	TDP_Dp (mrem·m ²)/μCi	ExXF (mR·m ²)/(hr·μCi)	Dp_DRL μCi/m ²	XR_DRL mR/hr
1	Am-241	4.53E+01	1.94E+02	2.39E+02	2.38E-04	2.09E+01	4.98E-03
2	Ba-140/La-140	1.12E+01	1.93E-03	1.12E+01	2.56E-02	-	2.29E-03
	Ba-140	9.12E-01	1.61E-03	9.13E-01	2.09E-03	4.47E+02	-
	La-140	1.03E+01	3.15E-04	1.03E+01	2.35E-02	4.47E+02	-
3	Ce-141	8.37E-01	1.32E-03	8.38E-01	7.63E-04	5.97E+03	9.10E-04
4	Ce-144/Pr-144/Pr-144m	1.64E+01	2.79E-02	1.64E+01	1.95E-03	-	5.94E-01
	Ce-144	1.59E+00	2.79E-02	1.62E+00	1.89E-04	3.04E+02	-
	Pr-144m	1.00E+00	0.00E+00	1.00E+00	1.19E-04	5.42E+00	-
	Pr-144	1.48E+01	9.69E-06	1.48E+01	1.76E-03	3.04E+02	-
5	Cf-252	1.13E+02	2.42E+01	1.37E+02	4.72E-03	3.65E+01	1.72E-01
6	Cm-242	3.72E-02	2.86E+00	2.90E+00	7.28E-06	1.73E+03	1.26E-02
7	Cm-244	6.41E-01	7.01E+01	7.08E+01	6.39E-06	7.06E+01	4.66E-04
8	Co-60	1.06E+03	2.40E-02	1.06E+03	2.51E-02	4.73E+00	1.19E-01
9	Cs-134	3.14E+02	1.27E-02	3.14E+02	1.62E-02	1.59E+01	2.58E-01
10	Cs-136	9.77E+00	7.73E-04	9.77E+00	2.18E-02	5.12E+02	1.11E+01
11	Cs-137/Ba-137m	7.60E+02	5.70E-02	7.60E+02	6.00E-03	-	3.94E-02
	Cs-137	4.34E+00	5.70E-02	4.39E+00	3.42E-05	6.57E+00	-
	Ba-137m	7.99E+02	0.00E+00	7.99E+02	6.31E-03	6.22E+00	-
12	Gd-153	7.33E+00	1.24E-03	7.34E+00	1.01E-03	6.82E+02	6.86E-01
13	I-129	4.28E+01	7.42E-02	4.28E+01	2.18E-04	1.17E+02	2.54E-02
14	I-131	1.10E+00	1.77E-03	1.11E+00	3.99E-03	4.52E+03	1.81E+01
15	I-132	7.90E-02	1.29E-06	7.90E-02	2.38E-02	6.33E+04	1.51E+03
16	I-133	2.04E-01	1.21E-04	2.04E-01	6.80E-03	2.45E+04	1.67E+02
17	I-134	3.44E-02	2.42E-07	3.44E-02	2.72E-02	1.45E+05	3.96E+03
18	I-135/Xe-135m	1.60E-01	1.03E-05	1.60E-01	1.67E-02	-	5.24E+02
	I-135	1.53E-01	1.03E-05	1.53E-01	1.60E-02	3.13E+04	-
	Xe-135m	4.32E-02	0.00E+00	4.32E-02	4.54E-03	4.82E+03	-
19	Ir-192	2.06E+01	2.77E-03	2.06E+01	8.47E-03	2.42E+02	2.05E+00
20	Kr-87	1.68E-02	0.00E+00	1.68E-02	9.17E-03	2.98E+04	2.72E+03
21	Kr-88/Rb-88	1.11E-01	3.87E-07	1.11E-01	2.70E-02	-	1.22E+03
	Kr-88	7.70E-02	0.00E+00	7.70E-02	1.88E-02	4.53E+04	-
	Rb-88	3.35E-02	3.87E-07	3.35E-02	8.19E-03	4.53E+04	-
22	La-140	1.36E+00	1.40E-04	1.36E+00	2.35E-02	3.67E+02	2.35E-02
23	Mo-99/Tc-99m	2.87E-01	1.60E-04	2.87E-01	3.02E-03	-	5.26E+01
	Mo-99	1.84E-01	1.57E-04	1.84E-01	1.93E-03	1.74E+04	-
	Tc-99m	1.18E-01	3.17E-06	1.18E-01	1.25E-03	1.52E+04	-
24	Nb-95	9.41E+00	6.26E-04	9.41E+00	7.91E-03	5.31E+02	4.21E+00
25	Np-237/Pa-233	4.86E+02	1.03E+02	5.89E+02	2.47E-03	-	2.10E-02
	Np-237	5.24E+01	1.03E+02	1.55E+02	2.67E-04	8.49E+00	-
	Pa-233	4.34E+02	7.98E-03	4.34E+02	2.21E-03	8.49E+00	-
26	Np-239	1.44E-01	1.51E-04	1.44E-01	1.77E-03	3.47E+04	6.14E+01
27	Pm-147	7.29E-03	4.57E-03	1.18E-02	3.07E-07	4.22E+05	1.30E-01
28	Pu-238	1.09E+00	1.95E+02	1.96E+02	6.55E-06	2.55E+01	1.67E-04
29	Pu-239	6.57E-01	2.46E+02	2.46E+02	3.35E-06	2.03E+01	6.78E-05
30	Pu-241/U-237	4.26E-03	2.58E+00	2.59E+00	4.85E-08	-	9.38E-05
	Pu-241	1.37E-03	2.58E+00	2.59E+00	1.56E-08	1.93E+03	-
	U-237	1.18E+02	2.12E-03	1.18E+02	1.34E-03	4.73E-02	-

#	Radionuclide	ExDP_Dp (mrem·m ²)/μCi	InhDP_Dp (mrem·m ²)/μCi	TDP_Dp (mrem·m ²)/μCi	ExXF (mR·m ²)/(hr·μCi)	Dp_DRL μCi/m ²	XR_DRL mR/hr
31	Ra-226/Rn-222...	3.55E+03	1.96E+01	3.57E+03	1.83E-02	-	2.55E-02
	Ra-226	1.42E+01	1.95E+01	3.37E+01	7.28E-05	1.40E+00	-
	Rn-222	7.92E-01	0.00E+00	7.92E-01	4.07E-06	1.40E+00	-
	Po-218	1.42E-05	0.00E+00	1.42E-05	7.28E-11	1.40E+00	-
	At-218	2.66E-01	0.00E+00	2.66E-01	1.37E-06	2.80E-04	-
	Pb-214	5.17E+02	3.01E-02	5.17E+02	2.65E-03	1.40E+00	-
	Bi-214	3.02E+03	3.16E-02	3.02E+03	1.55E-02	1.40E+00	-
Po-214	1.68E-01	0.00E+00	1.68E-01	8.61E-07	1.40E+00	-	
32	Ru-103/Rh-103m	6.86E+00	1.08E-03	6.86E+00	5.19E-03	-	3.78E+00
	Ru-103	6.85E+00	1.08E-03	6.85E+00	5.18E-03	7.29E+02	-
	Rh-103m	1.19E-02	1.00E-06	1.19E-02	9.03E-06	7.27E+02	-
33	Ru-106/Rh-106	3.99E+01	1.81E-03	3.99E+01	3.78E-03	-	4.73E-01
	Ru-106	0.00E+00	1.81E-03	3.62E-02	0.00E+00	1.25E+02	-
	Rh-106	3.99E+01	0.00E+00	3.99E+01	3.78E-03	1.25E+02	-
34	Sb-127/Te-127	1.00E+00	3.64E-04	1.00E+00	7.51E-03	-	3.76E+01
	Sb-127	9.87E-01	3.43E-04	9.88E-01	7.42E-03	5.00E+03	-
	Te-127	1.52E-02	2.56E-05	1.53E-02	1.15E-04	4.12E+03	-
35	Sb-129/Te-129	1.01E-01	5.96E-06	1.01E-01	1.62E-02	-	8.05E+02
	Sb-129	9.46E-02	5.31E-06	9.46E-02	1.52E-02	4.96E+04	-
	Te-129	7.90E-03	8.35E-07	7.90E-03	1.27E-03	3.85E+04	-
36	Se-75	1.49E+01	6.14E-04	1.49E+01	3.89E-03	3.35E+02	1.30E+00
37	Sr-89	1.27E+00	3.08E-03	1.27E+00	7.49E-04	3.93E+03	2.95E+00
38	Sr-90/Y-90	1.53E+02	2.28E-01	1.53E+02	1.22E-03	-	3.98E-02
	Sr-90	2.25E+00	2.26E-01	2.47E+00	1.79E-05	3.27E+01	-
	Y-90	1.51E+02	2.16E-03	1.51E+02	1.20E-03	3.27E+01	-
39	Sr-91/Y-91m	1.54E-01	1.84E-05	1.54E-01	1.13E-02	-	3.65E+02
	Sr-91	1.10E-01	1.81E-05	1.10E-01	8.05E-03	3.25E+04	-
	Y-91m	7.60E-02	5.07E-07	7.60E-02	5.55E-03	1.88E+04	-
40	Te-129m/Te-129	1.66E+00	2.81E-03	1.66E+00	1.46E-03	-	4.40E+00
	Te-129m	7.23E-01	2.80E-03	7.26E-01	6.37E-04	3.01E+03	-
	Te-129	1.44E+00	1.39E-05	1.44E+00	1.27E-03	1.96E+03	-
41	Te-131m/Te-131	6.92E-01	1.12E-04	6.93E-01	1.60E-02	-	1.16E+02
	Te-131m	6.42E-01	1.11E-04	6.43E-01	1.48E-02	7.22E+03	-
	Te-131	2.23E-01	2.96E-06	2.23E-01	5.16E-03	1.60E+03	-
42	Te-132/I-132	2.94E+00	3.68E-04	2.94E+00	2.61E-02	-	4.45E+01
	Te-132	2.62E-01	3.49E-04	2.62E-01	2.32E-03	1.70E+03	-
	I-132	2.68E+00	1.94E-05	2.68E+00	2.38E-02	1.70E+03	-
43	Tm-170	1.11E+00	4.31E-03	1.12E+00	2.72E-04	4.47E+03	1.22E+00
44	Xe-133	8.02E-02	0.00E+00	8.02E-02	4.44E-04	6.23E+04	2.77E+01
45	Xe-135	3.58E-02	0.00E+00	3.58E-02	2.73E-03	1.40E+05	3.82E+02
46	Xe-138	3.98E-03	0.00E+00	3.98E-03	1.17E-02	1.26E+06	1.47E+04
47	Y-91	1.58E+00	3.57E-03	1.58E+00	8.12E-04	3.16E+03	2.57E+00
48	Yb-169	3.49E+00	1.04E-03	3.49E+00	3.22E-03	1.43E+03	4.61E+00
49	Zr-95/Nb-95m/Nb-95	3.29E+01	3.08E-03	3.29E+01	1.55E-02	-	2.36E+00
	Zr-95	1.61E+01	2.37E-03	1.61E+01	7.63E-03	1.52E+02	-
	Nb-95m	1.45E+00	3.58E-04	1.45E+00	6.83E-04	1.06E+00	-
	Nb-95	1.68E+01	7.12E-04	1.68E+01	7.91E-03	1.52E+02	-

This Table is RESERVED for the future inclusion of Skin Dose Data.

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Table 6-1 Gamma Cloud Source Shielding Factors

Structure or Location	Shielding Factor ^a
Outside	1.0
Vehicles	1.0
Wood frame house ^b (no basement)	0.9
Basement of wood frame house	0.6
Masonry house (no basement)	0.6
Basement of masonry house	0.4
Large office or industrial building	0.2

Source: EGG75

^a Ratio of the interior dose to the exterior dose.

^b A wood frame house with brick or stone veneer is approximately equivalent to a masonry house for shielding purposes.

Table 6-2 Surface Deposition Shielding Factors

Structure or Location	Representative Shielding Factor ^a
Cars on fully contaminated road	0.5
Cars on fully decontaminated 50-foot road	0.25
Trains	0.4
One- and two-story wood-frame house (no basement)	0.4 ^b
One- and two-story block and brick house (no basement)	0.2 ^b
House basement, one or two walls fully exposed	0.1 ^b
One story, less than two feet of basement, wall exposed	0.05 ^b
Two stories, less than two feet of basement, wall exposed	0.03 ^b
Three- or four-story structures, 5,000 to 10,000 square feet per floor	
First and second floors	0.05 ^b
Basement	0.01 ^b
Multi-story structures, greater than 10,000 square feet per floor	
Upper floors	0.01 ^b
Basement	0.005 ^b

Source: EGG75

^a Ratio of the interior dose to the exterior dose.

^b Away from doors and windows.

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The default breathing rate used in the Methods in Volume 1 is the average breathing rate for an adult male. This table lists the breathing rates for all age groups from ICRP Publication 66 (ICRP94).

Age Group	Activity								Total Volume m ³ /day	Activity Avg. Rate m ³ /hr
	Sleeping		Sitting		Light Activity		Heavy Activity			
	Rate m ³ /hr	Time hr/day								
Newborn (3 month)	0.09	17.0	NA	NA	0.19	7.0	NA	NA	2.86	0.12
Infant (1 year)	0.15	14.0	0.22	3.33	0.35	6.67	NA	NA	5.17	0.22
5 yr old	0.24	12.0	0.32	4.0	0.57	8.0	NA	NA	8.72	0.36
10 yr old	0.31	10.0	0.38	4.67	1.12	9.33	NA	NA	15.33	0.64
15 yr old (f)	0.35	10.0	0.4	7.0	1.3	6.75	2.57	0.25	15.72	0.65
15 yr old (m)	0.42	10.0	0.48	5.5	1.38	7.5	2.92	1.0	20.11	0.84
Adult (f) (Sedentary)	0.32	8.5	0.39	5.5	1.25	9.75	2.7	0.25	17.73	0.74
Adult (m) (Sedentary)	0.45	8.5	0.54	5.5	1.5	9.75	3.0	0.25	22.17	0.92

See ICRP94, Tables 8, B.16A, and B.16B for methods to calculate breathing rates.

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This table includes an abbreviated list of radionuclides compared to the list tabulated in other sections of this appendix. Parent radionuclides with a half life less than 6 hours are excluded from ingestion pathway analysis because it is unlikely that a quantity that is sufficient to cause an ingestion concern could be dispersed. Noble Gases are excluded from ingestion pathway analysis because Ingestion Dose Coefficients are currently not available.

Daughter radionuclides in transient (or secular) equilibrium are excluded from independent ingestion pathway analysis because their contribution to dose is included in the dose coefficient of the ultimate parent. Daughter radionuclides with a half life greater than 6 hours **are included in the list below separately from the parent radionuclide** because it may be possible to disperse a quantity of these radionuclides that is sufficient to cause an ingestion concern before significant decay occurs without the parent radionuclide being present.

Radionuclide	FDA Listed	DIL ^a ($\mu\text{Ci}/\text{kg}$)	Mature Crop_DRL ^b ($\mu\text{Ci}/\text{m}^2$)	Leafy TF ($\text{kg}_{\text{soil}}/\text{kg}$)	Fruit TF ($\text{kg}_{\text{soil}}/\text{kg}$)	Root TF ($\text{kg}_{\text{soil}}/\text{kg}$)	Grain TF ($\text{kg}_{\text{soil}}/\text{kg}$)	Milk_DRL ^c (area) ($\mu\text{Ci}/\text{m}^2$)	Milk_DRL ^c (mass) ($\mu\text{Ci}/\text{kg}_{\text{wet}}$)	Milk_DRL ^c (water) ($\mu\text{Ci}/\text{l}$)	Milk TF ^c (d/l)	Meat TF ^d (d/kg)
Am-241	Y ^e	5.4E-05	5.4E-04	4.7E-04	2.5E-04	3.5E-04	2.2E-05	1.0E+00	7.2E-01	6.0E-01	1.5E-06	4.0E-05
Ba-140	Y	1.9E-01	1.9E+00	1.5E-01	1.5E-02	1.5E-02	1.5E-02	1.1E+01	7.9E+00	6.6E+00	4.8E-04	2.0E-04
Ce-141	Y	1.9E-01	1.9E+00	2.0E-02	2.0E-02	2.0E-02	2.0E-02	1.8E+02	1.3E+02	1.1E+02	3.0E-05	2.0E-05
Ce-144	Y	1.4E-02	1.4E-01	2.0E-02	2.0E-02	2.0E-02	2.0E-02	1.3E+01	9.4E+00	7.8E+00	3.0E-05	2.0E-05
Cf-252		1.0E-04	1.0E-03	4.7E-04 ^f	2.5E-04	3.5E-04	2.2E-05	1.9E+00	1.3E+00	1.1E+00	1.5E-06	4.0E-05
Cm-242	Y	5.1E-04	5.1E-03	7.7E-04	1.5E-05	4.3E-04	2.1E-05	7.1E-01	5.1E-01	4.3E-01	2.0E-05	4.0E-05
Cm-244	Y	5.4E-05	5.4E-04	7.7E-04	1.5E-05	4.3E-04	2.1E-05	7.5E-02	5.4E-02	4.5E-02	2.0E-05	4.0E-05
Co-60		2.0E-02	2.0E-01	2.3E-01	7.0E-03	6.7E-02	3.7E-03	1.9E+00	1.3E+00	1.1E+00	3.0E-04	1.0E-02
Cs-134	Y ^g	2.5E-02	2.5E-01	4.6E-01	2.2E-01	1.3E-01	2.6E-02	8.8E-02	6.3E-02	5.3E-02	7.9E-03	5.0E-02
Cs-136		3.1E-01	3.3E+00	4.6E-01	2.2E-01	1.3E-01	2.6E-02	1.2E+00	8.7E-01	7.3E-01	7.9E-03	5.0E-02
Cs-137	Y ^g	3.7E-02	3.7E-01	4.6E-01	2.2E-01	1.3E-01	2.6E-02	1.3E-01	9.4E-02	7.8E-02	7.9E-03	5.0E-02
Gd-153		3.6E-01	3.6E+00	2.0E-02	2.0E-02	2.0E-02	2.0E-02	3.3E+02	2.4E+02	2.0E+02	3.0E-05	2.0E-05
I-129	Y	1.5E-03	3.0E-03	4.0E-02	4.0E-02	4.0E-02	4.0E-02	2.3E-03	3.3E-03	2.8E-03	9.0E-03	4.0E-02
I-131	Y	4.6E-03	1.0E-02	4.0E-02	4.0E-02	4.0E-02	4.0E-02	8.5E-03	1.2E-02	1.0E-02	9.0E-03	4.0E-02
I-133	Y	1.9E-01	8.5E-01	4.0E-02	4.0E-02	4.0E-02	4.0E-02	1.5E+00	2.1E+00	1.7E+00	9.0E-03	4.0E-02
I-135		3.2E+00	8.0E+01	4.0E-02	4.0E-02	4.0E-02	4.0E-02	7.7E+02	1.1E+03	9.2E+02	9.0E-03	4.0E-02
Ir-192		7.9E-02	8.0E-01	5.5E-02	1.5E-02	1.5E-02	1.5E-02	1.1E+03	8.0E+02	6.7E+02	2.0E-06	1.5E-03
La-140		1.8E+00	2.7E+01	5.2E-03	4.0E-03	3.5E-04	4.0E-03	5.7E+03	4.1E+03	3.4E+03	2.0E-05	2.0E-03
Mo-99		4.0E+00	5.1E+01	8.0E-01	5.0E-02	8.0E-01	8.0E-01	1.1E+02	7.8E+01	6.5E+01	1.7E-03	1.0E-03
Nb-95	Y	3.2E-01	3.3E+00	2.5E-02	2.5E-02	2.5E-02	2.5E-02	2.3E+04	1.6E+04	1.4E+04	4.1E-07	3.0E-07
Nb-95m		2.3E+00	2.8E+01	2.5E-02	2.5E-02	2.5E-02	2.5E-02	2.3E+05	1.6E+05	1.4E+05	4.1E-07	3.0E-07
Np-237	Y	1.1E-04	1.1E-03	3.2E-02	1.0E-02	1.3E-02	2.7E-03	6.1E-01	4.4E-01	3.7E-01	5.0E-06	1.0E-03

Radionuclide	FDA Listed	DIL ^a ($\mu\text{Ci}/\text{kg}$)	Mature Crop_DRL ^b ($\mu\text{Ci}/\text{m}^2$)	Leafy TF ($\text{kg}_{\text{soil}}/\text{kg}$)	Fruit TF ($\text{kg}_{\text{soil}}/\text{kg}$)	Root TF ($\text{kg}_{\text{soil}}/\text{kg}$)	Grain TF ($\text{kg}_{\text{soil}}/\text{kg}$)	Milk_DRL ^c (area) ($\mu\text{Ci}/\text{m}^2$)	Milk_DRL ^c (mass) ($\mu\text{Ci}/\text{kg}_{\text{wet}}$)	Milk_DRL ^c (water) ($\mu\text{Ci}/\text{l}$)	Milk TF ^c (d/l)	Meat TF ^d (d/kg)
Np-239	Y	7.6E-01	1.0E+01	3.2E-02	1.0E-02	1.3E-02	2.7E-03	7.6E+03	5.5E+03	4.6E+03	5.0E-06	1.0E-03
Pa-233		1.9E-01	1.9E+00	4.7E-04	2.5E-04	3.5E-04	2.2E-05	1.1E+03	8.0E+02	6.7E+02	5.0E-06	4.0E-05
Pm-147		3.0E-01	3.0E+00	2.0E-02	2.0E-02	2.0E-02	2.0E-02	2.8E+02	2.0E+02	1.7E+02	3.0E-05	2.0E-05
Pu-238	Y ^e	6.8E-05	6.8E-04	6.0E-05	4.5E-05	1.1E-03	8.6E-06	1.7E+00	1.2E+00	1.0E+00	1.1E-06	1.0E-05
Pu-239	Y ^e	6.0E-05	6.0E-04	6.0E-05	4.5E-05	1.1E-03	8.6E-06	1.5E+00	1.1E+00	9.1E-01	1.1E-06	1.0E-05
Pu-241	Y	3.2E-03	3.2E-02	6.0E-05	4.5E-05	1.1E-03	8.6E-06	8.1E+01	5.8E+01	4.8E+01	1.1E-06	1.0E-05
Ra-226		5.5E-05	5.5E-04	4.9E-02	6.1E-03	2.0E-03	1.2E-03	1.2E-03	8.5E-04	7.1E-04	1.3E-03	9.0E-04
Ru-103	Y ^h	1.8E-01	1.8E+00	4.0E-02	4.0E-02	4.0E-02	5.0E-03	1.6E+03	1.1E+03	9.4E+02	3.3E-06	5.0E-02
Ru-106	Y ^h	1.2E-02	1.2E-01	4.0E-02	4.0E-02	4.0E-02	5.0E-03	1.0E+02	7.3E+01	6.1E+01	3.3E-06	5.0E-02
Sb-127		8.5E-01	1.0E+01	1.3E-04	8.0E-05	5.6E-04	3.0E-02	1.4E+03	9.7E+02	8.1E+02	2.5E-05	1.0E-03
Se-75		5.5E-02	5.5E-01	2.5E-01	5.0E-02	5.0E-02	2.5E-01	3.9E-01	2.8E-01	2.3E-01	4.0E-03	1.5E-02
Sr-89	Y	3.8E-02	3.9E-01	3.0E+00	2.0E-01	5.0E-01	2.1E-01	3.9E-01	2.8E-01	2.3E-01	2.8E-03	8.0E-03
Sr-90	Y	4.3E-03	4.3E-02	3.0E+00	2.0E-01	5.0E-01	2.1E-01	4.3E-02	3.1E-02	2.6E-02	2.8E-03	8.0E-03
Sr-91		2.9E+01	1.7E+03	3.0E+00	2.0E-01	5.0E-01	2.1E-01	9.5E+03	6.9E+03	5.7E+03	2.8E-03	8.0E-03
Tc-99m		1.2E+03	1.9E+05	2.1E+02	1.5E+00	2.4E-01	7.3E-01	5.9E+07	4.3E+07	3.6E+07	1.4E-04	1.0E-04
Te-127		1.0E+02	5.9E+03	2.5E-02	4.0E-03	4.0E-03	4.0E-03	2.2E+05	1.6E+05	1.3E+05	4.5E-04	7.0E-03
Te-129m		4.0E-02	4.1E-01	2.5E-02	4.0E-03	4.0E-03	4.0E-03	2.6E+00	1.9E+00	1.5E+00	4.5E-04	7.0E-03
Te-131m		1.8E+00	3.1E+01	2.5E-02	4.0E-03	4.0E-03	4.0E-03	3.4E+02	2.4E+02	2.0E+02	4.5E-04	7.0E-03
Te-132	Y	1.2E-01	1.5E+00	2.5E-02	4.0E-03	4.0E-03	4.0E-03	1.1E+01	8.2E+00	6.8E+00	4.5E-04	7.0E-03
Tm-170 ⁱ		5.6E-02	5.6E-01	2.0E-02	2.0E-02	2.0E-02	2.0E-02	5.2E+01	3.8E+01	3.1E+01	3.0E-05	2.0E-05
U-237		9.2E-01	1.0E+01	8.3E-03	4.0E-03	1.2E-02	1.3E-03	7.8E+01	5.7E+01	4.7E+01	4.0E-04	3.0E-04
Y-90		6.2E-01	8.0E+00	1.0E-02	1.0E-02	1.0E-02	1.0E-02	1.4E+03	1.0E+03	8.7E+02	2.0E-05	1.0E-03
Y-91	Y	3.2E-02	3.2E-01	1.0E-02	1.0E-02	1.0E-02	1.0E-02	4.5E+01	3.3E+01	2.7E+01	2.0E-05	1.0E-03
Yb-169 ⁱ		2.4E-01	2.5E+00	2.0E-02	2.0E-02	2.0E-02	2.0E-02	3.5E+02	2.5E+02	2.1E+02	3.0E-05	2.0E-05
Zr-95	Y	1.1E-01	1.1E+00	1.0E-03	1.0E-03	1.0E-03	1.0E-03	5.7E+03	4.1E+03	3.4E+03	5.5E-07	1.0E-06

Notes:

- ^a Calculated DILs are based on the ICRP 60+ dosimetry model for the most sensitive organ of the most sensitive age group. Fraction of Diet Contaminated is assumed to be 0.3 except for ¹³²Te, ¹³¹I, ¹³³I and ²³⁹Np in the diet of an Infant, where it is assumed to be 1.0. (See Volume 1, Method 4.1.)
- ^b Assumes Crops are ready to harvest. (See Volume 1, Method 4.2 for assumptions and default inputs.)
- ^c Values for Cow's Milk. See Volume 1, Method 4.3. Transfer Factors from PNNL-13421.
- ^d Values for Beef. See Volume 1, Method 4.4. Transfer Factors from PNNL-13421.
- ^e These radionuclides are grouped for evaluation purposes. When more than one of these nuclides is present the TOTAL amount of the radionuclides is compared to a group DIL of 5.4E-05 μCi/kg.
- ^f Two values for Cf are reported in the reference. The most conservative is in the table, the other is 2.5E-04.
- ^g These radionuclides are grouped for evaluation purposes. When more than one of these nuclides is present the TOTAL amount of the radionuclides is compared to a group DIL of 3.2E-02 μCi/kg.
- ^h ¹⁰³Ru and ¹⁰⁶Ru DIL is based on Sum of Fractions (¹⁰³Ru /0.18) +(¹⁰⁶Ru /0.012) <1. For the purposes of this table, we are assuming only ONE isotope is present.
- ⁱ No specific Transfer Factors listed in PNNL-13421. Lanthanides are assigned the Ce value per Section 1.3 of the document.

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Table 9-1 Dry-to-Wet Mass ^a

Plant Type	Mass Conversion Factor kg_{dry}/kg_{wet}
Leafy vegetables	0.2
Other/root vegetables	0.25
Fruit	0.18
Grain	0.91
Animal Feed	
Forage	0.22
Stored hay	0.22
Stored grain	0.91

^a Values from PNNL03, Table 2.1.

Inverse values for converting from wet to dry:

Table 9-2 Wet-to-Dry Mass

Plant Type	Mass Conversion Factor kg_{wet}/kg_{dry}
Leafy vegetables	5
Other/root vegetables	4
Fruit	5.56
Grain	1.1
Animal Feed	
Forage	4.55
Stored hay	4.55
Stored grain	1.1

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This table lists the average DFIR for populations of various ages in the United States. All values except the total annual intake are given in grams per day. The annual intake is given in kilograms per year.

Food Category	Daily Consumption (kg/day)					
	3 months	1 year	5 years	10 years	15 years	Adult
Total Dairy	5.7E-01	4.9E-01	4.6E-01	5.0E-01	4.8E-01	2.9E-01
Fresh Cow's Milk	2.7E-01	3.2E-01	4.1E-01	4.5E-01	4.3E-01	2.4E-01
Other	3.0E-01	1.7E-01	4.4E-02	5.0E-02	5.3E-02	5.2E-02
Fresh Eggs	4.9E-03	1.2E-02	1.8E-02	1.8E-02	2.2E-02	2.9E-02
Total Meat	4.5E-02	6.9E-02	1.1E-01	1.4E-01	1.7E-01	1.9E-01
Beef	1.8E-02	3.0E-02	5.3E-02	7.3E-02	9.1E-02	9.8E-02
Pork	5.8E-03	9.7E-03	1.6E-02	2.0E-02	2.6E-02	3.1E-02
Poultry	1.8E-02	1.9E-02	2.2E-02	2.7E-02	3.2E-02	3.3E-02
Other	2.6E-03	1.0E-02	2.0E-02	2.4E-02	2.7E-02	2.7E-02
Total Fish	9.0E-04	3.8E-03	8.8E-03	1.2E-02	1.5E-02	1.9E-02
Fin Fish	6.0E-04	3.5E-03	8.2E-03	1.1E-02	1.3E-02	1.6E-02
Shellfish	3.0E-04	3.0E-04	6.0E-04	1.1E-03	1.7E-03	3.0E-03
Total Produce	1.6E-01	1.6E-01	1.9E-01	2.4E-01	2.6E-01	2.9E-01
Leafy	3.2E-03	6.2E-03	1.5E-02	2.3E-02	2.9E-02	4.2E-02
Exposed	7.6E-02	6.6E-02	6.2E-02	7.3E-02	7.4E-02	8.3E-02
Protected	5.1E-02	7.3E-02	1.1E-01	1.4E-01	1.5E-01	1.5E-01
Other	2.6E-02	1.5E-02	6.2E-03	7.8E-03	7.2E-03	6.5E-03
Total Grains	5.6E-02	1.1E-01	1.9E-01	2.3E-01	2.5E-01	2.1E-01
Breads	1.6E-02	6.0E-02	1.3E-01	1.7E-01	1.9E-01	1.6E-01
Cereals	3.8E-02	3.8E-02	3.9E-02	3.8E-02	3.3E-02	2.6E-02
Other	1.8E-03	8.3E-03	1.9E-02	2.4E-02	2.7E-02	2.5E-02
Total Beverages	3.1E-01	5.2E-01	8.0E-01	9.4E-01	1.1	1.5
Tap Water	1.7E-01	3.0E-01	4.8E-01	5.7E-01	6.4E-01	6.8E-01
Water-Based Drinks	8.3E-03	5.3E-02	1.1E-01	1.3E-01	1.7E-01	4.7E-01
Soups	1.0E-02	2.7E-02	4.0E-02	3.6E-02	3.5E-02	4.4E-02
Other	1.2E-01	1.4E-01	1.8E-01	2.1E-01	2.9E-01	3.3E-01
Miscellaneous	5.5E-03	1.6E-02	3.1E-02	3.9E-02	3.9E-02	3.4E-02
Total Daily Intake	1.1	1.4	1.8	2.1	2.4	2.6
Total Annual Intake (kg/yr)	420	510	660	780	870	940

Sources: EPA84, FDA98 (Rounded to 2 significant figures.)

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The parameters in this table can vary depending on several environmental factors. The FRMAC Assessment Working Group has determined that these values are reasonable over a wide variety of conditions and should be used as the defaults for the methods in this Manual.

Parameter	Description	Value ^a
Animal Feed Daily Ingestion Rate (AFDIR)	Milk Cow	50 kg/d
	Beef Cattle	50 kg/d
	Goat	6 kg/d
Animal Soil Daily Ingestion Rate (ASDIR)	Milk Cow	0.5 kg/d ^b
	Beef Cattle	0.5 kg/d ^b
	Goat	0.06 kg/d ^{b,c}
Animal Water Daily Ingestion Rate (AWDIR)	Milk Cow	60 l/d
	Beef Cattle	50 l/d
	Goat	8 l/d
Crop Retention Factor (CRF)	Pastureland	0.5 ^d
	Pastureland, Iodines	1.0
	Fresh produce, particulates	0.2
	Fresh produce, Iodines	1.0
	Crops planted AFTER deposition	0.0
Time to Market (t _m)	Crop/Produce	1 d
	Milk	2 d
	Meat	20 d
Crop Yield (Y)	Produce	2.0 kg/m ²
	Pastureland	0.7 kg/m ²
Crop Weathering Half life (t _{1/2})		15 d ^e

^a All values from NRC77 unless otherwise indicated.

^b ANL01

^c Goat value estimated based on ratio of Feed to Soil for Cows (100:1).

^d Ng77 (Appendix B, page 113)

^e NCRP07 (Page 165)

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SI PREFIXES

E	exa	10 ¹⁸
P	peta	10 ¹⁵
T	tera	10 ¹²
G	giga	10 ⁹

M	mega	10 ⁶
k	kilo	10 ³
c	centi	10 ⁻²
m	milli	10 ⁻³

μ	micro	10 ⁻⁶
n	nano	10 ⁻⁹
p	pico	10 ⁻¹²

RADIATION

Absorbed Dose:	100 rad = 1 Gy
Dose Equivalent:	100 rem = 1 Sv
Activity:	1 Ci = 3.7E+10 dps = 37 GBq 1 Bq = 1 dps = 27 pCi
Specific Activity:	1 μCi/kg = 1000 pCi/g
Areal Activity:	1 μCi/m ² = 1 Ci/km ² = 100 pCi/cm ²
Volumetric Activity:	1 Ci/m ³ = 1 mCi/L = 1 μCi/cm ³
Dose Conversion:	1 Sv/Bq = 3.7E+11 rem/Ci
Dose Rate Conversion:	1 (mrem/yr)/(μCi/m ²) = 0.114 (rem/hr)/(Ci/m ²)

TIME

		s	min	hr	d	yr
1 s	=	1	1.67E-02	2.78E-04	1.16E-05	3.17E-08
1 m	=	60	1	1.67E-02	6.94E-04	1.90E-06
1 hr	=	3600	60	1	4.17E-02	8760
1 d	=	8.64E+04	1.44E+03	24	1	2.74E-03
1 yr	=	3.15E+07	5.26E+05	8760	365	1

TEMPERATURE & PRESSURE

$^{\circ}\text{K} = ^{\circ}\text{C} + 273$ $^{\circ}\text{F} = (^{\circ}\text{C} \times 1.8) + 32$ $^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$		lb/in 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

MiscWater Density = (1 g/cm³ at 4°C)Air Density = (0.001293 g/cm³ at STP)1 ft³ = 7.48 gal = 62.4 lb1 ft³ = 0.0807 lb

1 gal = 8.33 lb

1 m³ = 1.29 kg

Avogadro 's number

Molar Volume

6.02E+23 per g-mole

22.4 L/g-mole

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SUPPLEMENTS

Supplement 1: Decay and Ingrowth calculations..... F1-1

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Reference	Title
10 CFR 20	<i>Standards for Protection Against Radiation</i> , Code of Federal Regulations, Title 10, Energy, Part 20.
An02	Anspaugh, L. R., et al., “Movement of Radionuclides in Terrestrial Exosystems by Physical Processes” in <i>Health Physics</i> , Vol. 82, pp. 670-679, April 2002.
ANL01	Yu, C., et al., <i>User's Manual for RESRAD</i> , ver. 6, Argonne National Laboratory, Argonne, IL, 2001.
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DHS08	<i>Planning Guidance for Protection and Recovery Following Radiological Dispersal Device and Improvised Nuclear Device Incidents</i> , U.S. Department of Homeland Security, Washington, DC, Federal Register, August 1, 2008.
DNA75	Place, W. M., Cobb, F. C., and Defferding, C. G., <i>Palomares Summary Report</i> , AD-A955702, U.S. Defense Nuclear Agency, Washington, DC, January 1975.
DOE01	<i>Radiological Emergency Response Health and Safety Manual</i> , DOE/NV/11718--440, U.S. Department of Energy, Washington, DC, May 2001.
DOE01a	<i>A Preliminary Review of the Flow and Characteristics of Recycled Uranium Throughout the DOE Complex 1952-1999</i> , U.S. Department of Energy, Washington, DC, March 2001.
DOE01b	<i>Guide of Good Practices for Occupational Radiological Protection in Uranium Facilities</i> , DOE-STD-1136-2000, rev. 2, U.S. Department of Energy, Washington, DC, March 2001.
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