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FEDERAL RADIOLOGICAL

MONITORING AND ASSESSMENT CENTER

FRMAC ASSESSMENT MANUAL

VOLUME 3

Pre-Assessed Default Scenarios

The Federal Manual for Assessing Environmental Data During a Radiological Emergency

May 2023

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FRMAC Assessment Manual

Volume 3

Pre-Assessed Default Scenarios

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PREFACE

The Federal Radiological Monitoring and Assessment Center (FRMAC) Assessment Manual is the tool used to organize and guide activities of the FRMAC Assessment Division. The mission of the FRMAC Assessment Division in a radiological emergency is to interpret radiological data and predict worker and public doses. This information is used by Decision Makers to recommend protective actions in accordance with Protection Action Guides (PAGs) issued by government agencies. This manual integrates many health physics tools and techniques used to make these assessments.

The objectives of the FRMAC Assessment Manual are:

A. Document the assessment process.

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

B. Provide technical basis for assessments.

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

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

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

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

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

E. Provide Federal family consensus.

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

This manual:

1) Is intended for use by trained FRMAC Assessment Scientists. It is the basis for training FRMAC Assessment Scientists in standard FRMAC technical methods, and defines the standard technical methods used when responding to radiological incidents.

2) Represents the technical consensus of multiple federal agencies with expertise in and authority over aspects of radiological emergency response.
3) Defines methods to make many different radiological assessment calculations based on default assumptions agreed upon by the interagency FRMAC AWG as being most applicable to a wide variety of conditions. These default assumptions may or may not be appropriate for a specific incident.
4) Frequently uses the word “would” to define the result of the calculation, and it is important to be aware that this result is based on the established default assumptions. Should circumstances of the specific incident be different than the default assumptions, the predicted results may not reflect actual conditions. It is recommended that assessors obtain real-world data as soon as possible to validate the predictions made by the methods in this manual.
5) Is only intended to address the early and intermediate phases of a radiological incident. It does not address Late Phase issues, such as remediation.
6) Incorporates the EPA PAG Manual’s Avoidable Dose concept.
   - Projected doses used to support protective action decisions are normally based upon the dose that can be avoided by taking protective actions (i.e., avoidable dose). The dose that is received before protective actions are taken (i.e., unavoidable dose) is normally not included in these dose projections.

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

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

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

   - When there is sufficient warning to implement protective actions before the release occurs (e.g., some Nuclear Power Plant accident scenarios) , the entire dose (including that from the Plume) is considered avoidable and should be included in Early Phase dose assessments. In this case, the start of the Early Phase should be the time of the release.
7) Defaults to the ICRP 60+dosimetry model based on agreement with the EPA. ICRP 60+ refers to ICRP 60 (ICRP90) and the collection of ICRP documents relating to the ICRP 60 dosimetry model published subsequently. ICRP 60+ terminology is used throughout the manual.

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

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

8) Is not prescriptive. Situations may arise when the methods described in the Assessment Manual will not be sufficient, so the user may employ alternative methods or assumptions. Assessment Scientists must be sufficiently skilled in health physics to recognize when, which, and how alternative methods or assumptions may be employed. Possible alternatives may include dosimetry models, weathering factor, and resuspension factor.

The manual is organized as follows:

<u>Volume 1</u> describes the roles and responsibilities of the Assessment Division during a response.

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

Section 1 – Public Protection

Section 2 – Worker Protection

Section 3 – Ingestion Pathway

Section 4 – Supplemental Methods

<u>Volume 3</u> provides analyses for pre-assessed scenarios. These default scenarios include:

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

Differences between FRMAC approach and other published guidance

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

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

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

ACKNOWLEDGMENTS

Development of this revision of the FRMAC Assessment Manual, Volume 3 was a major undertaking to which many people contributed. The primary authors for this revision were Lainy Cochran and Kevin Hart (SNL). Editorial support was provided by Monica Bigney and Marie Dosanjh (SNL). Special recognition also goes to the members of the FRMAC Assessment Working Group for their work on this revision in developing radiological assessment guidance for the default scenarios of interest described in this volume.

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

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Please check this table periodically to ensure that your printed copy of Volume 3 is up to date by comparing the "Effective Date" in this table with the date in the header of each section. When a section is added or updated, only that section will need to be printed – the page numbers in the rest of the volume will be unaffected.

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ACRONYMS AND ABBREVIATIONS

α	Alpha
β	Beta
γ	Gamma
AC	alternating current
AMAD	Activity Median Aerodynamic Diameter
APF	Assigned Protection Factor
AWG	Assessment Working Group
BFP	building protection factor
BWR	Boiling Water Reactor
CDC	Centers for Disease Control and Prevention
CMHT	Consequence Management Home Team
DC	direct current
DCFPAK	Dose Coefficient File Package
DIL	Derived Intervention Level
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DRL	Derived Response Level
$\mathbf{DRL_{DP}}$	Deposition Derived Response Level
$\mathbf{DRL_{\tilde{A}}}$	Integrated Air Derived Response Level
$\mathbf{DRL_{DR}}$	Dose Rate Derived Response Level
DTPA	diethylenetriamine pentaacetate
ECAM	Environmental Continuous Air Monitor
EMP	electromagnetic pulse
EPA	U.S. Environmental Protection Agency
EPZ	Emergency Planning Zone
FDA	U.S. Food and Drug Administration
FEMA	Federal Emergency Management Agency
FIDLER	Field Instruments for Detection of Low Energy Radiation
FIL	FRMAC Intervention Level
FRMAC	Federal Radiological Monitoring and Assessment Center
HALEU	high assay low enriched uranium
HEVR	high-explosive violent reaction
HF	hydrogen fluoride
HOB	height of burst
HTO	Tritiated Water Vapor
ICRP	International Commission on Radiological Protection
IND	improvised nuclear device
JTOT	Joint Technical Operations Team
KI	potassium iodide

Kt	kiloton
LCT	Lung Clearance Type
LEU	low enriched uranium
MOX	mixed oxide
NARAC	National Atmospheric Release Advisory Center
NASA	National Aeronautics and Space Administration
NCRP	National Council on Radiation Protection
NDA	National Defense Area
NNSA	National Nuclear Security Administration
NRC	U.S. Nuclear Regulatory Commission
NPP	Nuclear Power Plant
NSA	National Security Area
NW	nuclear weapon
OF	occupancy factor
PAG	Protective Action Guide
PPE	Personal Protective Equipment
PSD	Particle Size Distribution
PWR	Pressurized Water Reactor
RADCC	Radiological Control Center
RASCAL	Radiological Assessment System for Consequence Analysis
RCIC	Reactor Core Isolation Cooling
RDD	Radiological Dispersal Device
REAC/TS	Radiation Emergency Assistance Center/Training Site
RHU	Radioisotope Heater Unit
RTG	Radioisotope Thermoelectric Generator
SF	Spontaneous Fission
SFP	spent fuel pool
SNL	Sandia National Laboratories
SOARCA	State-of-the-Art Reactor Consequence Analyses
STSBO	Short-Term Station Blackout
TBL	Turn-Back Limit
TF	Transfer Factor
TNT	trinitrotoluene

OVERVIEW

Purpose of this Volume

This volume of the Federal Radiological Monitoring and Assessment Center (FRMAC) Assessment Manual was developed to serve as a quick-start guide to expedite response for pre-assessed scenarios before event-specific information becomes available. The objective of Volume 3 is to provide dose assessors with the scenario-specific protective action guidance questions likely to be asked at the start of a response, along with supporting technical information and assumptions that differ from the default assumptions defined in Volume 2 of the Assessment Manual.

Using this Volume

The goal of this volume is to aid the timely initial assessment of the pre-assessed scenarios. The information in this volume should be used until event-specific data allows for more detailed assessments.

Each of the pre-assessed scenarios included in this volume has the same structure for easy reference and understanding at the start of a response. The scenarios are structured to include:

1. **Introduction**: A brief description of the scenario.
2. **Scenario-Specific Concerns**: A list of protective action guidance questions likely to be asked for the scenario to aid in understanding which types of assessments might be needed to support public and worker protection decisions.
3. **Data Needs and Sources**: The basic information that should be used for an assessment for the scenario and where it can be acquired.
4. **Technical Caveats**: Scenario-specific technical information that differs from the default assumptions defined in Volume 2.
5. **Default Results**: Public Protection Derived Response Levels (DRLs), Worker Protection Turn-Back Limits (TBLs), and Ingestion Derived Response Levels (DRLs) that are pre-calculated using the scenario-specific technical caveats. Default results are to be used until sufficient data have been collected to eliminate assumptions.

It is expected that readers are already familiar with terms such as DRLs and TBLs as defined in Volume 2, and as such these terms will not be redefined in Volume 3.

ACTION	Action boxes like this one are included throughout this volume to indicate when the Assessment Scientist should take an action to acquire data or work with other skill sets

Default Scenarios

The scenarios in this volume are events that are most likely to initiate a FRMAC response. These events could be initiated by an accident or malicious activity.

Nuclear Power Plant

Major accidents at nuclear power plants (NPPs) have the potential to release large amounts of radioactive material to the environment. Fission products make up most of the radionuclide inventory in a reactor core. Some of the fission products are particulate, some are in gaseous form (krypton and xenon), and others are highly volatile (iodines). Filtration and holdup systems limit the release of radioactive material from the reactor under normal operating conditions. Catastrophic accidents that pose the greatest risk are those that defeat the control measures designed to prevent the release of radioactive material. The mixture of fission products released is highly dependent on the accident progression sequence, including mechanism of release and timing.

Nuclear Fuel Fabrication

There are several forms that unirradiated nuclear fuel can take through the fuel fabrication process. Unirradiated nuclear fuel can be assembled into nuclear fuel rods and bundles. It can be present in metallic, ceramic, or gaseous forms. Unirradiated fuel does not pose a large dose concern from a release due to the high temperatures required to aerosolize solid forms of uranium. Uranium hexafluoride (UF_6) releases while in storage or transport from the enrichment facility to the fuel fabrication facility are the primary accident of concern.

Nuclear Fuel Accident

Accidents related to spent nuclear fuel will most likely involve nuclear reactor wastes or fuel reprocessing materials. The severity of the accident primarily depends on the quantity and the age of the material, the mechanism by which it is released, and engineering controls at the facility to scrub radioactive effluent. Spent fuel accidents are significantly lower in probability as the fuel continues to cool and decay after its removal from the operating reactor. If the fuel has cooled for fewer than 100 days, shorter-lived radionuclides will be present and the consequences will be similar to a power reactor accident. Like NPP accidents, fission products make up the majority of the radionuclide inventory in spent fuel. Some of the fission products are particulate, some are in gaseous form (krypton and xenon), and others are highly volatile (iodines). The mixture of radionuclides released is primarily dependent on the age of the fuel after it is removed from the operating reactor.

Radiological Dispersal Device

A radiological dispersal device (RDD) is a device that is designed to spread radioactive material with the intent to cause panic and economic impact, and to render contaminated areas unusable. The term “dirty bomb” is an often-used, non-technical term for an explosive RDD. The explosive force of an RDD would most likely cause more physical harm than the released radioactive material. An RDD can also involve non-explosive, mechanical means of dispersing material (e.g., aerosol sprayer).

Nuclear Detonation

A detonation of a nuclear weapon (NW) producing nuclear yield results in the production of blast pressure, thermal radiation, initial nuclear radiation, radioactive fallout, and electromagnetic pulse (EMP). Initial nuclear radiation consists of prompt gamma and neutron radiation resulting from the fission process, and residual radiation resulting from the decay of fission and activation products. The prompt radiation is primarily a local hazard (e.g., within a few kilometers). Radioactive fallout, however, has the potential to present a hazard for much greater distances and for a much greater amount of time. Fallout consists of fission and activation products entrained and condensed onto material such as dirt and dust that were vaporized in the detonation. The height of the detonation above ground influences the amount of fallout produced. Detonations that occur at ground level produce a much greater amount of fallout than those that occur at higher elevation above the ground. The primary radiological hazard of fallout is the beta and gamma radiation resulting from the decay of fission products produced in the detonation.

Nuclear Weapon Accident

Accidents involving NW could produce several results, including:

- no detonation of the high explosives and no release
- a high-explosive violent reaction (HEVR) with release
- a fire
- mechanical disassembly of the weapon resulting in only localized dispersal of radioactive materials

The two primary NW accidents of concern for consequence management are HEVR (in which an NW undergoes a high-explosive detonation/violent reaction) and fire (the NW is burned in a fully engulfing fire with resulting dispersal of radioactive material). Weapons-grade plutonium isotopes, americium, uranium isotopes, and tritium present the radiological hazards from a damaged NW. Pu-239 is expected to deliver the major portion of the radiation dose following an NW incident involving a high-explosive detonation or HEVR without nuclear yield. Tritium and uranium could also be dispersed, but with less radiological consequence.

Radioisotope Thermoelectric Generator Accident

Radioisotope power systems can be used by spacecraft as sources of heat and/or electrical power. Radioisotope power systems used in spacecraft consist of radioisotope thermoelectric generators (RTGs) and radioisotope heater units (RHUs). Because of mission power and longevity requirements, U.S. mission planners have relied exclusively on the use of RTGs. The most commonly used radionuclide fuel for RTGs is Pu-238 dioxide (PuO_2) in ceramic form. There is the potential for an accident during launch that may be severe enough to release the radioactive fuel from the radioisotope power systems to the environment. These accidents include an early launch accident, an orbital decay resulting in reentry to the earth's atmosphere, and reentry at higher than orbital velocities during a fly-by maneuver for deep space missions.

1. SCENARIO 1: NUCLEAR POWER PLANT

1.1. Introduction

Major accidents at nuclear power plants (NPPs) have the potential to release large amounts of radioactive material to the environment. Fission products make up most of the radionuclide inventory in a reactor core. Some of the fission products are particulate, some are in gaseous form (krypton and xenon), and others are highly volatile (iodines). Filtration and holdup systems limit the release of radioactive material from the reactor under normal operating conditions. Catastrophic accidents that pose the greatest risk are those that defeat the control measures designed to prevent the release of radioactive material. The mixture of fission products released is highly dependent on the accident progression sequence, including mechanism of release and timing.

This pre-assessed scenario is written for U.S. commercial NPPs. The reactors are pressurized water reactors (PWRs) and boiling water reactors (BWRs) that use low-enriched uranium oxide fuel. This scenario considers source terms from a reactor core. Accidents involving fuel pools and dry cask storage are covered in Section 2. Other reactor types and fuels will likely generate different source terms than those discussed in this scenario.

> ***NOTE**: The U.S. Naval Nuclear Propulsion Program uses different assumptions (e.g., for iodine partitioning) than the Federal Radiological Monitoring and Assessment Center (FRMAC) for its Predictive Plume Model (NNPP19).*

This pre-assessed scenario is based on defaults and methods as specified in the May 2023 version of the FRMAC Assessment Manual, Volume 2 (SNL23) and may need to be updated to reflect future changes. Default results were calculated using Turbo FRMAC 2021.

1.2. Scenario-Specific Concerns

The Assessment Scientist should be prepared to address the following questions to support protective action decisions:

1. **Should the population be evacuated or sheltered?**
   Some protective actions may begin prior to the release of radioactive material when there is notice of deteriorating plant conditions. In this case, there will likely be time for an orderly evacuation. Sheltering in place may be warranted in situations where evacuation poses a greater risk of exposure or physical harm, or when there is no prior notice or warning. The EPA recommends these protective actions when the projected effective dose to an individual is 1 rem over the first four days after a release.

   Each U.S. NPP has emergency planning zones (EPZ) that are established by State and Local governments in consultation with Federal Emergency Management Agency (FEMA) and NRC. There is a plume exposure pathway EPZ within a 10-mile radius of the plant and an ingestion exposure pathway EPZ within a 50-mile radius of the plant. Evacuation does not always call for completely emptying the 10-mile zone around an NPP. In many cases, in the event of a General Emergency, a two-mile ring around the plant is evacuated (at a minimum), along with people living in the 5-mile zone directly downwind and slightly to either side of the projected path of the release. This "keyhole" pattern helps account for potential wind shifts and fluctuations in the release path. Evacuation beyond 5 miles is assessed as the accident progresses (NRC18).

Predetermined protective action plans are in place for the EPZs. It is important for the Assessment Scientist to be aware that some actions (e.g., evacuation, sheltering, administration of potassium iodide) might be taken before FRMAC involvement.

2. **Given the possibility of Protective Action Recommendations to be made before FRMAC involvement, how is FRMAC expected to assist?**
   FRMAC might be asked to assist with updating the source term to validate protective action decisions based on available data, calculating dose estimates for reentry activities, and verifying acceptable dose rates and/or contamination levels for allowing evacuated populations to return. Note, "reentry" is temporary entry into a restricted zone under controlled conditions and "return" is reoccupation of areas cleared for unrestricted residence or use.
3. **What are the likely exposure pathways?**
   The released radionuclide mixture can vary greatly, depending on the type and timing of the release. An initial release could be dominated by noble gases for which the plume submersion pathway could be dominant. Once the accident progresses and more particulate radionuclides are released, inhalation is expected to be the dominant pathway. Following plume passage, the primary exposure pathway is external exposure from radioactive material that is deposited on the ground (i.e., groundshine).
4. **Should potassium iodide (KI) be administered?**
   Administration of KI to both children and adults should be considered if the projected child thyroid dose from iodine radionuclides exceeds 5 rem (FDA01). The 2017 EPA Protective Action Guide (PAG) Manual recommends using the one-year-old age group for thyroid dose projections as it is expected to be the limiting age group.

   Table 1.7 through Table 1.9 contain Derived Response Levels (DRLs) to support decisions to administer KI. Note, States may choose to include KI in predetermined protective action plans for the 10-mile plume exposure pathway EPZ and, as such, KI might be pre-distributed to the population within this EPZ.
5. **Should the population be relocated?**
   Relocation is an intermediate phase protective action. Relocation should be considered in areas where projected dose exceeds the corresponding PAG.
6. **Do emergency workers need protective equipment?**
   Use of respiratory protection may be advised to minimize intake of radioactive materials, particularly during plume passage as workers are likely to already be on site prior to a release. Note that use of respiratory protection is not always conservative, given that it can prolong exposure time. The need for personal protective equipment (PPE) for contamination control should also be evaluated. FRMAC Monitoring and Sampling Manual, Volume 1 provides default guidance for PPE for FRMAC field teams (FRMAC19).
7. **What precautions should be taken regarding surface water?**
   Most NPPs in the U.S. are built near bodies of water such as rivers, lake, and oceans. Consideration should be given to prohibiting shoreline, boating, and swimming activities as appropriate.

Answers to the following questions are dependent on the circumstances of the event to which you are responding (e.g., radionuclide mixture, deposition, weather conditions, etc.):

- When can the evacuated population be allowed to return?
- What is the potential economic/infrastructure impact?
- Can foodstuffs grown in the contaminated area be consumed?
- Can foodstuffs be grown in the impacted area in the future?

1.3. Data Needs and Sources

The following sections describe the default assumptions to use for an NPP scenario until event-specific information is known.

1.3.1. Time Phase

Use FRMAC default time phases and evaluation time as specified in FRMAC Assessment Manual, Volume 2, Table 2-3.

> ***NOTE****: NPP accidents have historically resulted in prolonged releases lasting several days. DRL calculations can account for prolonged releases by adjusting the time phase and adding together available source terms, as allowed by Decision Makers.*

ACTION	Determine whether to include Plume Pathways (i.e., Total Dose or Avoidable Dose). **NOTE:** Because there is typically notice for an NPP release, Plume Pathways will likely be included

1.3.2. Mixture

The mixture of fission products released is dependent on the burnup of the fuel and on the accident progression sequence, including mechanism of release and timing. Table 1.1 includes mixture information for an unmitigated release from a BWR or PWR. These mixtures should be used until event-specific information is provided. Projected source terms for an event can be obtained through the NRC or from an accident modeling software such as the Radiological Assessment System for Consequence Analysis (RASCAL).

The mixtures in Table 1.1 are based on core inventories[1] and release fractions[2] from Volumes 1 and 2 of the NRC State-of-the-Art Reactor Consequence Analyses (SOARCA) project (NRC13). The BWR mixture is represented by a short-term station blackout (STSBO) without reactor core isolation cooling (RCIC) blackstart scenario[3] for Peach Bottom Nuclear Power Station. The PWR mixture is represented by a STSBO scenario for Surry Nuclear Power Station. These scenarios were selected because they are conservative and generally representative of other accident scenario types. The release fractions for the selected scenarios were applied to the core

[1] Volume 1, Appendix A for Peach Bottom and Volume 2, Appendix B for Surry (NRC13)
[2] Table 7-1 (NRC13)
[3] Blackstart of the RCIC system refers to starting RCIC without any alternating current (AC) or direct current (DC) control power.

inventories and then aged to the start of the atmospheric release. The applied release fractions result in a release of less than 10% of the core inventories for both BWR and PWR.

A dose parameter analysis was performed in order to limit the mixtures in Table 1.1 to only the radionuclides that contribute at least 99% of the total effective dose for each of the Early Phase (Total Dose), Early Phase (Avoidable Dose), First Year, Second Year, and Fifty Year time phases.[4] The mixtures in Table 1.1 are applicable at the Release Time and should be entered in Turbo FRMAC as an Integrated Air Concentration and an NPP type mixture, with equilibrium set to OFF to avoid double-counting daughters. Note that Integrated Air Concentration units are different than the activity units provided in Table 1.1. This is acceptable in the case of DRL calculations, for which the relative concentrations of the radionuclides in the mixture are important.

Table 1.1. Representative Mixtures for Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR) Unmitigated Releases

Radionuclide	Released Activity (Ci)	
	BWR	PWR
Ba-140	1.6E+07	0
Ce-141	1.1E+06	0
Ce-144	7.9E+05	0
Cs-134	1.7E+05	1.2E+04
Cs-136	6.4E+04	4.0E+03
Cs-137	1.7E+05	8.2E+03
I-129	3.4E-05	4.1E-06
I-131	1.0E+07	4.2E+05
I-132	1.3E+07	5.7E+05
I-133	1.7E+07	3.9E+05
I-134	4.5E+04	1.2E-03
I-135	9.1E+06	5.8E+04
Kr-88	1.0E+07	5.3E+04
La-140	2.1E+06	0
Nb-95	3.3E+05	0
Np-239	9.6E+06	0
Pu-238	1.3E+03	0
Pu-239	2.6E+02	0
Pu-240	2.1E+02	0
Pu-241	7.3E+04	0
Sr-89	9.7E+06	0
Sr-90	7.6E+05	0
Sr-91	6.8E+06	0
Te-127m	1.2E+05	6.8E+03
Te-129m	4.3E+05	2.4E+04
Te-131m	1.4E+06	5.1E+04
Te-132	1.3E+07	5.5E+05
Xe-133	1.7E+08	7.4E+07
Xe-135	4.3E+07	3.7E+06
Zr-95	1.2E+06	0

[4] The Fifty Year time phase is not in the 2017 EPA PAG Manual but was considered for completeness.

Radionuclide	Released Activity (Ci)	
	BWR	PWR
Zr-97	8.3E+05	0

ACTION — Review available data and work with Monitoring & Sampling to determine what radiation type(s) and/or radionuclide(s) have been detected, relative activity ratios, and instruments being used

ACTION — Coordinate with the NRC representative to conduct a source term calculation using RASCAL or event-specific data

1.3.3. Protective Action Guides

Use FRMAC default PAGs unless instructed otherwise by Decision Makers. The PAGs are located in FRMAC Assessment Manual, Volume 2, Table 2-1.

1.4. Technical Caveats

ACTION — Determine whether the 1992 EPA PAG Manual or FRMAC default methods should be used. At the time of writing this section, FRMAC default methods follow 2017 EPA PAG Manual guidance

1.4.1. Inhalation Pathway

NPP releases are assumed to be composed of 1-µm Activity Median Aerodynamic Diameter (AMAD) particles. Use the ICRP Recommended lung clearance type (LCT) as specified in ICRP Publication 72 (ICRP96).

ACTION — Work with NARAC to ensure consistent source term assumptions, including LCT and particle size distribution

1.4.2. Multiple Physical/Chemical Forms

Iodine released from an NPP under accident conditions will likely exist in multiple physical forms. Table 1.2 includes the FRMAC default approach for iodine portioning, which is consistent with NRC methodology (NUREG-1940). Deposition velocities for each form are also provided. For resuspension dose calculations, all deposited Iodine Vapor/Reactive Gas is assumed to be converted to 1-µm particulate.

Table 1.2. Default Iodine Partitioning

Form	Partition	Deposition Velocity (m/s)
Methyl Iodide/Non-reactive Gas (CH_3I)	45%	0
Iodine Vapor/Reactive Gas (I_2)	30%	6.4E-03
Particulate	25%	6.5E-03

For the default NPP mixtures, tritium is not a significant dose contributor. If included, tritium should be modeled as existing in the Tritiated Water Vapor (HTO) form with a deposition velocity of 0 m/s to be consistent with NRC.

ACTION	Request that the field teams use appropriate air sampling equipment and filters to detect all chemical/physical forms of iodine

ACTION	Work with the Advisory Team to determine appropriate KI protection factors for workers

ACTION	Work with Health & Safety to evaluate the need for respirators, turn-back limits, stay times, etc.

ACTION	Request that the field teams perform resuspension measurements to support dose projections

1.4.3. Ingestion Pathway

The FDA provides Derived Intervention Levels (DILs) for radionuclides expected to deliver the major portion of the dose from ingestion during the first year following an accident.

ACTION	DILs for grouped radionuclides (Cs-134 + Cs-137, Pu-238 + Pu-239 + Am-241, and Ru-103 + Ru-106) should be used in ingestion calculations

1.5. Default Results

1.5.1. Public Protection Derived Response Levels

Table 1.3 and Table 1.4 contain DRLs for the representative BWR mixture provided in Table 1.1. Table 1.5 and Table 1.6 contain DRLs for the representative PWR mixture provided in Table 1.1. The DRLs are appropriate for the Adult Whole Body and are reported for parents and daughters.

> ***NOTE**: Early Phase DRLs are provided for completeness. It is possible that protective action decisions for the Early Phase might be made before FRMAC involvement.*

> ***NOTE**: Radionuclides that are noble gases when initially released to the air are not deposited on the ground. Noble gases that are daughters of ground-deposited radionuclides are assumed to remain on the ground. Also, iodine Integrated Air DRLs are summed over multiple physical forms.*

ACTION

Because NPP source terms undergo rapid decay, DRLs should be recalculated for the appropriate evaluation time. An example of this is provided in Figure 1.1

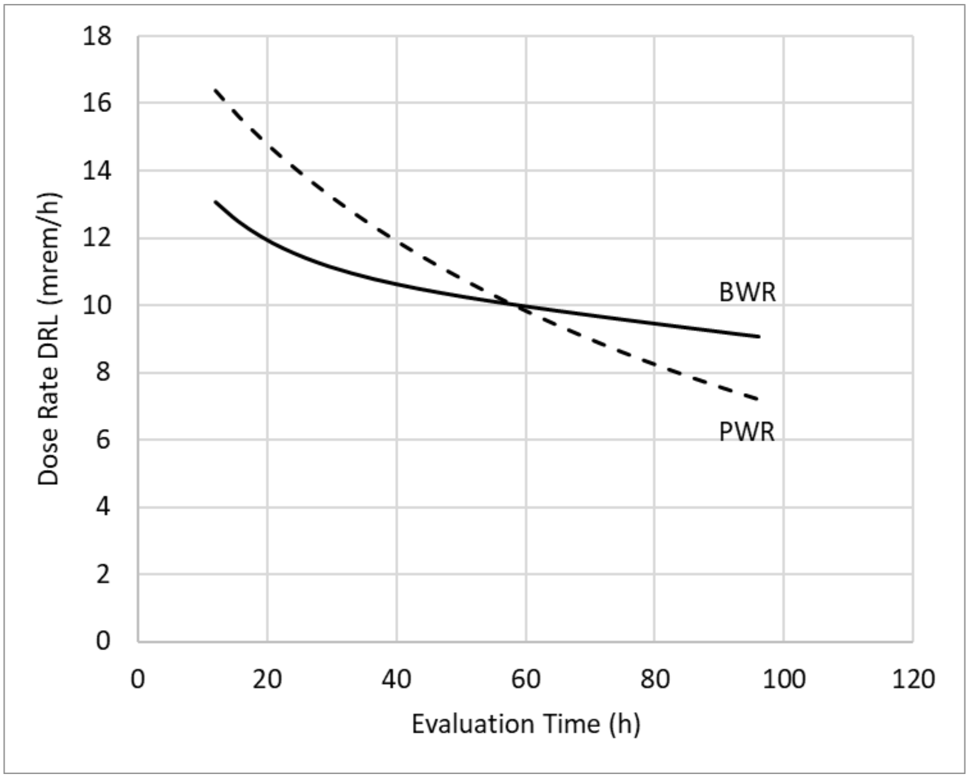

Figure 1.1. Early Phase (Avoidable Dose) Dose Rate Derived Response Levels with Varying Evaluation Time

Table 1.3. BWR Radionuclide-Specific Derived Response Levels

Radionuclide	Early Phase (Total Dose)		Early Phase (Avoidable Dose)		First Year	
	DRL_{Dp} ($\mu Ci/m^2$)	$DRL_{\tilde{A}}$ ($\mu Ci•s/m^3$)[a]	DRL_{Dp} ($\mu Ci/m^2$)	$DRL_{\tilde{A}}$ ($\mu Ci•s/m^3$)[a]	DRL_{Dp} ($\mu Ci/m^2$)	$DRL_{\tilde{A}}$ ($\mu Ci•s/m^3$)[a]
Am-241	4.20E-07	NA	2.78E-06	NA	9.54E-07	NA
Ba-137m	4.20E-01	NA	2.78E+00	NA	9.55E-01	NA
Ba-140	4.08E+01	1.40E+04	2.70E+02	9.24E+04	9.26E+01	3.17E+04
Ce-141	2.85E+00	9.60E+02	1.88E+01	6.35E+03	6.48E+00	2.18E+03
Ce-144	2.07E+00	6.90E+02	1.37E+01	4.56E+03	4.69E+00	1.57E+03
Cs-134	4.45E-01	1.48E+02	2.94E+00	9.82E+02	1.01E+00	3.37E+02
Cs-135	2.64E-09	NA	1.75E-08	NA	6.00E-09	NA
Cs-136	1.63E-01	5.59E+01	1.08E+00	3.70E+02	3.71E-01	1.27E+02
Cs-137	4.45E-01	1.48E+02	2.94E+00	9.82E+02	1.01E+00	3.37E+02
I-129	1.67E-10	2.97E-08	1.10E-09	1.96E-07	3.79E-10	6.75E-08
I-131	2.98E+01	8.73E+03	1.97E+02	5.77E+04	6.76E+01	1.98E+04
I-132	3.16E+01	1.13E+04	2.09E+02	7.51E+04	7.19E+01	2.58E+04
I-133	3.53E+01	1.48E+04	2.33E+02	9.82E+04	8.01E+01	3.37E+04
I-134	1.04E-05	3.93E+01	6.85E-05	2.60E+02	2.35E-05	8.93E+01
I-135	7.94E+00	7.94E+03	5.25E+01	5.25E+04	1.80E+01	1.81E+04

Radionuclide	Early Phase (Total Dose)		Early Phase (Avoidable Dose)		First Year	
	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3)[a]	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3)[a]	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3)[a]
Kr-88	NA	8.73E+03	0.00E+00	5.77E+04	0.00E+00	1.98E+04
La-140	1.22E+01	1.83E+03	8.06E+01	1.21E+04	2.77E+01	4.17E+03
Nb-95	8.86E-01	2.88E+02	5.86E+00	1.91E+03	2.01E+00	6.55E+02
Nb-95m	3.10E-03	NA	2.05E-02	NA	7.04E-03	NA
Nb-97	1.42E+00	NA	9.41E+00	NA	3.23E+00	NA
Nd-144	8.27E-19	NA	5.47E-18	NA	1.88E-18	NA
Np-237	1.45E-16	NA	9.60E-16	NA	3.30E-16	NA
Np-239	2.17E+01	8.38E+03	1.44E+02	5.54E+04	4.93E+01	1.90E+04
Pr-144	2.07E+00	NA	1.37E+01	NA	4.69E+00	NA
Pr-144m	2.02E-02	NA	1.34E-01	NA	4.59E-02	NA
Pu-238	3.40E-03	1.13E+00	2.25E-02	7.51E+00	7.73E-03	2.58E+00
Pu-239	6.82E-04	2.27E-01	4.51E-03	1.50E+00	1.55E-03	5.16E-01
Pu-240	5.50E-04	1.83E-01	3.64E-03	1.21E+00	1.25E-03	4.17E-01
Pu-241	1.91E-01	6.37E+01	1.26E+00	4.22E+02	4.34E-01	1.45E+02
Rb-88	NA	NA	NA	NA	NA	NA
Sr-89	2.52E+01	8.47E+03	1.67E+02	5.60E+04	5.73E+01	1.92E+04
Sr-90	1.99E+00	6.63E+02	1.32E+01	4.39E+03	4.52E+00	1.51E+03
Sr-91	7.51E+00	5.94E+03	4.96E+01	3.93E+04	1.71E+01	1.35E+04
Te-127	1.80E-01	NA	1.19E+00	NA	4.10E-01	NA
Te-127m	3.13E-01	1.05E+02	2.07E+00	6.93E+02	7.12E-01	2.38E+02
Te-129	7.02E-01	NA	4.65E+00	NA	1.60E+00	NA
Te-129m	1.11E+00	3.75E+02	7.37E+00	2.48E+03	2.53E+00	8.53E+02
Te-131	6.25E-01	NA	4.14E+00	NA	1.42E+00	NA
Te-131m	2.78E+00	1.22E+03	1.84E+01	8.08E+03	6.31E+00	2.78E+03
Te-132	3.05E+01	1.13E+04	2.02E+02	7.51E+04	6.94E+01	2.58E+04
U-234	1.32E-11	NA	8.70E-11	NA	2.99E-11	NA
U-235	8.70E-16	NA	5.75E-15	NA	1.98E-15	NA
U-235m	6.80E-04	NA	4.50E-03	NA	1.55E-03	NA
U-236	2.23E-14	NA	1.47E-13	NA	5.06E-14	NA
U-237	2.34E-07	NA	1.55E-06	NA	5.33E-07	NA
Xe-131m	1.03E-02	NA	6.81E-02	NA	2.34E-02	NA
Xe-133	2.69E+00	1.48E+05	1.78E+01	9.82E+05	6.12E+00	3.37E+05
Xe-133m	1.82E-01	NA	1.20E+00	NA	4.14E-01	NA
Xe-135	8.67E+00	3.75E+04[a]	5.73E+01	2.48E+05	1.97E+01	8.53E+04
Xe-135m	1.37E+00	NA	9.05E+00	NA	3.11E+00	NA
Y-90	2.42E-01	NA	1.60E+00	NA	5.50E-01	NA
Y-91	6.76E-02	NA	4.47E-01	NA	1.54E-01	NA
Y-91m	4.78E+00	NA	3.16E+01	NA	1.09E+01	NA
Zr-95	3.12E+00	1.05E+03	2.07E+01	6.93E+03	7.10E+00	2.38E+03
Zr-97	1.32E+00	7.25E+02	8.75E+00	4.79E+03	3.01E+00	1.65E+03

[a] Integrated Air DRLs are not decayed to an evaluation time and are therefore NA for daughter radionuclides not present in the initial mixture.

Table 1.4. BWR Dose Rate, Alpha, and Beta Derived Response Levels

DRL Type	Early Phase (Total Dose)	Early Phase (Avoidable Dose)	First Year
Dose Rate (mrem/h)	1.98E+00	1.31E+01	4.49E+00
Alpha Deposition ($µCi_{alpha}$/m^2)	4.64E-03	3.07E-02	1.05E-02

Alpha Integrated Air (μCi_{alpha}•s/m^3)	1.55E+00	1.02E+01	3.51E+00
Beta Deposition (μCi_{beta}/m^2)	2.42E+02	1.60E+03	5.49E+02
Beta Integrated Air (μCi_{beta}•s/m^3)	2.81E+05	1.86E+06	6.38E+05

Table 1.5. PWR Radionuclide-Specific Derived Response Levels

Radionuclide	Early Phase (Total Dose)		Early Phase (Avoidable Dose)		First Year	
	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3) [a]	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3) [a]	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3) [a]
Ba-137m	1.24E+00	NA	6.77E+00	NA	3.94E+00	NA
Cs-134	1.93E+00	6.42E+02	1.05E+01	3.50E+03	6.11E+00	2.04E+03
Cs-135	1.03E-09	NA	5.62E-09	NA	3.27E-09	NA
Cs-136	6.26E-01	2.14E+02	3.41E+00	1.17E+03	1.99E+00	6.80E+02
Cs-137	1.32E+00	4.39E+02	7.17E+00	2.39E+03	4.18E+00	1.39E+03
I-129	9.89E-10	2.19E-07	5.39E-09	1.20E-06	3.14E-09	6.97E-07
I-131	7.66E+01	2.25E+04	4.17E+02	1.22E+05	2.43E+02	7.14E+04
I-132	8.22E+01	3.05E+04	4.48E+02	1.66E+05	2.61E+02	9.68E+04
I-133	4.96E+01	2.09E+04	2.70E+02	1.14E+05	1.57E+02	6.63E+04
I-134	1.69E-11	6.42E-05	9.23E-11	3.50E-04	5.38E-11	2.04E-04
I-135	3.10E+00	3.11E+03	1.69E+01	1.69E+04	9.85E+00	9.85E+03
Kr-88	NA	2.84E+03	NA	1.55E+04	NA	9.01E+03
Rb-88	NA	NA	NA	NA	NA	NA
Te-127	6.27E-01	NA	3.41E+00	NA	1.99E+00	NA
Te-127m	1.09E+00	3.64E+02	5.93E+00	1.98E+03	3.45E+00	1.16E+03
Te-129	2.40E+00	0.00E+00	1.31E+01	NA	7.63E+00	NA
Te-129m	3.81E+00	1.28E+03	2.08E+01	7.00E+03	1.21E+01	4.08E+03
Te-131	1.40E+00	NA	7.61E+00	NA	4.43E+00	NA
Te-131m	6.21E+00	2.73E+03	3.38E+01	1.49E+04	1.97E+01	8.67E+03
Te-132	7.93E+01	2.94E+04	4.32E+02	1.60E+05	2.52E+02	9.34E+04
Xe-131m	2.65E-02	NA	1.44E-01	NA	8.41E-02	NA
Xe-133	3.79E+00	3.96E+06	2.06E+01	2.16E+07	1.20E+01	1.26E+07
Xe-133m	2.56E-01	NA	1.40E+00	NA	8.13E-01	NA
Xe-135	3.39E+00	1.98E+05	1.85E+01	1.08E+06	1.08E+01	6.29E+05
Xe-135m	5.35E-01	NA	2.91E+00	NA	1.70E+00	NA

[a] Integrated Air DRLs are not decayed to an evaluation time and are therefore NA for daughter radionuclides not present in the initial mixture.

Table 1.6. PWR Dose Rate, Alpha, and Beta Derived Response Levels

DRL Type	Early Phase (Total Dose)	Early Phase (Avoidable Dose)	First Year
Dose Rate (mrem/h)	3.00E+00	1.64E+01	9.53E+00
Alpha Deposition (μCi_{alpha}/m^2)[a]	NA	NA	NA
Alpha Integrated Air (μCi_{alpha}•s/m^3)[a]	NA	NA	NA
Beta Deposition (μCi_{beta}/m^2)	2.31E+02	1.26E+03	7.32E+02
Beta Integrated Air (μCi_{beta}•s/m^3)	4.24E+06	2.31E+07	1.35E+07

a Alpha DRLs are NA because the radionuclides assumed to be released for the PWR scenario are not alpha-emitters.

1.5.2. *Derived Response Levels for Administration of KI*

Table 1.7 through Table 1.9 contain DRLs to support decisions to administer KI. The DRLs are based on the 5 rem 1-year-old thyroid PAG and are reported for parents and daughters.

> ***NOTE****: States may choose to include KI in predetermined protective action plans for the 10-mile plume exposure pathway EPZ and, as such, KI might be pre-distributed to the population within this EPZ.*

> ***NOTE****: Radionuclides that are noble gases when initially released to the air are not deposited on the ground. Noble gases that are daughters of ground-deposited radionuclides are assumed to remain on the ground. Also, iodine Integrated Air DRLs are summed over multiple physical forms.*

Table 1.7. BWR Radionuclide-Specific Derived Response Levels for Administration of KI

Radionuclide	DRL_{Dp} (μCi/m^2)	$DRL_{\bar{A}}$ (μCi•s/m^3)
Am-241	1.82E-07	NA
Ba-137m	1.82E-01	NA
Ba-140	1.77E+01	6.06E+03
Ce-141	1.24E+00	4.17E+02
Ce-144	8.97E-01	2.99E+02
Cs-134	1.93E-01	6.44E+01
Cs-135	1.15E-09	NA
Cs-136	7.09E-02	2.43E+01
Cs-137	1.93E-01	6.44E+01
I-129	7.25E-11	1.29E-08
I-131	1.29E+01	3.79E+03
I-132	1.37E+01	4.93E+03
I-133	1.53E+01	6.44E+03
I-134	4.50E-06	1.71E+01
I-135	3.45E+00	3.45E+03
Kr-88	NA	3.79E+03
La-140	5.29E+00	7.96E+02
Nb-95	3.85E-01	1.25E+02
Nb-95m	1.34E-03	NA
Nb-97	6.17E-01	NA
Nd-144	3.59E-19	NA
Np-237	6.30E-17	NA
Np-239	9.42E+00	3.64E+03
Pr-144	8.97E-01	NA
Pr-144m	8.76E-03	NA
Pu-238	1.48E-03	4.93E-01
Pu-239	2.96E-04	9.85E-02
Pu-240	2.39E-04	7.96E-02
Pu-241	8.30E-02	2.77E+01
Rb-88	NA	NA
Sr-89	1.09E+01	3.68E+03
Sr-90	8.64E-01	2.88E+02
Sr-91	3.26E+00	2.58E+03
Te-127	7.83E-02	NA
Te-127m	1.36E-01	4.55E+01

Radionuclide	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)
Te-129	3.05E-01	NA
Te-129m	4.84E-01	1.63E+02
Te-131	2.71E-01	NA
Te-131m	1.21E+00	5.31E+02
Te-132	1.33E+01	4.93E+03
U-234	5.71E-12	NA
U-235	3.78E-16	NA
U-235m	2.95E-04	NA
U-236	9.67E-15	NA
U-237	1.02E-07	NA
Xe-131m	4.47E-03	NA
Xe-133	1.17E+00	6.44E+04
Xe-133m	7.90E-02	NA
Xe-135	3.76E+00	1.63E+04
Xe-135m	5.94E-01	NA
Y-90	1.05E-01	NA
Y-91	2.93E-02	NA
Y-91m	2.08E+00	NA
Zr-95	1.36E+00	4.55E+02
Zr-97	5.74E-01	3.15E+02
[a] Integrated Air DRLs are not decayed to an evaluation time and are therefore NA for daughter radionuclides not present in the initial mixture.		

Table 1.8. PWR Radionuclide-Specific Derived Response Levels for Administration of KI

Radionuclide	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)
Ba-137m	2.48E-01	NA
Cs-134	3.84E-01	1.28E+02
Cs-135	2.06E-10	NA
Cs-136	1.25E-01	4.27E+01
Cs-137	2.62E-01	8.75E+01
I-129	1.97E-10	4.37E-08
I-131	1.53E+01	4.48E+03
I-132	1.64E+01	6.08E+03
I-133	9.89E+00	4.16E+03
I-134	3.38E-12	1.28E-05
I-135	6.18E-01	6.19E+02
Kr-88	NA	5.66E+02
Rb-88	NA	NA
Te-127	1.25E-01	NA
Te-127m	2.17E-01	7.26E+01
Te-129	4.79E-01	NA
Te-129m	7.60E-01	2.56E+02
Te-131	2.78E-01	NA
Te-131m	1.24E+00	5.44E+02
Te-132	1.58E+01	5.87E+03
Xe-131m	5.28E-03	NA
Xe-133	7.55E-01	7.90E+05
Xe-133m	5.11E-02	NA
Xe-135	6.75E-01	3.95E+04

Radionuclide	DRL_{Dp} (μCi/m^2)	$DRL_{\tilde{A}}$ (μCi•s/m^3)
Xe-135m	1.07E-01	NA
[a] Integrated Air DRLs are not decayed to an evaluation time and are therefore NA for daughter radionuclides not present in the initial mixture.		

Table 1.9. Dose Rate, Alpha, and Beta Derived Response Levels for Administration of KI

DRL Type	BWR	PWR
Dose Rate (mrem/h)	8.58E-01	5.99E-01
Alpha Deposition ($μCi_{alpha}$/m^2)[a]	2.01E-03	NA
Alpha Integrated Air ($μCi_{alpha}$•s/m^3)[a]	6.71E-01	NA
Beta Deposition ($μCi_{beta}$/m^2)	1.05E+02	4.59E+01
Beta Integrated Air ($μCi_{beta}$•s/m^3)	1.22E+05	8.45E+05
[a] Alpha DRLs are NA because the radionuclides assumed to be released for the PWR scenario are not alpha-emitters.		

1.5.3. Worker Protection Turn-Back Limits

Table 1.10 and Table 1.11 contain worker Turn-Back Limits (TBLs) for the representative BWR and PWR mixtures, respectively. Dose Rate, Alpha, and Beta TBLs are calculated for an 8-h shift starting 12 h after the plume has passed. The TBLs are provided per rem dose limit and are appropriate for the Adult Whole Body. To scale a listed TBL for a different dose limit (in units of rem), multiply the values in the tables by the desired dose limit.

> ***NOTE****: TBLs are not provided for during plume passage because of the inability of field instrumentation to differentiate between ground and air activity. The provided TBLs should be adjusted to instrument-specific values for field team use.*

> ***NOTE****: Assigned protection factors (APF) for respirators are included in the tables for completeness, even though the impact of the dose from inhalation of resuspended material is expected to be so low that respirators do not provide significant total dose reduction and may instead unnecessarily prolong exposure time. Therefore, it might not be advisable to use respirators for activities after the plume has passed.*

Table 1.10. BWR Worker Protection Turn-Back Limits for Varying Assigned Protection Factors (APF)

TBL Type	TBL per rem Effective Dose Limit			
	APF			
	1	50	100	1000
Dose Rate (mrem/h)	1.20E+02	1.25E+02	1.25E+02	1.25E+02
Alpha (μCiα/m2)	2.97E-01	3.08E-01	3.08E-01	3.08E-01
Beta (μCiβ/m2)	1.48E+04	1.53E+04	1.53E+04	1.54E+04

Table 1.11. PWR Worker Protection Turn-Back Limits for Varying Assigned Protection Factors (APF)

TBL Type	TBL per rem Effective Dose Limit			
	APF			
	1	50	100	1000
Dose Rate (mrem/h)	1.23E+02	1.25E+02	1.25E+02	1.25E+02
Alpha ($\mu Ci_\alpha/m^2$)[a]	NA	NA	NA	NA
Beta ($\mu Ci_\beta/m^2$)	9.47E+03	9.62E+03	9.62E+03	9.63E+03

[a] Alpha TBLs are NA because the radionuclides assumed to be released for the PWR scenario are not alpha-emitters.

1.5.4. Ingestion Pathway

Table 1.12 and Table 1.13 include FRMAC Intervention Levels (FILs) and Ingestion DRLs for radionuclides in Table 1.1 that are **NOT** included in FRMAC Assessment Manual, Volume 2, Appendix C, Tables 8-1 and 8-2.

Table 1.12. Ingestion Pathway – FILs, Crop DRLs, and Transfer Factors for NPP Radionuclides

Radionuclide	FIL ($\mu Ci/kg_{wet}$)	Crop DRL[a] ($\mu Ci/m^2$)	Leafy TF[b] (kg_{soil}/kg_{dry})	Fruit TF[b] (kg_{soil}/kg_{dry})	Non-Leafy TF[b] (kg_{soil}/kg_{dry})	Grain TF[b] (kg_{soil}/kg_{dry})
I-132	6.66E+02	4.99E+04	4.0E-02	1.3E-03	4.0E-02	4.0E-02
I-134	8.27E+03	2.22E+08	4.0E-02	1.3E-03	4.0E-02	4.0E-02
Pu-240	5.80E-04	5.80E-03	8.3E-05	4.5E-05	6.5E-05	9.5E-06
Te-127m	1.25E-01	1.25E+00	3.0E-01	3.0E-01	8.0E-04	1.0E-01
Zr-97	2.23E+01	3.66E+02	4.0E-03	1.1E-03	4.0E-03	1.0E-03

[a] Assumes crops are ready to harvest (e.g., Time to Harvest = 0). The displayed Crop DRL uses the largest Transfer Factor of the four crop types included in this table.
[b] Transfer Factors from PNNL20.

Table 1.13. Ingestion Pathway– FILs, Milk and Meat DRLs, and Transfer Factors for NPP Radionuclides

Radionuclide	FIL (µCi/kg$_{wet}$)	Forage TF[a] (kg$_{soil}$/kg$_{dry}$)	Milk_DRL[b] (area) (µCi/m^2)	Milk_DRL[b] (mass) (µCi/kg$_{wet}$)	Milk_DRL[b] (water) (µCi/l)	Milk TF[b] (d/l)	Meat_DRL[c] (area) (µCi/m^2)	Meat_DRL[c] (mass) (µCi/kg$_{wet}$)	Meat_DRL[c] (water) (µCi/l)	Meat TF[c] (d/kg$_{wet}$)
I-132	6.66E+02	3.7E-03	9.43E+07	1.35E+08	1.13E+08	5.4E-03	3.37E+64	4.84E+64	4.84E+64	6.7E-03
I-134	8.27E+03	3.7E-03	5.39E+16	7.73E+16	6.44E+16	5.4E-03	1.75E+165	2.51E+165	2.51E+165	6.7E-03
Pu-240	5.80E-04	5.5E-04	1.67E+00	1.21E+00	1.01E+00	1.0E-05	1.46E+01	1.05E+01	1.05E+01	1.1E-06
Te-127m	1.25E-01	1.0E+00	1.07E+01	7.70E+00	6.42E+00	3.4E-04	5.59E-01	4.03E-01	4.03E-01	7.0E-03
Zr-97	2.23E+01	1.0E-02	7.93E+05	5.72E+05	4.76E+05	3.6E-06	1.34E+14	9.64E+13	9.64E+13	1.2E-06

[a] Forage Transfer Factors from IAEA10 for available elements. Transfer Factors for elements not covered by IAEA10 were inferred using the methodology described in PNNL03.
[b] Values for Cow's Milk ready to harvest (e.g., Time to Grazing and Time to Harvest = 0). Transfer factors from PNNL20.
[c] Values for Beef ready to harvest (e.g., Time to Grazing and Time to Harvest = 0). Transfer factors from PNNL20.

1.6. References

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ICRP96 *Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 5 Compilation of Ingestion and Inhalation Dose Coefficients*, ICRP Publication 72, International Commission on Radiological Protection, Ottawa, Ontario, Canada, 1996.

NNPP19 *Unclassified Predictive Plume Model Technical Manual*, U.S. Nuclear Naval Propulsion Program, Washington, DC, January 2019.

NRC13 *State-of-the-Art Reactor Consequence Analyses Project, Volume 1: Peach Bottom Integrated Analysis and Volume 2: Surry Integrated Analysis*, NUREG/CR-7110, U.S. Nuclear Regulatory Commission, Washington, DC, 2013.

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2. SCENARIO 2: NUCLEAR FUEL FABRICATION

2.1. Introduction

There are several forms that unirradiated nuclear fuel can take through the fuel fabrication process. Unirradiated nuclear fuel can be assembled into nuclear fuel rods and bundles. It can be present in metallic, ceramic, or gaseous forms. Unirradiated fuel does not pose a large dose concern from a release due to the high temperatures required to aerosolize solid forms of uranium. Uranium hexafluoride (UF_6) releases while in storage or transport from the enrichment facility to the fuel fabrication facility are the primary accident of concern, and as such this section only focuses on UF_6 release accidents that may occur in the top left of Figure 2.1. This scenario focuses on the radiological consequences of a release while in most cases, for low enriched uranium (LEU), the chemical consequences would be greater. It does not cover other potential fuel fabrication accidents such as criticality or solid uranium fuel fire events, as the offsite consequences are expected to be low or nonexistent (NUREG-1140). Additionally, it does not cover assumptions for highly enriched uranium (HEU, high assay low enriched uranium (HALEU), or mixed oxide (MOX) fuel fabrication. Turbo FRMAC 2021 contains default mixtures for HEU that can be used in the event that an accident occurs with enriched UF_6.

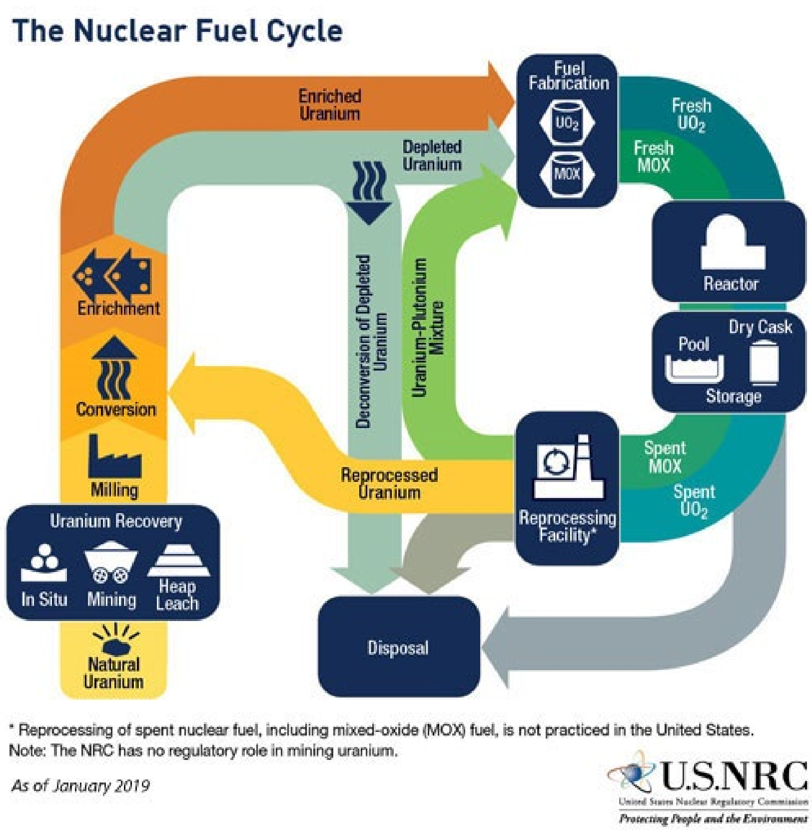

Figure 2.1. Nuclear Fuel Cycle (NRC20)

Uranium hexafluoride is a chemical form of uranium that is used during the uranium enrichment process. Within a reasonable range of temperature and pressure, it can be a solid, liquid, or gas. Solid UF_6 is a white, dense, crystalline material that resembles rock salt. Liquid UF_6 is formed only at temperatures greater than 147°F (64°C) and at pressures greater than 1.5 times atmospheric pressure (22 psia). At atmospheric pressure, solid UF_6 will transform directly to UF_6 gas (sublimation) when the temperature is raised to 134°F (57°C), without going through a liquid phase (NUREG-1198). Uranium hexafluoride can be present in a variety of enrichments from depleted, natural, or enriched (nominal 5%). The higher the enrichment, the larger the potential dose from external or internal exposure, due to the increased isotopic ratios of U-234 and U-235.

Uranium hexafluoride does not react with oxygen, nitrogen, carbon dioxide, or dry air, but it does react with water or water vapor. For this reason, UF_6 is always handled in leak-tight containers and processing equipment (USEC651). When UF_6 comes into contact with water, such as water vapor in the air, the UF_6 and water react, forming corrosive hydrogen fluoride (HF) and a uranium-fluoride compound called uranyl fluoride (UO_2F_2) (NUREG-1198).

While the chemical injury to the kidneys and lungs from a release of UF_6 are thought to be more severe, the radiological dose contribution from the release will be addressed in this scenario (NUREG-1140).

This pre-assessed scenario is based on defaults and methods as specified in the May 2023 version of the FRMAC Assessment Manual, Volume 2 (SNL23) and may need to be updated to reflect future changes. Default results were calculated using Turbo FRMAC 2021.

2.2. Scenario-Specific Concerns

The Assessment Scientist should be prepared to address the following questions to support protective action decisions:

1. **Should the population be evacuated or sheltered?**
   Evacuation or sheltering-in-place are early phase protective actions. These actions should be considered in areas where projected dose exceeds the corresponding PAG. In the case of an UF_6 incident, it is possible that a significant dispersal of uranium may occur. It must be noted that HF exposure is by far a greater concern due to the damaged caused to lung tissue (NUREG-1140). In the early phase, emergency actions will be dominated by guidance for chemical releases to protect from HF exposure (ERPG). During the early phase of a release, it will be important to measure or estimate the amount and concentration of the HF released.
2. **Should the population be relocated?**
   Relocation is an intermediate phase protective action. Relocation should be considered in areas where projected dose exceeds the corresponding PAG.
3. **What are the likely exposure pathways?**
   During plume passage, inhalation is expected to be the dominant pathway. Following plume passage, the primary exposure pathway is internal dose from inhalation of resuspended material, inadvertent ingestion, and consumption of contaminated foods. Note, inadvertent ingestion is not included in typical FRMAC ingestion calculations and should be addressed separately if expected to exceed 10% of the appropriate EPA PAG for the time phase of interest. A method for projecting dose from inadvertent soil ingestion is provided in FRMAC Assessment Manual, Volume 2, see Method 3.7.
4. **Should potassium iodide (KI) be administered?**

KI administration is not appropriate because iodine radionuclides are not included in UF_6. Chelating agents can be used to help remove uranium from the body to both reduce the radiological as well as the chemical injury. Contact the Radiation Emergency Assistance Center/Training Site (REAC/TS) for advice regarding uranium chelation.

5. **Do emergency workers need protective equipment?**
   Use of respiratory protection may be advised to minimize intakes of radioactive materials due to resuspension. Because uranium is primarily an internal exposure hazard, a prolonged exposure time due to slower work wearing respiratory protection should not cause a significant increase in external dose. The need for PPE for contamination control should also be evaluated. FRMAC Monitoring and Sampling Manual, Volume 1 provides default guidance for PPE for FRMAC field teams.

Answers to the following questions are dependent on the circumstances of the event to which you are responding (e.g., source size, radionuclide, dispersal method, weather conditions, etc.):

- When can the evacuated population be allowed to return?
- What is the potential economic/infrastructure impact?
- Can foodstuffs grown in the contaminated area be consumed?
- Can foodstuffs be grown in the impacted area in the future?

2.3. Data Needs and Sources

The following sections describe the default assumptions to use for a nuclear fuel scenario until event-specific information is known.

2.3.1. Time Phase

Use FRMAC default time phases and evaluation time as specified in FRMAC Assessment Manual, Volume 2, Table 2-3.

ACTION	Determine whether to include Plume Pathways (i.e., Total Dose or Avoidable Dose)

2.3.2. Mixture

The isotopic mixture of the uranium in the UF_6 should be readily available from the fabrication facility or shipping documents. Table 2.1 shows the isotopic mixture for a nominal 5% (4.63% actual) enriched UF_6 as the typical enrichment used by commercial reactors (SNL10). Nominal isotopic mixtures for other enrichments can be found in Mixture Manager©.

Note that relative value by mass and activity are provided for the radionuclides in Table 2.1. This is acceptable in the case of DRL calculations, for which the relative concentrations of the radionuclides in the mixture are important. It is recommended that relative value by activity is used in Turbo FRMAC as activity is requested in calculations by default. The mixture should be imported with equilibrium set to OFF, under the assumption that uranium daughters would have been removed during the separation process. If time from separation is known, then the mixture can be decayed to account for daughter ingrowth. The mixture is calculated using the method specified in NUREG/BR-150 from a given U-235 enrichment.

Table 2.1. 5% Enriched Uranium Mixture

Radionuclide	Relative Value by Mass	Relative Value by Activity
U-234	5.10E-04	8.82E-01
U-235	4.63E-02	2.76E-02
U-236	7.15E-05	1.28E-03
U-238	9.53E-01	8.86E-02

ACTION — Review available data and work with Monitoring & Sampling to determine what radiation type(s) and/or radionuclide(s) have been detected, relative activity ratios, and instruments being used

2.3.3. Protective Action Guides

Use FRMAC default PAGs unless instructed otherwise by Decision Makers. The PAGs are located in FRMAC Assessment Manual, Volume 2, Table 2-1.

2.4. Technical Caveats

2.4.1. Inhalation Pathway

The lung clearance type (LCT) Type F is the recommended LCT by DOE for UF_6 and UO_2F_2 (DOE1136).

In the absence of actual measurement of particle size distributions (PSD), use the FRMAC default PSD to estimate dose from inhalation of the plume and resuspended material.

ACTION — Work with NARAC to ensure consistent source term assumptions, including LCT and PSD

ACTION — Work with Health & Safety to evaluate the need for respirators, turn-back limits, etc.

ACTION — Request that the field teams perform resuspension measurements to support dose projections

2.4.2. Field Measurements

Dose rates from dispersed uranium are likely too low to be useful. Therefore, field measurements are likely to come from handheld alpha/beta survey meters.

2.5. Default Results

2.5.1. Public Protection Derived Response Levels

Table 2.2 and Table 2.3 contain DRLs for the 5% enriched UF_6 mixture in Table 2.1. The DRLs are appropriate for the Adult Whole Body.

Table 2.2. UF_6 (5% Enriched) Radionuclide-Specific Derived Response Levels

Radionuclide	Early Phase (Total Dose)		Early Phase (Avoidable Dose)		First Year	
	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3)	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3)	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3)
U-234	3.08E+00	1.03E+03	5.69E+02	1.90E+05	2.30E+02	7.67E+04
U-235	9.65E-02	3.22E+01	1.78E+01	5.94E+03	7.20E+00	2.40E+03
U-236	4.48E-03	1.49E+00	8.26E-01	2.76E+02	3.34E-01	1.11E+02
U-238	3.10E-01	1.03E+02	5.72E+01	1.91E+04	2.31E+01	7.71E+03

Table 2.3. UF_6 (5% Enriched) Dose Rate, Alpha, and Beta Derived Response Levels

DRL Type	Early Phase (Total Dose)	Early Phase (Avoidable Dose)	First Year
Dose Rate (mrem/h)	1.88E-04	3.48E-02	1.40E-02
Alpha Deposition (µCi$_{alpha}$/m^2)	3.50E+00	6.45E+02	2.61E+02
Alpha Integrated Air (µCi$_{alpha}$•s/m^3)	1.17E+03	2.15E+05	8.69E+04
Beta Deposition (µCi$_{beta}$/m^2)	2.68E-02	4.94E+00	2.00E+00
Beta Integrated Air (µCi$_{beta}$•s/m^3)[a]	NA	NA	NA

[a] Beta Integrated Air DRLs are NA because the parent radionuclides in the UF_6 mixture emit beta particles with average energies less than the instrument threshold. See FRMAC Assessment Manual, Volume 2, Method 1.4 Beta DRL for more discussion.

2.5.2. Worker Protection Turn-Back Limits

Table 2.4 contains worker TBLs 5% enriched UF_6 mixture in Table 2.1. Dose Rate, Alpha, and Beta TBLs are calculated for an 8-h shift starting 12 h after the plume has passed. The TBLs are provided per rem dose limit and are appropriate for the Adult Whole Body. To scale a listed TBL for a different dose limit (in units of rem), multiply the values in the tables by the desired dose limit.

> ***NOTE:*** *TBLs are not provided for during plume passage because of the inability of field instrumentation to differentiate between ground and air activity. The provided TBLs should be adjusted to instrument-specific values for field team use.*

> ***NOTE:*** *Dose rates from dispersed uranium are likely to be too low to be a useful TBL but are included for completeness.*

Table 2.4. UF_6 (5% Enriched) Worker Protection Turn-Back Limits for Varying Assigned Protection Factors (APF)

TBL Type	TBL per rem Dose Limit			
	APF			
	1	50	100	1000
Dose Rate (mrem/h)	2.22E-01	1.02E+01	1.89E+01	8.00E+01
Alpha ($\mu Ci_\alpha/m^2$)	3.71E+03	1.70E+05	3.15E+05	1.34E+06
Beta ($\mu Ci_\beta/m^2$)	5.04E+01	2.32E+03	4.29E+03	1.82E+04

2.5.3. Ingestion Pathway

Table 2.5 and Table 2.6 include FILs and Ingestion DRLs for radionuclides in Table 2.1 that are **NOT** included in FRMAC Assessment Manual Volume 2 Appendix C, Tables 8-1 and 8-2.

Table 2.5. Ingestion Pathway – FILs, Crop DRLs, and Transfer Factors for 5% Enriched Uranium

Radionuclide	FIL ($\mu Ci/kg_{wet}$)	Crop DRL[a] ($\mu Ci/m^2$)	Leafy TF[b] (kg_{soil}/kg_{dry})	Fruit TF[b] (kg_{soil}/kg_{dry})	Non-Leafy TF[b] (kg_{soil}/kg_{dry})	Grain TF[b] (kg_{soil}/kg_{dry})
U-234	2.21E-03	2.21E-02	2.0E-02	1.5E-02	1.5E-02	6.2E-03
U-235	2.38E-03	2.38E-02	2.0E-02	1.5E-02	1.5E-02	6.2E-03
U-236	2.35E-03	2.34E-02	2.0E-02	1.5E-02	1.5E-02	6.2E-03
U-238	2.47E-03	2.47E-02	2.0E-02	1.5E-02	1.5E-02	6.2E-03

[a] Assumes crops are ready to harvest (e.g., Time to Harvest = 0). The displayed Crop DRL uses the largest Transfer Factor of the four crop types included in this table.
[b] Transfer Factors from PNNL20.

Table 2.6. Ingestion Pathway – FILs, Milk and Meat DRLs, and Transfer Factors for 5% Enriched Uranium

Radionuclide	FIL ($\mu Ci/kg_{wet}$)	Forage TF[a] (kg_{soil}/kg_{dry})	Milk DRL[b] (area) ($\mu Ci/m^2$)	Milk DRL[b] (mass) ($\mu Ci/kg_{wet}$)	Milk DRL[b] (water) (µCi/l)	Milk TF[b] (d/l)	Meat DRL[c] (area) ($\mu Ci/m^2$)	Meat DRL[c] (mass) ($\mu Ci/kg_{wet}$)	Meat DRL[c] (water) (µCi/l)	Meat TF[c] (d/kg_{wet})
U-234	2.21E-03	4.6E-02	3.55E-02	2.56E-02	2.13E-02	1.8E-03	1.58E-01	1.14E-01	1.14E-01	3.9E-04
U-235	2.38E-03	4.6E-02	3.81E-02	2.75E-02	2.29E-02	1.8E-03	1.69E-01	1.22E-01	1.22E-01	3.9E-04
U-236	2.35E-03	4.6E-02	3.76E-02	2.71E-02	2.26E-02	1.8E-03	1.67E-01	1.20E-01	1.20E-01	3.9E-04
U-238	2.47E-03	4.6E-02	3.96E-02	2.85E-02	2.38E-02	1.8E-03	1.76E-01	1.27E-01	1.27E-01	3.9E-04

[a] Forage Transfer Factors from IAEA10 for available elements. Transfer Factors for elements not covered by IAEA10 were inferred using the methodology described in PNNL03.
[b] Values for Cow's Milk ready to harvest (e.g., Time to Grazing and Time to Harvest = 0). Transfer factors from PNNL20.
[c] Values for Beef ready to harvest (e.g., Time to Grazing and Time to Harvest = 0). Transfer factors from PNNL20.

2.6. References

DOE1136	*Guide of Good Practices for Occupational Radiological Protection in Uranium Facilities*, DOE-STD-1136-2017, US DOE, Washington, DC, 2017.
ERPG	*Emergency Release Planning Guidelines, Workplace Environmental Exposure Level*, American Industrial Hygiene Association, 2020.
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3. SCENARIO 3: NUCLEAR FUEL ACCIDENT

3.1. Introduction

Accidents related to spent nuclear fuel will most likely involve nuclear reactor wastes or fuel reprocessing materials. The severity of the accident primarily depends on the quantity and the age of the material, the mechanism by which it is released, and engineering controls at the facility to scrub radioactive effluent. Spent fuel accidents are significantly lower in probability, as the fuel continues to cool and decay after its removal from the operating (NPP (NUREG/ BR-0150). This scenario addresses a range of release scenarios for fuel stored in a spent fuel pool (SFP). If the fuel has cooled for fewer than 100 days, shorter-lived radionuclides will be present and the consequences will be similar to a power reactor accident (NUREG-2161) (NUREG-4982). Like NPP accidents, fission products make up the majority of the radionuclide inventory in spent fuel. Some of the fission products are particulate, some are in gaseous form (krypton and xenon), and others are highly volatile (iodines). The mixture of radionuclides released is primarily dependent on the age of the fuel after it is removed from the operating NPP.

This pre-assessed scenario is written for U.S. commercial NPP spent fuel. This section focuses on spent fuel fires where the pool is unable to cool the fuel (e.g., pool leakage) (NRC16a). Spent fuel accident scenarios for fuel handling accidents and dry cask storage or terrorist incidents are not included in this section, as the offsite doses/consequences are expected to be minimal (NUREG-1864). Spent fuel accidents at fuel reprocessing plants are also considered to involve spent nuclear fuel but are not considered in this scenario as there are no commercial reprocessing facilities operating in the U.S.

This pre-assessed scenario is based on defaults and methods as specified in the May 2023 version of the FRMAC Assessment Manual, Volume 2 (SNL23) and may need to be updated to reflect future changes. Default results were calculated using Turbo FRMAC 2021.

3.2. Scenario-Specific Concerns

The Assessment Scientist should be prepared to address the following questions to support protective action decisions:

1. **Should the population be evacuated or sheltered?**
   Some protective actions may begin prior to the release of radioactive material when there is notice of deteriorating plant conditions. In this case, there will likely be time for an orderly evacuation. Sheltering in place may be warranted in situations where evacuation poses a greater risk of exposure or physical harm, or when there is no prior notice or warning. The EPA recommends these protective actions when the projected effective dose to an individual is 1 rem over the first four days after a release.

   Spent fuel locations are generally co-located with NPPs. Each U.S. NPP has EPZs established by State and Local governments in consultation with FEMA and NRC. There is a plume exposure pathway EPZ within a 10-mile radius of the plant and an ingestion exposure pathway EPZ within a 50-mile radius of the plant. Evacuation does not always call for completely emptying the 10-mile zone around an NPP. In many cases, in the event of a General Emergency, a two-mile ring around the plant is evacuated, along with people living in the 5-mile zone directly downwind and slightly to either side of the projected path of the release. This "keyhole" pattern helps account for potential wind shifts and fluctuations in the release path. Evacuation beyond 5 miles is assessed as the accident progresses (NRC18).

Predetermined protective action plans are in place for the EPZs. It is important for the Assessment Scientist to be aware that some actions (e.g., evacuation, sheltering, administration of potassium iodide) might be taken before FRMAC involvement.

2. **Should the population be relocated?**
   Relocation is an intermediate phase protective action. Relocation should be considered in areas where projected dose exceeds the corresponding PAG.

3. **What are the likely exposure pathways?**
   During plume passage, inhalation is expected to be the dominant pathway. Following plume passage, the primary exposure pathway is internal dose from inhalation of resuspended material, inadvertent ingestion, and consumption of contaminated foods. Note, inadvertent ingestion is not included in typical FRMAC ingestion calculations and should be addressed separately if expected to exceed 10% of the appropriate EPA PAG for the time phase of interest. A method for projecting dose from inadvertent soil ingestion is provided in FRMAC Assessment Manual, Volume 2, see Method 3.7.

4. **Should potassium iodide (KI) be administered?**
   Administration of KI to both children and adults should be considered if the projected child thyroid dose from radioiodines exceeds 5 rem (FDA01). The 2017 EPA PAG Manual recommends using the one-year-old age group for thyroid dose projections, as it is expected to be the limiting age group. Table 3.6 contains DRLs to support decisions to administer KI. Note, States may choose to include KI in predetermined protective action plans for the 10-mile plume exposure pathway EPZ and, as such, KI might be pre-distributed to the population within this EPZ. Spent fuel accidents in which the fuel has been out of an operating reactor for at least 2 months do not contain a significant amount of iodine; therefore, KI administration would not provide protection in these accidents.

5. **Do emergency workers need protective equipment?**
   Use of respiratory protection may be advised to minimize intakes of radioactive materials, particularly during plume passage, as workers are likely to already be on site prior to a release. Note that use of respiratory protection is not always conservative given that it can prolong exposure time. The need for PPE for contamination control should also be evaluated. FRMAC Monitoring and Sampling Manual, Volume 1 provides default guidance for PPE and respiratory protection for FRMAC field teams (FRMAC19).

Answers to the following questions are dependent on the circumstances of the event to which you are responding (e.g., e.g., radionuclide mixture, deposition, weather conditions, etc.):

- When can the evacuated population be allowed to return?
- What is the potential economic/infrastructure impact?
- Can foodstuffs grown in the contaminated area be consumed?

- Can foodstuffs be grown in the impacted area in the future?

3.3. Data Needs and Sources

The following sections describe the default assumptions to use for a spent nuclear fuel accident scenario until event-specific information is known.

3.3.1. *Time Phase*

Use FRMAC default time phases and evaluation time as specified in FRMAC Assessment Manual, Volume 2, Table 2-3.

ACTION	Determine whether to include Plume Pathways (i.e., Total Dose or Avoidable Dose)

3.3.2. *Mixture*

The mixture of fission products released from an SFP fire is highly dependent on the accident progression sequence, type of reactor, mechanism of release, fuel burnup history, amount of time since the fuel was removed from the reactor, and amount of time the fuel burned (NRC16). Table 3.1 includes mixture information for a mitigated release of uncovered spent fuel from a 3000 MW PWR. Pool inventory was assumed to contain fuel from the equivalent of four operating cores (approximate U.S. average fuel pool inventory). The youngest batch (one-third of an operating core) was removed from the operating reactor five days post-shutdown and each of the subsequent 11 batches were aged an additional 18 months, for a total of 12 batches. The mixture was determined using Radiological Assessment System for Consequence Analysis (RASCAL).

The mixture in Table 3.1 should be used until event-specific information is provided. Projected source terms for an event can be obtained through the NRC using accident response modelling software, including RASCAL.

The mixture is applicable at the Release Time and should be entered in Turbo FRMAC as an Integrated Air Concentration and an NPP type mixture, with equilibrium set to OFF to avoid double-counting daughters. Note that Integrated Air Concentration units are different than the activity units provided in Table 3.1. This is acceptable in the case of DRL calculations, for which the relative concentrations of the radionuclides in the mixture are important.

Table 3.1. Representative Mixture for SFP Fire

Radionuclide	Released Activity (Ci)	Radionuclide	Released Activity (Ci)
Am-241	1.30E+00	Rb-88	3.60E-07
Ba-140	2.10E+04	Rh-103m	2.40E+02
Ce-141	7.90E+01	Rh-105	1.40E+01
Ce-143	4.90E+00	Ru-103	2.40E+02
Ce-144	9.50E+01	Ru-105	2.60E-07
Cm-242	2.40E+00	Ru-106	1.90E+02
Cs-134	4.60E+06	Sb-127	5.30E+03
Cs-136	3.40E+05	Sb-129	4.30E-05

Radionuclide	Released Activity (Ci)
Cs-137	1.30E+07
I-131	1.20E+07
I-132	8.20E+05
I-133	4.50E+05
I-135	3.70E+01
Kr-85	2.70E+06
Kr-85m	1.10E-02
Kr-88	3.20E-07
La-140	4.50E+03
La-141	9.20E-09
Mo-99	7.30E+01
Nb-95	9.10E+01
Nb-95m	4.00E-01
Nb-97	2.10E-02
Nd-147	2.50E+01
Np-239	2.20E+02
Pm-147	9.50E-01
Pr-143	6.60E+01
Pr-144	9.50E+01
Pu-238	1.20E-01
Pu-239	3.60E-03
Pu-241	9.20E+01

Radionuclide	Released Activity (Ci)
Sr-89	1.30E+04
Sr-90	1.90E+04
Sr-91	1.20E+00
Tc-99m	7.10E+01
Te-127	8.30E+03
Te-127m	2.40E+03
Te-129	5.90E+03
Te-129m	9.10E+03
Te-131	3.40E+02
Te-131m	1.50E+03
Te-132	7.00E+04
Xe-131m	2.70E+05
Xe-133	2.70E+07
Xe-133m	3.00E+05
Xe-135	5.50E+03
Xe-135m	5.90E+00
Y-90	2.60E+03
Y-91	6.00E+01
Y-91m	7.30E-01
Y-92	2.30E-09
Y-93	5.80E-03
Zr-95	8.40E+01

ACTION Review available data and work with Monitoring & Sampling to determine what radiation type(s) and/or radionuclide(s) have been detected, relative activity ratios, and instruments being used

ACTION Coordinate with the NRC representative to conduct a source term calculation using RASCAL or event-specific data

3.3.3. Protective Action Guides

Use FRMAC default PAGs unless instructed otherwise by Decision Makers. The PAGs are located in FRMAC Assessment Manual, Volume 2, Table 2-1.

3.4. Technical Caveats

ACTION Determine whether the 1992 EPA PAG Manual or FRMAC default methods should be used. At the time of writing this section, FRMAC default methods follow 2017 EPA PAG Manual guidance

3.4.1. Inhalation Pathway

Spent nuclear fuel releases are assumed to be composed of 1-µm Activity Median Aerodynamic Diameter (AMAD) particles. Use the ICRP Recommended LCT as specified in ICRP Publication 72 (ICRP96).

ACTION	Work with NARAC to ensure consistent source term assumptions, including LCT and particle size distribution (PSD)

3.4.2. Multiple Physical/Chemical Forms

Iodine released from an SFP accident will likely exist in multiple physical forms. Table 3.2 includes the FRMAC default approach for iodine portioning, which is consistent with NRC methodology (NUREG-1940). Iodine partitioning is automatically included when NPP mixture type is selected. Deposition velocities for each form are also provided. For resuspension dose calculations, all deposited Iodine Vapor/Reactive Gas is assumed to be converted to 1-µm particulate.

Table 3.2. Default Iodine Partitioning

Form	Partition	Deposition Velocity (m/s)
Methyl Iodide/Non-reactive Gas (CH_3I)	45%	0
Iodine Vapor/Reactive Gas (I_2)	30%	6.4E-03
Particulate	25%	6.5E-03

Tritium is not expected to be a significant dose contributor for SFP accidents. If included, tritium should be modeled as existing in the Tritiated Water Vapor (HTO) form with a deposition velocity of 0 m/s to be consistent with NRC.

ACTION	Request that the field teams use appropriate air sampling equipment to detect all chemical/physical forms of iodine

ACTION	Work with the Advisory Team to determine appropriate KI protection factors for workers

ACTION	Work with Health & Safety to evaluate the need for respirators, turn-back limits, stay times, etc.

ACTION	Request that the field teams perform resuspension measurements to support dose projections

3.4.3. Ingestion Pathway

The FDA provides DILs for radionuclides expected to deliver the major portion of the dose from ingestion during the first year following an incident.

ACTION	DILs for grouped radionuclides (Cs-134 + Cs-137, Pu-238 + Pu-239 + Am-241, and Ru-103 + Ru-106) should be used in ingestion calculations

3.5. Default Results

3.5.1. Public Protection Derived Response Levels

Table 3.3 and Table 3.4 contain DRLs for the representative SFP fire mixture in Table 3.1. The DRLs are appropriate for the Adult Whole Body and are reported for parents and daughters.

> ***NOTE:*** *Early Phase DRLs are provided for completeness. It is possible that protective action decisions for the Early Phase might be made before FRMAC involvement.*

> ***NOTE:*** *Radionuclides that are noble gases when initially released to the air are **not** deposited on the ground. Noble gases that are daughters of ground-deposited radionuclides **are** assumed to remain on the ground. Also, iodine Integrated Air DRLs are summed over multiple physical forms.*

Table 3.3. Spent Fuel Incident Radionuclide-Specific Derived Response Levels

Radionuclide	Early Phase (Total Dose)		Early Phase (Avoidable Dose)		First Year	
	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3) [a]	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3) [a]	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3) [a]
Am-241	8.07E-06	2.69E-03	6.40E-05	2.13E-02	2.27E-06	7.56E-04
Ba-137m	7.62E+01	NA	6.04E+02	NA	2.14E+01	NA
Ba-140	1.27E-01	4.35E+01	1.01E+00	3.45E+02	3.56E-02	1.22E+01
Ce-141	4.85E-04	1.63E-01	3.85E-03	1.30E+00	1.36E-04	4.59E-02
Ce-143	2.36E-05	1.01E-02	1.88E-04	8.05E-02	6.64E-06	2.85E-03
Ce-144	5.89E-04	1.97E-01	4.67E-03	1.56E+00	1.65E-04	5.52E-02
Cm-242	1.49E-05	4.97E-03	1.18E-04	3.94E-02	4.17E-06	1.39E-03
Cs-134	2.85E+01	9.52E+03	2.26E+02	7.55E+04	8.01E+00	2.67E+03
Cs-135	2.54E-14	NA	2.02E-13	NA	7.15E-15	NA
Cs-136	2.06E+00	7.03E+02	1.63E+01	5.58E+03	5.77E-01	1.98E+02
Cs-137	8.07E+01	2.69E+04	6.40E+02	2.13E+05	2.27E+01	7.56E+03
I-129	3.41E-12	NA	2.70E-11	NA	9.57E-13	NA
I-131	8.43E+01	2.48E+04	6.69E+02	1.97E+05	2.37E+01	6.97E+03
I-132	5.50E-01	1.70E+03	4.37E+00	1.35E+04	1.55E-01	4.77E+02
I-133	2.21E+00	9.31E+02	1.76E+01	7.39E+03	6.21E-01	2.62E+02
I-135	7.65E-05	7.66E-02	6.07E-04	6.08E-01	2.15E-05	2.15E-02
Kr-85	NA	5.59E+03	NA	4.43E+04	NA	1.57E+03
Kr-85m	NA	2.28E-05	NA	1.81E-04	NA	6.39E-06
Kr-88	NA	6.62E-10	NA	5.26E-09	NA	1.86E-10
La-140	4.67E-02	9.31E+00	3.71E-01	7.39E+01	1.31E-02	2.62E+00
La-141	6.84E-15	1.90E-11	5.43E-14	1.51E-10	1.92E-15	5.35E-12
Mo-99	3.99E-04	1.51E-01	3.17E-03	1.20E+00	1.12E-04	4.24E-02
Nb-95	5.64E-04	1.88E-01	4.48E-03	1.49E+00	1.58E-04	5.29E-02
Nb-95m	2.77E-06	8.28E-04	2.20E-05	6.57E-03	7.78E-07	2.32E-04
Nb-97	1.28E-10	4.35E-05	1.02E-09	3.45E-04	3.61E-11	1.22E-05
Nd-144	2.44E-22	NA	1.94E-21	NA	6.86E-23	NA
Nd-147	1.50E-04	5.17E-02	1.19E-03	4.11E-01	4.22E-05	1.45E-02
Np-237	3.57E-15	NA	2.83E-14	NA	1.00E-15	NA
Np-239	1.18E-03	4.55E-01	9.35E-03	3.61E+00	3.31E-04	1.28E-01

Radionuclide	Early Phase (Total Dose)		Early Phase (Avoidable Dose)		First Year	
	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³) [a]	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³) [a]	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³) [a]
Pm-147	5.95E-06	1.97E-03	4.72E-05	1.56E-02	1.67E-06	5.52E-04
Pr-143	4.00E-04	1.37E-01	3.17E-03	1.08E+00	1.12E-04	3.84E-02
Pr-144	5.89E-04	1.97E-01	4.67E-03	1.56E+00	1.65E-04	5.52E-02
Pr-144m	5.75E-06	NA	4.57E-05	NA	1.62E-06	NA
Pu-238	7.45E-07	2.48E-04	5.91E-06	1.97E-03	2.09E-07	6.97E-05
Pu-239	2.24E-08	7.45E-06	1.78E-07	5.91E-05	6.29E-09	2.09E-06
Pu-241	5.71E-04	1.90E-01	4.53E-03	1.51E+00	1.60E-04	5.35E-02
Rb-88	1.44E-24	7.45E-10	1.14E-23	5.91E-09	4.05E-25	2.09E-10
Rh-103m	1.46E-03	4.97E-01	1.16E-02	3.94E+00	4.10E-04	1.39E-01
Rh-105	6.87E-05	2.90E-02	5.45E-04	2.30E-01	1.93E-05	8.14E-03
Rh-106	1.18E-03	NA	9.35E-03	NA	3.31E-04	NA
Ru-103	1.48E-03	4.97E-01	1.17E-02	3.94E+00	4.15E-04	1.39E-01
Ru-105	2.48E-13	5.38E-10	1.97E-12	4.27E-09	6.96E-14	1.51E-10
Ru-106	1.18E-03	3.93E-01	9.35E-03	3.12E+00	3.31E-04	1.10E-01
Sb-127	3.01E-02	1.10E+01	2.39E-01	8.70E+01	8.44E-03	3.08E+00
Sb-129	4.03E-11	8.90E-08	3.20E-10	7.06E-07	1.13E-11	2.50E-08
Sm-147	5.30E-20	NA	4.21E-19	NA	1.49E-20	NA
Sr-89	8.01E-02	2.69E+01	6.36E-01	2.13E+02	2.25E-02	7.56E+00
Sr-90	1.18E-01	3.93E+01	9.36E-01	3.12E+02	3.31E-02	1.10E+01
Sr-91	3.14E-06	2.48E-03	2.49E-05	1.97E-02	8.82E-07	6.97E-04
Tc-99	2.09E-12	NA	1.66E-11	NA	5.87E-13	NA
Tc-99m	3.86E-04	1.47E-01	3.07E-03	1.17E+00	1.09E-04	4.13E-02
Te-127	4.49E-02	1.72E+01	3.56E-01	1.36E+02	1.26E-02	4.82E+00
Te-127m	1.49E-02	4.97E+00	1.18E-01	3.94E+01	4.18E-03	1.39E+00
Te-129	3.53E-02	1.22E+01	2.80E-01	9.69E+01	9.91E-03	3.43E+00
Te-129m	5.59E-02	1.88E+01	4.44E-01	1.49E+02	1.57E-02	5.29E+00
Te-131	1.59E-03	7.03E-01	1.26E-02	5.58E+00	4.46E-04	1.98E-01
Te-131m	7.05E-03	3.10E+00	5.60E-02	2.46E+01	1.98E-03	8.72E-01
Te-132	3.90E-01	1.45E+02	3.09E+00	1.15E+03	1.10E-01	4.07E+01
U-234	2.88E-15	NA	2.28E-14	NA	8.09E-16	NA
U-235	2.85E-20	NA	2.27E-19	NA	8.02E-21	NA
U-235m	2.23E-08	NA	1.77E-07	NA	6.27E-09	NA
U-237	7.00E-10	NA	5.56E-09	NA	1.97E-10	NA
Xe-131m	2.92E-02	5.59E+02	2.32E-01	4.43E+03	8.20E-03	1.57E+02
Xe-133	1.69E-01	5.59E+04	1.34E+00	4.43E+05	4.75E-02	1.57E+04
Xe-133m	1.14E-02	6.21E+02	9.07E-02	4.93E+03	3.21E-03	1.74E+02
Xe-135	8.36E-05	1.14E+01	6.63E-04	9.03E+01	2.35E-05	3.20E+00
Xe-135m	1.32E-05	1.22E-02	1.05E-04	9.69E-02	3.70E-06	3.43E-03
Y-90	2.85E-02	5.38E+00	2.26E-01	4.27E+01	8.01E-03	1.51E+00
Y-91	3.70E-04	1.24E-01	2.94E-03	9.85E-01	1.04E-04	3.49E-02
Y-91m	2.00E-06	1.51E-03	1.59E-05	1.20E-02	5.62E-07	4.24E-04
Y-92	1.36E-15	4.76E-12	1.08E-14	3.78E-11	3.82E-16	1.34E-12
Y-93	1.59E-08	1.20E-05	1.26E-07	9.52E-05	4.47E-09	3.37E-06
Zr-93	1.53E-17	NA	1.21E-16	NA	4.28E-18	NA
Zr-95	5.18E-04	1.74E-01	4.11E-03	1.38E+00	1.46E-04	4.88E-02

[a] Integrated Air DRLs are not decayed to an evaluation time and are therefore NA for daughter radionuclides not present in the initial mixture.

Table 3.4. Spent Fuel Dose Rate, Alpha, and Beta Derived Response Levels

DRL Type	Early Phase (Total Dose)	Early Phase (Avoidable Dose)	First Year
Dose Rate (mrem/h)	1.36E+00	1.08E+01	3.81E-01
Alpha Deposition ($\mu Ci_{alpha}/m^2$)	2.37E-05	1.88E-04	6.66E-06
Alpha Integrated Air (μCi_{alpha}•s/m^3)	7.92E-03	6.28E-02	2.22E-03
Beta Deposition ($\mu Ci_{beta}/m^2$)	1.89E+02	1.50E+03	5.32E+01
Beta Integrated Air (μCi_{beta}•s/m^3)	1.23E+05	9.77E+05	3.46E+04

3.5.2. Derived Response Levels for Administration of KI

Table 3.6 through Table 3.7 contain DRLs to support decisions to administer KI using the mixture and assumptions in Table 3.1. The DRLs are based on the 5 rem 1-year-old thyroid PAG and are reported for parents and daughters.

> ***NOTE:*** *States may choose to include KI in predetermined protective action plans for the 10-mile plume exposure pathway EPZ and, as such, KI might be pre-distributed to the population within this EPZ.*

> ***NOTE:*** *Radionuclides that are noble gases when initially released to the air are **not** deposited on the ground. Noble gases that are daughters of ground-deposited radionuclides **are** assumed to remain on the ground. Also, iodine Integrated Air DRLs are summed over multiple physical forms.*

Table 3.5. Spent Fuel Radionuclide-Specific Derived Response Levels for Administration of KI

Radionuclide	DRL_{Dp} ($\mu Ci/m^2$)	$DRL_{\tilde{A}}$ (μCi•s/m^3) [a]
Am-241	1.81E-06	6.02E-04
Ba-137m	1.71E+01	NA
Ba-140	2.84E-02	9.73E+00
Ce-141	1.09E-04	3.66E-02
Ce-143	5.29E-06	2.27E-03
Ce-144	1.32E-04	4.40E-02
Cm-242	3.33E-06	1.11E-03
Cs-134	6.39E+00	2.13E+03
Cs-135	5.70E-15	NA
Cs-136	4.60E-01	1.58E+02
Cs-137	1.81E+01	6.02E+03
I-129	7.63E-13	NA
I-131	1.89E+01	5.56E+03
I-132	1.23E-01	3.80E+02
I-133	4.95E-01	2.09E+02
I-135	1.71E-05	1.71E-02
Kr-85	NA	1.25E+03
Kr-85m	NA	5.10E-06
Kr-88	NA	1.48E-10
La-140	1.05E-02	2.09E+00
La-141	1.53E-15	4.26E-12
Mo-99	8.94E-05	3.38E-02

Radionuclide	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³) [a]
Nb-95	1.26E-04	4.22E-02
Nb-95m	6.20E-07	1.85E-04
Nb-97	2.88E-11	9.73E-06
Nd-144	5.47E-23	NA
Nd-147	3.37E-05	1.16E-02
Np-237	8.00E-16	NA
Np-239	2.64E-04	1.02E-01
Pm-147	1.33E-06	4.40E-04
Pr-143	8.96E-05	3.06E-02
Pr-144	1.32E-04	4.40E-02
Pr-144m	1.29E-06	NA
Pu-238	1.67E-07	5.56E-05
Pu-239	5.01E-09	1.67E-06
Pu-241	1.28E-04	4.26E-02
Rb-88	3.23E-25	1.67E-10
Rh-103m	3.27E-04	1.11E-01
Rh-105	1.54E-05	6.49E-03
Rh-106	2.64E-04	NA
Ru-103	3.31E-04	1.11E-01
Ru-105	5.55E-14	1.20E-10
Ru-106	2.64E-04	8.80E-02
Sb-127	6.73E-03	2.46E+00
Sb-129	9.02E-12	1.99E-08
Sm-147	1.19E-20	NA
Sr-89	1.79E-02	6.02E+00
Sr-90	2.64E-02	8.80E+00
Sr-91	7.03E-07	5.56E-04
Tc-99	4.68E-13	NA
Tc-99m	8.65E-05	3.29E-02
Te-127	1.00E-02	3.85E+00
Te-127m	3.33E-03	1.11E+00
Te-129	7.90E-03	2.73E+00
Te-129m	1.25E-02	4.22E+00
Te-131	3.56E-04	1.58E-01
Te-131m	1.58E-03	6.95E-01
Te-132	8.73E-02	3.24E+01
U-234	6.45E-16	NA
U-235	6.39E-21	NA
U-235m	5.00E-09	NA
U-237	1.57E-10	NA
Xe-131m	6.54E-03	1.25E+02
Xe-133	3.78E-02	1.25E+04
Xe-133m	2.56E-03	1.39E+02
Xe-135	1.87E-05	2.55E+00
Xe-135m	2.95E-06	2.73E-03
Y-90	6.39E-03	1.20E+00
Y-91	8.29E-05	2.78E-02
Y-91m	4.48E-07	3.38E-04
Y-92	3.05E-16	1.07E-12
Y-93	3.56E-09	2.69E-06
Zr-93	3.42E-18	NA

Radionuclide	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³) [a]
Zr-95	1.16E-04	3.89E-02

[a] Integrated Air DRLs are not decayed to an evaluation time and are therefore NA for daughter radionuclides not present in the initial mixture.

Table 3.6. Spent Fuel Dose Rate, Alpha, and Beta Derived Response Levels for Administration of KI

DRL Type	DRL Value
Dose Rate (mrem/h)	3.04E-01
Alpha Deposition ($\mu Ci_{alpha}/m^2$)	5.31E-06
Alpha Integrated Air ($\mu Ci_{alpha} \cdot s/m^3$)	1.77E-03
Beta Deposition ($\mu Ci_{beta}/m^2$)	4.24E+01
Beta Integrated Air ($\mu Ci_{beta} \cdot s/m^3$)	2.76E+04

3.5.3. Worker Protection Turn-Back Limits

Table 3.7 contains worker TBLs for the spent nuclear fuel product release listed in Table 3.1. Dose Rate, Alpha, and Beta TBLs are calculated for an 8-h shift starting 12 h after the plume has passed. The TBLs are provided per rem dose limit and are appropriate for the Adult Whole Body. To scale a listed TBL for a different dose limit (in units of rem), multiply the values in the tables by the desired dose limit.

> ***NOTE:*** *TBLs are not provided for during plume passage because of the inability of field instrumentation to differentiate between ground and air activity. The provided TBLs should be adjusted to instrument-specific values for field team use.*

> ***NOTE:*** *Assigned protection factors (APF) for respirators are included in the tables for completeness, even though the impact of the dose from inhalation of resuspended material is expected to be so low that respirators do not provide significant total dose reduction and may instead unnecessarily prolong exposure time. Therefore, it might not be advisable to use respirators for activities after the plume has passed.*

Table 3.7. Spent Nuclear Fuel Incident Worker Protection Turn-Back Limits for Varying Assigned Protection Factors (APF)

TBL Type	TBL per rem Effective Dose Limit			
	APF			
	1	50	100	1000
Dose Rate (mrem/h)	1.19E+02	1.25E+02	1.25E+02	1.25E+02
Alpha ($\mu Ci_{\alpha}/m^2$)	2.10E-03	2.20E-03	2.20E-03	2.20E-03
Beta ($\mu Ci_{\beta}/m^2$)	1.66E+04	1.74E+04	1.74E+04	1.74E+04

3.5.4. *Ingestion Pathway*

Table 3.8 and Table 3.9 include FRMAC Intervention Levels (FIL) and Ingestion DRLs for radionuclides in Table 3.1 that are **NOT** included in FRMAC Assessment Manual Volume 2, Appendix C, Tables 8-1 and 8-2.

Table 3.8. Ingestion Pathway – FILs, Crop DRLs, and Transfer Factors (TF) for Spent Fuel Radionuclides

Radionuclide	FIL ($\mu Ci/kg_{wet}$)	Crop DRL[a] ($\mu Ci/m^2$)	Leafy TF[b] (kg_{soil}/kg_{dry})	Fruit TF[b] (kg_{soil}/kg_{dry})	Non-Leafy TF[b] (kg_{soil}/kg_{dry})	Grain TF[b] (kg_{soil}/kg_{dry})
Ce-143	1.94E+01	2.49E+02	6.0E-03	1.0E-03	1.3E-02	3.1E-03
I-132	6.66E+02	4.99E+04	4.0E-02	1.3E-03	4.0E-02	4.0E-02
La-141	5.25E+02	4.38E+04	5.7E-03	1.0E-03	1.6E-03	2.0E-05
Nb-97	9.96E+03	1.01E+08	1.7E-02	2.5E-02	8.0E-03	1.4E-02
Nd-147	2.20E+00	2.27E+01	2.0E-02	5.4E-03	2.0E-02	9.4E-03
Pr-143	1.52E+00	1.56E+01	2.0E-02	2.0E-02	2.0E-02	2.0E-02
Pr-144	5.37E+04	1.87E+18	2.0E-02	2.0E-02	2.0E-02	2.0E-02
Rb-88	2.95E+04	4.56E+17	6.2E-01	1.0E-01	9.0E-01	9.0E-01
Rh-103m	2.16E+05	1.57E+10	1.5E-01	4.0E-02	4.0E-02	4.0E-02
Rh-105	5.53E+01	6.99E+02	1.5E-01	4.0E-02	4.0E-02	4.0E-02
Ru-105	6.81E+02	4.43E+04	9.0E-02	2.0E-02	2.0E-02	3.0E-03
Sb-129	4.30E+02	2.85E+04	9.4E-05	5.4E-02	1.3E-04	1.8E-03
Te-127m	1.25E-01	1.25E+00	3.0E-01	3.0E-01	8.0E-04	1.0E-01
Te-129	1.06E+04	1.37E+08	3.0E-01	3.0E-01	8.0E-04	1.0E-01
Te-131	1.77E+04	8.25E+13	3.0E-01	3.0E-01	8.0E-04	1.0E-01
Y-91m	1.07E+05	2.46E+10	2.0E-03	2.0E-03	2.0E-03	5.0E-04
Y-92	4.25E+02	4.45E+04	2.0E-03	2.0E-03	2.0E-03	5.0E-04
Y-93	6.20E+01	1.40E+03	2.0E-03	2.0E-03	2.0E-03	5.0E-04

[a] Assumes crops are ready to harvest (e.g., Time to Harvest = 0). The displayed Crop DRL uses the largest Transfer Factor of the four crop types included in this table.
[b] Transfer Factors from PNNL20.

Table 3.9. Ingestion Pathway – FILs, Milk and Meat DRLs, and Transfer Factors for Spent Fuel Radionuclides

Radionuclide	FIL (μCi/kg$_{wet}$)	Forage TF[a] (kg$_{soil}$/ kg$_{dry}$)	Milk DRL[b] (area) (μCi/m^2)	Milk DRL[b] (mass) (μCi/kg$_{wet}$)	Milk DRL[b] (water) (μCi/l)	Milk TF[b] (d/l)	Meat DRL[c] (area) (μCi/m^2)	Meat DRL[c] (mass) (μCi/kg$_{wet}$)	Meat DRL[c] (water) (μCi/l)	Meat TF[c] (d/kg$_{wet}$)
Ce-143	1.94E+01	3.7E-01	3.60E+04	2.60E+04	2.16E+04	3.3E-05	4.93E+07	3.56E+07	3.56E+07	2.0E-04
I-132	6.66E+02	3.7E-03	9.43E+07	1.35E+08	1.13E+08	5.4E-03	3.37E+64	4.84E+64	4.84E+64	6.7E-03
La-141	5.25E+02	2.0E-02	4.41E+08	3.17E+08	2.65E+08	2.0E-05	9.74E+40	7.02E+40	7.02E+40	1.3E-04
Nb-97	9.96E+03	2.0E-02	7.32E+17	5.27E+17	4.39E+17	4.1E-07	1.84E+126	1.33E+126	1.33E+126	2.6E-07
Nd-147	2.20E+00	3.7E-01	2.33E+03	1.68E+03	1.40E+03	3.0E-05	6.97E+02	5.02E+02	5.02E+02	3.0E-04
Pr-143	1.52E+00	3.7E-01	1.58E+03	1.14E+03	9.51E+02	3.0E-05	3.82E+02	2.75E+02	2.75E+02	3.0E-04
Pr-144	5.37E+04	3.7E-01	2.20E+45	1.58E+45	1.32E+45	3.0E-05	NA	NA	NA	3.0E-04
Rb-88	2.95E+04	2.6E-01	2.64E+41	1.90E+41	1.59E+41	1.2E-02	NA	NA	NA	1.0E-02
Rh-103m	2.16E+05	4.5E-02	2.41E17	1.74E+17	1.45E+17	1.0E-02	3.22E+157	9.36E+156	9.39E+156	2.0E-03
Rh-105	5.53E+01	4.5E-02	3.23E+02	2.33E+02	1.94E+02	1.0E-02	7.39E+06	5.33E+06	5.33E+06	2.0E-03
Ru-105	6.81E+02	2.0E-03	5.77E+08	4.16E+08	3.46E+08	9.4E-06	3.08E+35	2.22E+35	2.22E+35	3.3E-03
Sb-129	4.30E+02	2.0E+00	9.48E+07	6.84E+07	5.70E+07	3.8E-05	1.04E+36	7.48E+35	7.48E+35	1.2E-03
Te-127m	1.25E-01	1.0E+00	1.07E+01	7.70E+00	6.42E+00	3.4E-04	5.59E-01	4.03E-01	4.03E-01	7.0E-03
Te-129	1.06E+04	1.0E+00	1.97E+15	1.42E+15	1.18E+15	3.4E-04	1.18E+126	8.50E+125	8.50E+125	7.0E-03
Te-131	1.77E+04	1.0E+00	1.53E+32	1.10E+32	9.20E+31	3.4E-04	NA	NA	NA	7.0E-03
Y-91m	1.07E+05	5.0E-03	1.87E+21	1.34E+21	1.12E+21	2.0E-05	3.30E+176	2.38E+176	2.38E+176	1.0E-03
Y-92	4.25E+02	5.0E-03	7.06E+08	5.09E+08	4.24E+08	2.0E-05	7.39E+43	5.32E+43	5.32E+43	1.0E-03
Y-93	6.20E+01	5.0E-03	1.04E+06	7.49E+05	6.24E+05	2.0E-05	1.19E+17	8.57E+16	8.57E+16	1.0E-03

[a] Forage Transfer Factors from IAEA10 for available elements. Transfer Factors for elements not covered by IAEA10 were inferred using the methodology described in PNNL03.
[b] Values for Cow's Milk ready to harvest (e.g., Time to Grazing and Time to Harvest = 0). Transfer factors from PNNL20.
[c] Values for Beef ready to harvest (e.g., Time to Grazing and Time to Harvest = 0). Transfer factors from PNNL20.

3.6. References

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4. SCENARIO 4: RADIOLOGICAL DISPERSAL DEVICE

4.1. Introduction

A radiological dispersal device (RDD) is a device that is designed to spread radioactive material with the intent to cause panic and economic impact, and to render contaminated areas unusable. The term "dirty bomb" is an often-used, non-technical term for an explosive RDD. The explosive force of an RDD would most likely cause more physical harm than the released radioactive material. An RDD can also involve non-explosive, mechanical means of dispersing material (e.g., aerosol sprayer).

This pre-assessed scenario is based on defaults and methods as specified in the May 2023 version of the Federal Radiological Monitoring and Assessment Center (FRMAC) Assessment Manual, Volume 2 (SNL23) and may need to be updated to reflect future changes. Default results were calculated using Turbo FRMAC 2021.

4.2. Scenario-Specific Concerns

The Assessment Scientist should be prepared to address the following questions to support protective action decisions:

6. **Should the population be evacuated or sheltered?**
   Pre-detonation:

   In the case where an RDD has been located but not yet detonated, evacuation of the potentially-impacted population should be evaluated.

   Post-detonation:

   In the case of an RDD detonation, initial sheltering in place may be the preferred protective action because evacuation could expose the population to the plume, resulting in increased dose. Evacuation also increases the risk from other hazards (e.g., transportation). After plume passage, orderly evacuation may be appropriate to minimize dose.
7. **Should the population be relocated?**
   Relocation is an intermediate phase protective action. Relocation should be considered in areas where projected dose exceeds the corresponding PAG. In the case of an RDD detonation, it is possible that populations that were not previously evacuated might need to be relocated because of the longer half-lives of radionuclides of potential concern for use in an RDD.
8. **What are the likely exposure pathways?**
   During plume passage, inhalation is expected to be the dominant pathway. After plume passage, either the external or inhalation pathway could be dominant depending on the radionuclide. Dose from skin contamination may also be a concern for beta-emitting radionuclides.
9. **Should potassium iodide (KI) be administered?**
   Iodine is not likely to be used in an RDD. However, if it were used, KI use should be evaluated.

10. Do emergency workers need protective equipment?
Use of respiratory protection may be advised to minimize intakes of radioactive materials. Note that use of respiratory protection is not always conservative, given that it can prolong exposure time. The need for PPE for contamination control should also be evaluated. FRMAC Monitoring and Sampling Manual, Volume 1 provides default guidance for PPE for FRMAC field teams (FRMAC19).

Answers to the following questions are dependent on the circumstances of the event to which you are responding (e.g., radionuclide mixture, deposition, weather conditions, etc.):

- When can the evacuated population be allowed to return?
- What is the potential economic/infrastructure impact?
- Can foodstuffs grown in the contaminated area be consumed?
- Can foodstuffs be grown in the impacted area in the future?

4.3. Data Needs and Sources

The following sections describe the default assumptions to use for an RDD scenario until event-specific information is known.

4.3.1. Time Phase

Use FRMAC default time phases and evaluation time as specified in FRMAC Assessment Manual, Volume 2, Table 2-3.

ACTION	Determine whether to include Plume Pathways (i.e., Total Dose or Avoidable Dose)

4.3.2. Mixture

If the radionuclide(s) used in the RDD is not known, field measurements will give an idea of radiation type and source size. Table 4.1 contains default radionuclides for each radiation type that should be used until specific radionuclide information is available. For example, if alpha radiation is detected in the field, use Am-241 for the mixture until the radionuclide is identified. For RDDs, assume that the mixture is at equilibrium, unless specific source term information indicates otherwise.

Table 4.1. Default RDD Radionuclides

Primary Radiation Emission	Radionuclide
Alpha (α)	Am-241
Beta (β)	Sr-90
Beta-Gamma (β-γ)	Cs-137

ACTION	Review available data and work with Monitoring & Sampling to determine what radiation type(s) and/or radionuclide(s) have been detected, relative activity ratios, and instruments being used

ACTION	Request that the field teams provide estimates of physical effects of detonation such as crater size and distance of glass breakage (useful information for NARAC to help estimate explosive yield)

4.3.3. Protective Action Guides

Use FRMAC default PAGs unless instructed otherwise by Decision Makers. The PAGs are located in FRMAC Assessment Manual, Volume 2, Table 2-1.

4.4. Technical Caveats

4.4.1. Inhalation Pathway

Table 4.2 contains radiological data and LCTs for potential radionuclides of concern. These radionuclides were collated from two sources: a joint DOE and NRC study on the most likely sources available for potential terrorist use (DOE/NRC03) and a study by Sandia National Laboratories on source prioritization for use in an RDD of national security significance (SNL08, SNL20). Default results are provided for these radionuclides, should specific source term information or field measurements indicate they were used in the RDD.

The LCTs are ICRP Recommended as specified in ICRP Publication 72 (ICRP96), unless otherwise noted. Alternate PSDs have been determined for selected RDD radionuclides and should be used to estimate the dose from plume inhalation. Contact the Consequence Management Home Team (CMHT) to obtain realistic PSD information. The FRMAC default PSD is used to estimate the dose from inhalation of resuspended material.

Table 4.2. Radiological Data for Radioactive Materials of Concern[a]

Radionuclide	Decay Mode[a]	Half-Life (d)[a]	Decay Constant (d^{-1})[a]	Lung Clearance Type[b]
Am-241	α	1.58E+05	4.39E-06	
Cf-252	SF, α	9.64E+02	7.19E-04	
Cm-244	SF, α	6.61E+03	1.04E-04	
Co-60	β-γ	1.93E+03	3.60E-04	
Cs-137	β-γ	1.10E+04	6.33E-05	
Ir-192	β, EC	7.40E+01	9.36E-03	
Po-210	α	1.38E+02	5.01E-03	
Pu-238	SF, α	3.20E+04	2.16E-05	
Pu-239	α	8.79E+06	7.89E-08	Oxide: Slow[c]
Ra-226	α	5.84E+05	1.19E-06	
Se-75	EC	1.20E+02	5.79E-03	Elemental: Medium[d]
Sr-90	β	1.06E+04	6.52E-05	$SrTiO_3$: Slow[d]
Tm-170	EC, β	1.29E+02	5.39E-03	
Yb-169	EC	3.20+01	2.17E-02	

[a] Half-life and decay constant values generated using DCFPAK Version 2.0
SF = Spontaneous Fission
EC = Electron Capture
[b] ICRP Recommended as specified in ICRP Publication 72 (ICRP96) unless otherwise noted
[c] ICRP 68, Table F.1 (ICRP94) specifies lung clearance type Slow for insoluble oxides. However, based on Ryan82, the default ICRP Recommended (i.e., Medium) lung clearance type should be used for all forms of Pu-238 due to its higher specific activity.

Radionuclide	Decay Mode[a]	Half-Life (d)[a]	Decay Constant (d^{-1})[a]	Lung Clearance Type[b]
[d] ICRP Publication 68, Table F.1 (ICRP94)				

ACTION Work with NARAC to ensure consistent source term assumptions, including LCT and PSD

ACTION Work with Health & Safety to evaluate the need for respirators, turn-back limits, stay times, etc.

ACTION Request that the field teams perform resuspension measurements to support dose projections

4.5. Default Results

4.5.1. Public Protection Derived Response Levels

Table 4.3 and Table 4.4 contain DRLs for the RDD radionuclides of concern. The most conservative chemical/physical form was used for radionuclides, for which PSDs are available for multiple forms. The DRLs are appropriate for the Adult Whole Body and a mixture containing only one radionuclide (and associated daughters).

Table 4.3. RDD Radionuclide-Specific Derived Response Levels

Radionuclide	Early Phase (Total Dose)		Early Phase (Avoidable Dose)		First Year	
	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)
Am-241	9.06E-02	3.02E+01	8.66E+00	2.89E+03	4.15E+00	1.38E+03
Cf-252	9.76E-02	3.26E+01	1.81E+01	6.04E+03	7.74E+00	2.58E+03
Cm-244	7.27E-02	2.42E+01	1.36E+01	4.53E+03	6.55E+00	2.18E+03
Co-60	1.32E+02	4.42E+04	4.11E+02	1.37E+05	1.06E+01	3.52E+03
Cs-137	3.27E+02	1.09E+05	1.70E+03	5.68E+05	4.21E+01	1.40E+04
Ir-192	2.87E+02	9.61E+04	1.23E+03	4.13E+05	9.98E+01	3.34E+04
Po-210	5.90E-01	1.97E+02	1.12E+02	3.73E+04	5.74E+01	1.92E+04
Pu-238	5.01E-02	1.67E+01	7.82E+00	2.61E+03	3.76E+00	1.26E+03
Pu-239	4.62E-02	1.54E+01	7.20E+00	2.40E+03	3.46E+00	1.15E+03
Ra-226	5.54E-01	1.85E+02	8.77E+01	2.92E+04	1.07E+01	3.57E+03
Se-75	1.09E+03	3.64E+05	2.69E+03	9.00E+05	1.50E+02	5.00E+04
Sr-90	2.63E+01	8.78E+03	1.80E+03	6.00E+05	1.74E+02	5.80E+04
Tm-170	2.74E+02	9.17E+04	2.23E+04	7.44E+06	1.90E+03	6.34E+05
Yb-169	6.11E+02	2.06E+05	3.30E+03	1.11E+06	5.70E+02	1.92E+05

Table 4.4. RDD Dose Rate, Alpha, and Beta Derived Response Levels

Radionuclide	DRL Type	Early Phase (Total Dose)	Early Phase (Avoidable Dose)	First Year
Am-241	Dose Rate (mrem/h)	2.16E-05	2.06E-03	9.89E-04
	Alpha Deposition ($\mu Ci_{alpha}/m^2$)	9.06E-02	8.66E+00	4.15E+00
	Alpha Integrated Air (μCi_{alpha}•s/m^3)	3.02E+01	2.89E+03	1.38E+03
	Beta Deposition ($\mu Ci_{beta}/m^2$)	NA	NA	NA
	Beta Integrated Air (μCi_{beta}•s/m^3)	NA	NA	NA
Cf-252	Dose Rate (mrem/h)	4.60E-04	8.55E-02	3.65E-02
	Alpha Deposition ($\mu Ci_{alpha}/m^2$)	9.46E-02	1.76E+01	7.50E+00
	Alpha Integrated Air (μCi_{alpha}•s/m^3)	3.15E+01	5.86E+03	5.86E+03
	Beta Deposition ($\mu Ci_{beta}/m^2$)	NA	NA	NA
	Beta Integrated Air (μCi_{beta}•s/m^3)	NA	NA	NA
Cm-244	Dose Rate (mrem/h)	4.64E-07	8.68E-05	4.18E-05
	Alpha Deposition ($\mu Ci_{alpha}/m^2$)	7.27E-02	1.36E+01	6.55E+00
	Alpha Integrated Air (μCi_{alpha}•s/m^3)	2.42E+01	4.53E+03	2.18E+03
	Beta Deposition ($\mu Ci_{beta}/m^2$)	NA	NA	NA
	Beta Integrated Air (μCi_{beta}•s/m^3)	NA	NA	NA
Co-60	Dose Rate (mrem/h)	3.33E+00	1.03E+01	2.65E-01
	Alpha Deposition ($\mu Ci_{alpha}/m^2$)	NA	NA	NA
	Alpha Integrated Air (μCi_{alpha}•s/m^3)	NA	NA	NA
	Beta Deposition ($\mu Ci_{beta}/m^2$)	1.32E+02	4.11E+02	1.06E+01
	Beta Integrated Air (μCi_{beta}•s/m^3)	4.42E+04	1.37E+05	3.52E+03
Cs-137	Dose Rate (mrem/h)	1.96E+00	1.02E+01	2.52E-01
	Alpha Deposition ($\mu Ci_{alpha}/m^2$)	NA	NA	NA
	Alpha Integrated Air (μCi_{alpha}•s/m^3)	NA	NA	NA
	Beta Deposition ($\mu Ci_{beta}/m^2$)	3.27E+02	1.70E+03	4.21E+01
	Beta Integrated Air (μCi_{beta}•s/m^3)	1.09E+05	5.68E+05	1.40E+04
Ir-192	Dose Rate (mrem/h)	2.43E+00	1.04E+01	8.45E-01
	Alpha Deposition ($\mu Ci_{alpha}/m^2$)	NA	NA	NA
	Alpha Integrated Air (μCi_{alpha}•s/m^3)	NA	NA	NA
	Beta Deposition ($\mu Ci_{beta}/m^2$)	2.73E+02	1.17E+03	9.48E+01
	Beta Integrated Air (μCi_{beta}•s/m^3)	9.13E+04	3.93E+05	3.18E+04
Po-210	Dose Rate (mrem/h)	5.94E-08	1.12E-05	5.78E-06
	Alpha Deposition ($\mu Ci_{alpha}/m^2$)	5.90E-01	1.12E+02	5.74E+01
	Alpha Integrated Air (μCi_{alpha}•s/m^3)	1.97+02	3.73E+04	1.92E+04
	Beta Deposition ($\mu Ci_{beta}/m^2$)	NA	NA	NA
	Beta Integrated Air (μCi_{beta}•s/m^3)	NA	NA	NA
Pu-238	Dose Rate (mrem/h)	3.28E-07	5.12E-05	2.46E-05

Radionuclide	DRL Type	Early Phase (Total Dose)	Early Phase (Avoidable Dose)	First Year
	Alpha Deposition ($\mu Ci_{alpha}/m^2$)	5.01E-02	7.82E+00	3.76E+00
	Alpha Integrated Air ($\mu Ci_{alpha} \cdot s/m^3$)	1.67E+01	2.61E+03	1.26E+03
	Beta Deposition ($\mu Ci_{beta}/m^2$)	NA	NA	NA
	Beta Integrated Air ($\mu Ci_{beta} \cdot s/m^3$)	NA	NA	NA
Pu-239	Dose Rate (mrem/h)	1.54E-07	2.41E-05	1.16E-05
	Alpha Deposition ($\mu Ci_{alpha}/m^2$)	4.62E-02	7.20E+00	3.46E+00
	Alpha Integrated Air ($\mu Ci_{alpha} \cdot s/m^3$)	1.54E+01	2.40E+03	1.15E+03
	Beta Deposition ($\mu Ci_{beta}/m^2$)	NA	NA	NA
	Beta Integrated Air ($\mu Ci_{beta} \cdot s/m^3$)	NA	NA	NA
Ra-226	Dose Rate (mrem/h)	1.01E-02	1.60E+00	1.96E-01
	Alpha Deposition ($\mu Ci_{alpha}/m^2$)	2.21E+00	3.51E+02	4.29E+01
	Alpha Integrated Air ($\mu Ci_{alpha} \cdot s/m^3$)	7.38E+02	1.17E+05	1.43E+04
	Beta Deposition ($\mu Ci_{beta}/m^2$)	NA	NA	NA
	Beta Integrated Air ($\mu Ci_{beta} \cdot s/m^3$)	NA	NA	NA
Se-75	Dose Rate (mrem/h)	4.14E+00	1.05E+01	5.82E-01
	Alpha Deposition ($\mu Ci_{alpha}/m^2$)	NA	NA	NA
	Alpha Integrated Air ($\mu Ci_{alpha} \cdot s/m^3$)	NA	NA	NA
	Beta Deposition ($\mu Ci_{beta}/m^2$)	NA	NA	NA
	Beta Integrated Air ($\mu Ci_{beta} \cdot s/m^3$)	NA	NA	NA
Sr-90	Dose Rate (mrem/h)	3.21E-02	2.20E+00	2.12E-01
	Alpha Deposition ($\mu Ci_{alpha}/m^2$)	NA	NA	NA
	Alpha Integrated Air ($\mu Ci_{alpha} \cdot s/m^3$)	NA	NA	NA
	Beta Deposition ($\mu Ci_{beta}/m^2$)	5.27E+01	3.60E+03	3.48E+02
	Beta Integrated Air ($\mu Ci_{beta} \cdot s/m^3$)	1.76E+04	1.20E+06	1.16E+05
Tm-170	Dose Rate (mrem/h)	7.46E-02	6.05E+00	5.16E-01
	Alpha Deposition ($\mu Ci_{alpha}/m^2$)	NA	NA	NA
	Alpha Integrated Air ($\mu Ci_{alpha} \cdot s/m^3$)	NA	NA	NA
	Beta Deposition ($\mu Ci_{beta}/m^2$)	2.74E+02	2.22E+04	1.90E+03
	Beta Integrated Air ($\mu Ci_{beta} \cdot s/m^3$)	9.16E+04	7.43E+06	6.34E+05
Yb-169	Dose Rate (mrem/h)	1.97E+00	1.06E+01	1.84E+00
	Alpha Deposition ($\mu Ci_{alpha}/m^2$)	NA	NA	NA
	Alpha Integrated Air ($\mu Ci_{alpha} \cdot s/m^3$)	NA	NA	NA
	Beta Deposition ($\mu Ci_{beta}/m^2$)	NA	NA	NA
	Beta Integrated Air ($\mu Ci_{beta} \cdot s/m^3$)	NA	NA	NA

4.5.2. Worker Protection Turn-Back Limits

Table 4.5 and Table 4.6 contain worker TBLs for the RDD radionuclides of concern in Table 4.2. Dose Rate, Alpha, and Beta TBLs are calculated for an 8-h shift starting 12 h after the plume has passed and the LCTs listed in Table 4.2. The TBLs are provided per rem dose limit and are appropriate for the Adult Whole Body and a mixture containing only one radionuclide (and associated daughters). To scale a listed TBL for a different dose limit (in units of rem), multiply the values in the tables by the desired dose limit.

> ***NOTE****: TBLs are not provided for during plume passage because of the inability of field instrumentation to differentiate between ground and air activity. The provided TBLs should be adjusted to instrument-specific values for field team use.*

Table 4.5. RDD Worker Protection Dose Rate Turn-Back Limits for Varying Assigned Protection Factors (APF)

Radionuclide	Dose Rate TBL (mrem/h) per rem Effective Dose Limit			
	APF			
	1	50	100	1000
Am-241	1.28E-02	6.39E-01	1.27E+00	1.16E+01
Cf-252	5.34E-01	2.21E+01	3.75E+01	1.01E+02
Cm-244	5.40E-04	2.70E-02	5.40E-02	5.38E-01
Co-60	1.22E+02	1.25E+02	1.25E+02	1.25E+02
Cs-137	1.20E+02	1.25E+02	1.25E+02	1.25E+02
Ir-192	1.21E+02	1.25E+02	1.25E+02	1.25E+02
Po-210	6.93E-05	3.46E-03	6.93E-03	6.92E-02
Pu-238	3.19E-04	1.59E-02	3.18E-02	3.18E-01
Pu-239	1.50E-04	7.49E-03	1.50E-02	1.50E-01
Ra-226	1.08E+01	1.03E+02	1.13E+02	1.24E+02
Se-75	1.23E+02	1.25E+02	1.25E+02	1.25E+02
Sr-90	1.52E+01	1.09E+02	1.17E+02	1.24E+02
Tm-170	5.15E+01	1.22E+02	1.23E+02	1.25E+02
Yb-169	1.20E+02	1.25E+02	1.25E+02	1.25E+02

Table 4.6. RDD Worker Protection Alpha & Beta Turn-Back Limits for Varying Assigned Protection Factors (APF)

Radionuclide	TBL per rem Effective Dose Limit							
	Alpha ($\mu Ci_\alpha/m^2$)				Beta ($\mu Ci_\beta/m^2$)			
	APF				APF			
	1	50	100	1000	1	50	100	1000
Am-241	5.39E+01	2.68E+03	5.34E+03	4.89E+04	NA	NA	NA	NA
Cf-252	1.10E+02	4.53E+03	7.71E+03	2.08E+04	NA	NA	NA	NA
Cm-244	8.46E+01	4.23E+03	8.45E+03	8.42E+04	NA	NA	NA	NA
Co-60	NA	NA	NA	NA	4.87E+03	4.97E+03	4.97E+03	4.98E+03
Cs-137	NA	NA	NA	NA	2.00E+04	2.08E+04	2.08E+04	2.08E+04
Ir-192	NA	NA	NA	NA	1.36E+04	1.40E+04	1.40E+04	1.40E+04
Po-210	6.88E+02	3.44E+04	6.88E+04	6.88E+05	NA	NA	NA	NA
Pu-238	4.87E+01	2.43E+03	4.87E+03	4.86E+04	NA	NA	NA	NA

Radionuclide	TBL per rem Effective Dose Limit							
	Alpha ($\mu Ci_{\alpha}/m^2$)				Beta ($\mu Ci_{\beta}/m^2$)			
	APF				APF			
	1	50	100	1000	1	50	100	1000
Pu-239	4.48E+01	2.24E+03	4.48E+03	4.48E+04	NA	NA	NA	NA
Ra-226	2.36E+03	2.26E+04	2.48E+04	2.71E+04	1.16E+03	1.11E+04	1.22E+04	1.34E+04
Se-75[a]	NA	NA	NA	NA	NA	NA	NA	NA
Sr-90	NA	NA	NA	NA	2.49E+04	1.79E+05	1.91E+05	2.04E+05
Tm-170	NA	NA	NA	NA	1.89E+05	4.46E+05	4.53E+05	4.58E+05
Yb-169[a]	NA	NA	NA	NA	NA	NA	NA	NA

[a] Alpha and beta yields are zero for these radionuclides.

4.5.3. Ingestion Pathway

Table 4.7 and Table 4.8 include FILs and Ingestion DRLs for the radionuclides in Table 4.2 that are NOT included in FRMAC Assessment Manual, Volume 2, Appendix C, Tables 8-1 and 8-2.

Table 4.7. Ingestion Pathway – FILs, Crop DRLs, and Transfer Factors for RDD Radionuclides of Concern

Radionuclide	FIL ($\mu Ci/kg_{wet}$)	Crop DRL[a] ($\mu Ci/m^2$)	Leafy TF[b] (kg_{soil}/kg_{dry})	Fruit TF[b] (kg_{soil}/kg_{dry})	Non-Leafy TF[b] (kg_{soil}/kg_{dry})	Grain TF[b] (kg_{soil}/kg_{dry})
Po-210	2.21E-04	2.21E-03	7.4E-03	1.2E-03	5.8E-03	2.4E-03

[a] Assumes crops are ready to harvest (e.g., Time to Harvest = 0). The displayed Crop DRL uses the largest Transfer Factor of the four crop types included in this table.
[b] Transfer Factors from PNNL20.

Table 4.8. Ingestion Pathway – FILs, Milk and Meat DRLs, and Transfer Factors for RDD Radionuclides of Concern

Radionuclide	FIL ($\mu Ci/kg_{wet}$)	Forage TF[a] (kg_{soil}/kg_{dry})	Milk_DRL[b] (area) ($\mu Ci/m^2$)	Milk_DRL[b] (mass) ($\mu Ci/kg_{wet}$)	Milk_DRL[b] (water) ($\mu Ci/l$)	Milk TF[b] (d/l)	Meat_DRL[c] (area) ($\mu Ci/m^2$)	Meat_DRL[c] (mass) ($\mu Ci/kg_{wet}$)	Meat_DRL[c] (water) ($\mu Ci/l$)	Meat TF[c] (d/kg_{wet})
Po-210	2.21E-04	1.2E-01	3.06E-02	2.20E-02	1.83E-02	2.1E-04	1.35E-03	9.73E-04	9.73E-04	5.0E-03

[a] Forage Transfer Factors from IAEA10 for available elements. Transfer Factors for elements not covered by IAEA10 were inferred using the methodology described in PNNL03.
[b] Values for Cow's Milk ready to harvest (e.g., Time to Grazing and Time to Harvest = 0). Transfer factors from PNNL20.
[c] Values for Beef ready to harvest (e.g., Time to Grazing and Time to Harvest = 0). Transfer factors from PNNL20.

4.6. References

DOE/NRC03 *Radiological Dispersal Devices: An Initial Study to Identify Radioactive Materials of Greatest Concern and Approaches to their Tracking, Tagging, and Disposition*, prepared by the DOE/NRC Interagency Working Group on Radiological Dispersal Devices, report to the NRC and Secretary of Energy, May 2003.

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IAEA10 *Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments*, IAEA Technical Report Series No. 472, International Atomic Energy Agency, Vienna, Austria, 2010.

ICRP94 *Dose Coefficients for Intakes of Radionuclides by Workers*, ICRP Publication 68, International Commission on Radiological Protection, Ottawa, Ontario, Canada, 1994.

ICRP96 *Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 5 Compilation of Ingestion and Inhalation Dose Coefficients*, ICRP Publication 72, International Commission on Radiological Protection, Ottawa, Ontario, Canada, 1996.

PNNL03 *A Compendium of Transfer Factors for Agricultural and Animal Products*, PNNL-13421, Pacific Northwest National Laboratory, Richland, WA, 2003.

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SNL20 Potter, C., et al., *Identification of Radionuclides Representing Potential Security Risk through a Downselect Process*, SAND2020-2132, Sandia National Laboratories, Albuquerque, NM, February 2020.

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5. SCENARIO 5: NUCLEAR DETONATION

5.1. Introduction

A detonation of a nuclear weapon (NW) producing nuclear yield results in the production of blast pressure, thermal radiation, initial nuclear radiation, radioactive fallout, and electromagnetic pulse (EMP). This scenario addresses the radioactive fallout avoidable dose. Initial nuclear radiation consists of prompt gamma and neutron radiation resulting from the fission process, and residual radiation resulting from the decay of fission and activation products. The prompt radiation is primarily a local hazard (e.g., within a few kilometers) (Gl77). Radioactive fallout, however, has the potential to present a hazard for much greater distances and for a much greater amount of time. Fallout consists of fission and activation products entrained and condensed onto material such as dirt and dust that were vaporized in the detonation (Gl77). The height of the detonation above ground influences the amount of fallout produced. Detonations that occur at ground level produce a much greater amount of fallout than those that occur at higher elevation above the ground. The primary radiological hazard of fallout is the beta and gamma radiation resulting from the decay of fission products produced in the detonation.

This pre-assessed scenario is based in part on the DHS National Planning Scenarios: Scenario 1. Nuclear Detonation – Improvised Nuclear Device. The scenario is a surface detonation of a 10-kiloton (kt) highly enriched uranium (HEU) weapon (HSC04). In addition, a weapons-grade plutonium (WGPu) fueled weapon is included for completeness to address detonation of a U.S. nuclear weapon, other state sponsored weapons, or an improvised nuclear device (IND). This pre-assessed scenario is based on defaults and methods as specified in the May 2023 version of the FRMAC Assessment Manual, Volume 2 (SNL23) and may need to be updated to reflect future changes. Default results were calculated using Turbo FRMAC 2021.

5.2. Scenario-Specific Concerns

The Assessment Scientist should be prepared to address the following questions to support protective action decisions:

1. **Should the population be evacuated or sheltered?**
   In the case of a no-notice nuclear explosion, planning guidance recommends that everyone seek shelter, regardless of proximity to ground zero or orientation to the actual path of fallout. People should expect to remain sheltered for at least 12 to 24 hours following detonation, due to the high fallout dose rates and uncertainty in the fallout hazard areas following the detonation. Shelter-in-place and evacuation PAGs may be exceeded out to a distance of 10 to 100 miles. No evacuation should be attempted until basic information is available regarding fallout distribution and dose rates, or if current shelter is threatened or unsafe. More detailed information can be found in *Planning Guidance for a Response to a Nuclear Detonation*, June 2010 (DHS10).

   In addition to planning guidance for severe, moderate, and light blast damage zones, planning guidance includes a dangerous radiation zone[5] (formerly called a dangerous fallout zone)

[5] Terminology expected to be published in the updated version of *Planning Guidance for Response to a Nuclear Detonation*, Department of Homeland Security.

(>10 R/h) that extends 10-20 miles from ground zero (for a 10-kt explosion) (DHS10). The National Council on Radiation Protection and Measurements (NCRP) Report 165 recommends the establishment of a Hot Zone >10 mR/hr to help manage radiation risk (NCRP10). Due to rapid decay, the dangerous radiation zone is expected to reach its maximum extent after the first few hours and then shrinks in size from 10-20 miles to 1-2 miles in just one day, due to decay of short-lived fission and activation products. Outside of the dangerous fallout zone, radiation levels should generally not present an acute threat, but may still warrant protective actions such as sheltering or evacuation.

Assessment Scientists may be asked to contribute to a determination of the optimal time of sheltering or exit. The optimal time to shelter then exit is the time at which the total dose from sheltering and dose received during evacuation are the lowest. The optimal time to shelter is affected by the building protection factor (BPF) afforded by the structure and the fallout pattern along the evacuation route and time to evacuate. Turbo FRMAC can be used to calculate doses under various protection factor assumptions to verify the assumed optimal time to shelter. As this is a complex subject, Assessment Scientists should review the considerations outlined in the discussion of optimal time to shelter in *National Capital Region Key Response Planning Factor in the Aftermath of Nuclear Terrorism,* 2011 (Bu11).

2. **Where should individuals shelter?**
   An 'adequate shelter' is defined as shelter that protects against acute radiation effects and significantly reduces dose to occupants during an extended period. Basements and large concrete structures (e.g., buildings, underground parking garages, and tunnels) are good examples of adequate shelter. Cars and other vehicles are not adequate shelters because they lack good shielding material. Inadequate shelters are those with a BPF of less than 10. FRMAC Assessment Manual, Volume 2, Appendix C includes a diagram of the BPFs for various shelter types.

   Public Protection DRLs and Projected Public Dose calculations in Turbo FRMAC can account for Occupancy Factors (OFs) and/or BPFs according to FRMAC Assessment Manual, Volume 2, Method 4.7. However, Nuclear Fallout Calculations in Turbo FRMAC associated with Method 1.7 do not account for OFs or BPFs. Dose reduction based on OFs and BPFs can be applied manually to the result of Nuclear Fallout Dose and Nuclear Fallout Stay Time Calculations by multiplying the dose or stay time by the OF and/or dividing the dose or stay time by the BPF (Bu11). For additional information on the application of OF or BPF see FRMAC Assessment Manual, Volume 2, Method 4.7.

3. **Should the population be relocated?**
   Relocation is an intermediate phase protective action. Relocation should be considered in areas where projected dose exceeds the corresponding PAG.

4. **What are the likely exposure pathways?**
   Fallout that is immediately hazardous to the public and emergency responders will deposit within about 24 hours (DHS10). In a fallout zone, external exposure to gamma radiation is the expected dominant pathway. However, skin contamination from fallout can result in beta burns.

5. **Should potassium iodide (KI) be administered?**

KI can be used to block uptake of iodine radionuclides but will not protect against other fission products released from the detonation. Administration of KI is not useful in the early medical response to a nuclear detonation, as KI is most effective when taken prior to exposure or within a few hours of exposure and is only one of many high-risk radionuclides present (NSC16).

6. **Do emergency workers need protective equipment?**
   In the case of external exposure, reducing time spent in high dose rate areas is the greatest protective measure. Use of respiratory protection may be advised to minimize intakes of radioactive materials. Note that use of respiratory protection is not always conservative, given that it can prolong exposure time. The need for PPE for contamination control and respiratory protection should be evaluated based on a review of all the hazards at the site. FRMAC Monitoring and Sampling Manual, Volume 1 provides default guidance for PPE for FRMAC field teams (FRMAC19).

Answers to the following questions are dependent on the circumstances of the event to which you are responding (e.g., radionuclide mixture, deposition, weather conditions, etc.):

- When can the evacuated population be allowed to return?
- What is the potential economic/infrastructure impact?
- Can foodstuffs grown in the contaminated area be consumed?
- Can foodstuffs be grown in the impacted area in the future?

5.3. Data Needs and Sources

The following sections describe the default assumptions to use for a nuclear detonation scenario until event-specific information is known.

5.3.1. Time Phase

Use FRMAC default time phases and evaluation time as specified in FRMAC Assessment Manual, Volume 2, Table 2-3.

ACTION	Determine whether to include Plume Pathways (i.e., Total Dose or Avoidable Dose)

5.3.2. Dose Rates

In the Early Phase, Assessment Scientists will use the methods described in FRMAC Assessment Manual, Volume 2, Method 1.7 which rely on dose rate measurements in the fallout zone to calculate doses, stay times, and nuclear fallout DRLs.

ACTION	Determine the dose rate at a reference time and location

Dose rates at various distances downwind and transecting the plume will be required to validate fallout models. This information is also needed to develop public protection recommendations. Dose rates exceeding 10 R/hr are characterized as the dangerous radiation zone and areas that measure less than 10 R/hr are considered radiation control areas (DHS10). A reference dose rate and time should be identified. This reference dose rate will be location-specific, as dose rates will change drastically throughout the fallout zone due to varying levels of local fallout. Local fallout is fallout that has deposited within the first 24 hours and differentiated from global or delayed fallout, which consists of very small particles which are distributed over large portions of the earth's surface (Gl77).

Dose rate information from plume monitoring will be used to determine the fallout decay Power Function Exponent or X Factor. The default value of the Power Function Exponent is 1.2 (Gl77), but the actual Power Function Exponent should be determined for the fallout as soon as possible. The Power Function Exponent, which defines the decay of the fallout as a whole, is only valid for a specific location and time period and changes as a function of time and distance downwind due to fractionation. The Power Function Exponent should be periodically updated as the fallout decays (Gl77). The value of the Power Function Exponent can range from 0.9 to 2.0, depending on the circumstances of the detonation (Gl77). When the Power Function Exponent is 1, use FRMAC Assessment Manual, Volume 2, Method 1.7.5.

5.3.3. Mixture

While detonation of a nuclear weapon produces a large amount of fission and activation products, the primary concern in the Early Phase will be the external dose rate produced by the fallout. Intermediate and Late Phase concerns may make use of the fission and activation product mixture to develop DRLs, Intervention Levels, and estimate doses. By the Intermediate and Late Phases, the short-lived fission and activation products will have decayed away, leaving a manageable number of radionuclides that contribute dose to consider for the mixture.

Several factors affect the fallout mixture. Weapon design, whether WGPu or HEU, will affect the mixture only minimally, given the small differences in the fission product curves. Unfissioned Special Nuclear Materials are usually eliminated from the mixture in published literature to keep the mixture unclassified and because they contribute negligibly to the fallout dose rate (Kr14). Differences in the weapon component materials can have a large impact on the weapon component activation products and their daughters contained in fallout. Specifically, activation products such as Np-239 are not presented in the mixtures for this pre-assessed scenario due to the modeling assumptions used and downselection criteria applied, but may provide significant exposure for other specific scenarios (Kr14).

Soil type at ground zero can have a large impact on the short half-life induced radioactivity area and the resulting material drawn into the fireball. Height of burst (HOB) can greatly affect the fallout. Ground bursts or low air bursts where the fireball touches the ground produce the largest amount of local or early fallout. This is due to the soil being drawn into the fireball where fission and activation products mix with the vaporized soil. Fission and activation products with high melting points entrain themselves within the large, resolidified soil particles. These larger particles fall closer to ground zero. Gaseous fission products and their daughters and products with low melting points do not resolidify on soil particles until later (after the fireball has cooled) and are deposited much farther downwind. This process is known as fractionation and results in differences in the mixture as a function of distance downwind (Gl77).

Detonation at an HOB where the fireball does not come into contact with the ground results in very small particle fallout consisting of fission and weapon component activation products that deposit as delayed fallout far from ground zero and result in very small amount of local fallout (Gl77). Mixtures can be scaled easily for yield and put in terms of Ci/kt. Scaling for HOB is non-linear and cannot be done easily.

In an effort to provide mixtures with a manageable number of radionuclides, Table 5.1 includes the top 50 dose-producing radionuclides at a distance of 10 km downwind at one hour post-detonation, assuming no fractionation and an HEU weapon (Kr14). Table 5.2 includes the top 46 dose-producing radionuclides at a distance of 10 km downwind at one hour post-detonation, assuming no fractionation and a WGPu weapon (Kr12). The assumption in this scenario of a ground burst would normally be considered worst case for fallout, due to soil activation products. The modeling assumptions that result in the mixtures in Table 5.1 and Table 5.2 may not be representative of the actual device design, detonation conditions, weather conditions, and do not represent the most conservative case (Kr14). Additional modeling and analysis work are required to produce a range of mixtures that consider the range of parameters that affect the fallout constituents.

The mixtures in Table 5.1 and Table 5.2 should be entered in Turbo FRMAC as both Activity per Area and Integrated Air Concentration with equilibrium set to OFF. Deposition velocity is also provided in these tables for reference, but is auto-calculated by Turbo FRMAC for a mixture defined by both Activity per Area and Integrated Air Concentration.

Table 5.1. HEU IND Mixture for Public Protection Derived Response Levels

Radionuclide	Radionuclide Activity (Ci/kt) at 1 h post-detonation at a location 10 km Downwind		
	Deposited Activity at 1 hr post-Detonation (Ci/m^2)	Local Fallout Integrated Air Activity ($Ci \cdot s/m^3$)	Deposition Velocity (m/s)
Ba-140	4.79E-04	7.36E-04	0.651
Ba-141	4.88E-02	1.81E-01	0.270
Ba-142	1.50E-02	1.15E-01	0.130
Ce-141	1.86E-05	1.50E-05	1.240
Ce-143	3.92E-03	5.30E-03	0.740
Ce-144	1.88E-05	2.88E-05	0.653
Co-58	4.36E-06	6.52E-06	0.669
Co-58m	7.00E-04	1.11E-03	0.631
Cs-134	6.58E-09	9.55E-09	0.689
Cs-134m	2.66E-05	4.48E-05	0.594
Cs-137	5.78E-07	8.88E-07	0.651
Cs-138	1.15E-01	2.23E-01	0.516
I-131	2.03E-04	1.85E-04	1.097
I-133	6.39E-03	8.55E-03	0.747
I-134	8.91E-02	1.28E-01	0.696
I-135	2.11E-02	3.36E-02	0.628
La-141	2.95E-02	4.00E-02	0.738
La-142	6.19E-02	1.01E-01	0.613
Mn-54	7.57E-07	1.16E-06	0.653
Mn-56	5.24E-02	8.86E-02	0.591

Radionuclide	Radionuclide Activity (Ci/kt) at 1 h post-detonation at a location 10 km Downwind		
	Deposited Activity at 1 hr post-Detonation (Ci/m^2)	Local Fallout Integrated Air Activity ($Ci{\cdot}s/m^3$)	Deposition Velocity (m/s)
Mo-99	2.20E-03	3.39E-03	0.649
Mo-101	3.03E-02	1.43E-01	0.212
Nb-95	6.23E-08	5.32E-08	1.171
Rb-89	3.36E-02	1.51E-01	0.223
Ru-103	8.91E-05	1.37E-04	0.650
Ru-106	1.87E-06	2.90E-06	0.645
Sb-128	7.30E-04	8.26E-04	0.884
Sb-129	4.38E-03	7.05E-03	0.621
Sb-130	1.17E-02	2.66E-02	0.440
Sb-131	3.08E-02	9.45E-02	0.326
Sn-128	6.40E-03	1.28E-02	0.500
Sr-89	8.08E-05	1.04E-04	0.777
Sr-90	5.23E-07	8.07E-07	0.648
Sr-91	1.36E-02	2.14E-02	0.636
Sr-92	4.06E-02	6.85E-02	0.593
Tc-101	8.52E-02	2.34E-01	0.364
Tc-104	1.88E-02	6.99E-02	0.269
Te-131	5.61E-02	1.01E-01	0.555
Te-131m	1.95E-04	3.04E-04	0.641
Te-132	1.47E-03	2.26E-03	0.650
Te-133	2.20E-02	1.11E-01	0.198
Te-133m	2.70E-02	5.47E-02	0.494
Te-134	8.51E-02	1.89E-01	0.450
Y-91	4.25E-06	3.88E-06	1.095
Y-92	8.26E-03	8.73E-03	0.946
Y-93	1.41E-02	2.12E-02	0.665
Y-94	5.20E-02	1.89E-01	0.275
Y-95	1.54E-02	1.24E-01	0.124
Zr-95	9.63E-05	1.37E-04	0.703
Zr-97	8.43E-03	1.31E-02	0.644

Table 5.2. WGPu IND Mixture for Public Protection Derived Response Levels

Radionuclide	Radionuclide Activity (Ci/kt) at 1 h post-detonation at a location 10 km Downwind		
	Deposited Activity at 1 hr post-Detonation (Ci/m^2)	Local Fallout Integrated Air Activity ($Ci{\cdot}s/m^3$)	Deposition Velocity (m/s)
Ba-140	4.08E-04	6.41E-04	0.637
Ba-141	4.02E-02	1.53E-01	0.263
Ba-142	1.18E-02	9.21E-02	0.128
Ce-143	2.88E-03	3.98E-03	0.724
Ce-144	1.27E-05	1.97E-05	0.645
Co-58	5.23E-06	8.01E-06	0.653
Co-58m	8.43E-04	1.34E-03	0.629
Cs-134m	4.66E-05	7.86E-05	0.593

Radionuclide	Radionuclide Activity (Ci/kt) at 1 h post-detonation at a location 10 km Downwind		
	Deposited Activity at 1 hr post-Detonation (Ci/m^2)	Local Fallout Integrated Air Activity ($Ci \cdot s/m^3$)	Deposition Velocity (m/s)
Cs-137	5.88E-07	9.07E-07	0.648
Cs-138	9.65E-02	1.96E-01	0.492
I-131	2.12E-04	2.05E-04	1.034
I-132	1.47E-03	2.11E-03	0.697
I-133	5.84E-03	7.97E-03	0.733
I-134	8.19E-02	1.33E-01	0.616
I-135	1.95E-02	3.18E-02	0.613
La-141	2.48E-02	3.37E-02	0.736
La-142	5.08E-02	8.52E-02	0.596
Mn-54	9.10E-07	1.43E-06	0.636
Mn-56	6.23E-02	1.08E-01	0.577
Mo-99	2.11E-03	3.33E-03	0.634
Mo-101	3.72E-02	1.81E-01	0.206
Pu-239	1.11E-07	1.74E-07	0.638
Rb-89	1.26E-02	5.84E-02	0.216
Ru-103	1.70E-04	2.68E-04	0.634
Ru-105	2.51E-02	3.97E-02	0.632
Ru-106	1.17E-05	1.81E-05	0.646
Sb-128	1.12E-03	1.33E-03	0.842
Sb-129	6.81E-03	1.13E-02	0.603
Sb-130	1.29E-02	3.01E-02	0.429
Sb-131	2.90E-02	9.10E-02	0.319
Sn-128	9.42E-03	1.89E-02	0.498
Sr-90	1.93E-07	2.97E-07	0.650
Sr-91	5.80E-03	9.35E-03	0.620
Sr-92	2.02E-02	3.50E-02	0.577
Tc-99m	2.00E-04	2.03E-04	0.985
Tc-101	1.05E-01	2.94E-01	0.357
Te-131	5.47E-02	1.03E-01	0.531
Te-131m	5.66E-04	8.96E-04	0.632
Te-132	1.54E-03	2.43E-03	0.634
Te-133m	3.76E-02	7.80E-02	0.482
Te-134	5.95E-02	1.36E-01	0.438
Y-93	8.35E-03	1.29E-02	0.647
Y-94	3.38E-02	1.26E-01	0.268
Y-95	1.07E-02	8.80E-02	0.122
Zr-95	6.79E-05	9.86E-05	0.689
Zr-97	7.10E-03	1.13E-02	0.628

5.3.4. Protective Action Guides

Use FRMAC default PAGs unless instructed otherwise by Decision Makers. The PAGs are located in FRMAC Assessment Manual, Volume 2, Table 2-1.

5.4. Technical Caveats

5.4.1. Inhalation Pathway

The PSD in Table 5.3 should be used for the plume inhalation pathway if calculating Public Protection DRLs or Projected Public Doses for the Early Phase for ground bursts (Ha92). The PSD will change as a function of HOB, distance down range, soil type, etc. Note that the fallout is made up of multiple PSD, depending on the source of the particles. Small particles consist of resolidified material from the fireball, whereas large particles consist of resolidified soil mixed with resolidified material from the fireball. Coordinate with NARAC for an appropriate PSD for HOB other than ground burst. Use the ICRP Recommended lung clearance type (LCT) as specified in ICRP Publication 72 (ICRP96).

ACTION	Work with NARAC and Joint Technical Operations Team (JTOT) Home Team once event-specific information is available

Table 5.3. Particle Size Distribution for Nuclear Detonations

Particle Type	Distribution Type	Mass Median Aerodynamic Diameter (µm)	Geometric Standard Deviation	Minimum Diameter (µm)	Maximum Diameter (µm)	Fraction of Material
Small	Lognormal	28.8	4	10	1000	0.8
Large	Lognormal	303	2.69	10	1000	0.2

NOTE: *Turbo FRMAC assessments do not include small particles in the <10 µm size range because they are not deposited locally. These particles do contribute to global fallout and as such, should be included in atmospheric dispersion modeling.*

ACTION	Work with NARAC to ensure consistent source term assumptions, including LCT and PSD

ACTION	Work with Health & Safety to evaluate the need for respirators, turn-back limits, stay times, etc.

ACTION	Request that the field teams perform resuspension measurements to support dose projections as soon as practical

5.4.2. Ingestion Pathway

The FDA provides DILs for radionuclides expected to deliver the major portion of the dose from ingestion during the first year following an incident.

ACTION	DILs for grouped radionuclides (Cs-134 + Cs-137, Pu-238 + Pu-239 + Am-241, and Ru-103 + Ru-106) should be used in ingestion calculations

5.5. Default Results

5.5.1. Public Protection Derived Response Levels

Table 5.4 and Table 5.6 contain DRLs for the representative fallout mixture for an HEU IND and WGPu IND, respectively. Table 5.5 and Table 5.7 contain the Dose Rate, Alpha, and Beta DRLs for an HEU IND and WGPu IND, respectively. The DRLs are appropriate for the Adult Whole Body and are reported for parents and daughters. Use of these DRLs would likely not be appropriate until the Intermediate Phase. The Early Phase DRL determinations are more likely to be based on FRMAC Assessment Manual, Volume 2, Method 1.7 using external dose rates.

> ***NOTE:*** *Early Phase DRLs are provided for completeness. It is possible that protective action decisions for the Early Phase might be made before FRMAC involvement. During the Early Phase, the Nuclear Fallout DRL is highly sensitive to the evaluation time due to the rapid decay of the fallout. An example of this is provided in Figure 5.1.*

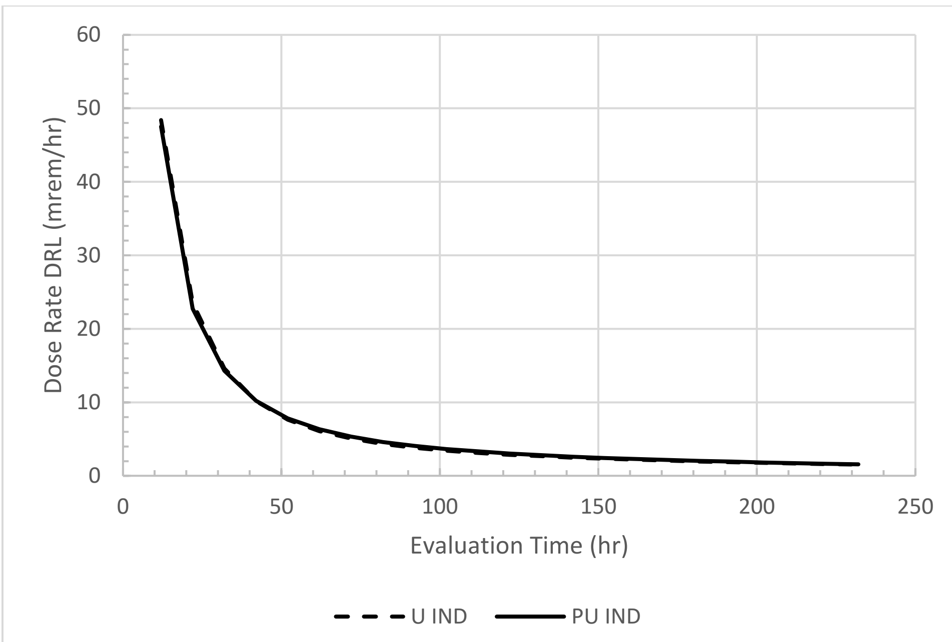

Figure 5.1. Early Phase (AD) Dose Rate DRL with Varying Evaluation Time

Table 5.4. HEU IND Radionuclide-Specific Derived Response Levels

Radionuclide	Early Phase (Total Dose)		Early Phase (Avoidable Dose)		First Year	
	DRL$_{Dp}$ (µCi/m^2)	DRL$_{\tilde{A}}$ (µCi•s/m^3)	DRL$_{Dp}$ (µCi/m^2)	DRL$_{\tilde{A}}$ (µCi•s/m^3)	DRL$_{Dp}$ (µCi/m^2)	DRL$_{\tilde{A}}$ (µCi•s/m^3)
Ba-137m	1.39E-02	NA[a]	5.17E-02	NA	4.92E-02	NA
Ba-140	1.18E+01	1.87E+01	4.42E+01	6.98E+01	4.21E+01	6.64E+01
Ba-141	1.70E-09	4.60E+03	6.34E-09	1.72E+04	6.03E-09	1.63E+04
Ba-142	1.36E-18	2.92E+03	5.08E-18	1.09E+04	4.83E-18	1.04E+04
Ce-141	4.18E+00	3.81E-01	1.56E+01	1.42E+00	1.48E+01	1.35E+00
Ce-143	7.74E+01	1.35E+02	2.89E+02	5.02E+02	2.75E+02	4.78E+02
Ce-144	4.77E-01	7.32E-01	1.78E+00	2.73E+00	1.69E+00	2.60E+00

Radionuclide	Early Phase (Total Dose)		Early Phase (Avoidable Dose)		First Year	
	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3)	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3)	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3)
Co-58	1.67E-01	1.66E-01	6.23E-01	6.18E-01	5.93E-01	5.89E-01
Co-58m	7.08E+00	2.82E+01	2.64E+01	1.05E+02	2.52E+01	1.00E+02
Cs-134	2.69E-04	2.43E-04	1.00E-03	9.05E-04	9.57E-04	8.62E-04
Cs-134m	3.85E-02	1.14E+00	1.44E-01	4.25E+00	1.37E-01	4.04E+00
Cs-135	5.02E-08	NA	1.88E-07	NA	1.79E-07	NA
Cs-137	1.47E-02	2.26E-02	5.48E-02	8.42E-02	5.22E-02	8.02E-02
Cs-138	9.51E-04	5.66E+03	3.55E-03	2.11E+04	3.38E-03	2.01E+04
I-129	2.19E-09	NA	8.18E-09	NA	7.79E-09	NA
I-131	9.48E+00	4.70E+00	3.54E+01	1.75E+01	3.37E+01	1.67E+01
I-132	3.35E+01	NA	1.25E+02	NA	1.19E+02	NA
I-133	1.34E+02	2.17E+02	5.00E+02	8.11E+02	4.76E+02	7.72E+02
I-134	7.41E-01	3.25E+03	2.77E+00	1.21E+04	2.63E+00	1.16E+04
I-135	1.51E+02	8.53E+02	5.64E+02	3.19E+03	5.37E+02	3.03E+03
La-140	2.24E+00	NA	8.35E+00	NA	7.95E+00	NA
La-141	1.02E+02	1.02E+03	3.82E+02	3.79E+03	3.63E+02	3.61E+03
La-142	6.78E+00	2.57E+03	2.53E+01	9.58E+03	2.41E+01	9.12E+03
Mn-54	1.92E-02	2.95E-02	7.17E-02	1.10E-01	6.82E-02	1.05E-01
Mn-56	5.29E+01	2.25E+03	1.97E+02	8.40E+03	1.88E+02	8.00E+03
Mo-99	4.92E+01	8.61E+01	1.84E+02	3.21E+02	1.75E+02	3.06E+02
Mo-101	1.12E-12	3.63E+03	4.20E-12	1.36E+04	4.00E-12	1.29E+04
Nb-95	2.58E-02	1.35E-03	9.62E-02	5.04E-03	9.16E-02	4.80E-03
Nb-95m	2.45E-03	NA	9.16E-03	NA	8.72E-03	NA
Nb-97	1.40E+02	NA	5.23E+02	NA	4.98E+02	NA
Nd-144	1.91E-19	NA	7.12E-19	NA	6.78E-19	NA
Pr-143	2.22E+00	NA	8.28E+00	NA	7.88E+00	NA
Pr-144	4.77E-01	NA	1.78E+00	NA	1.69E+00	NA
Pr-144m	4.66E-03	NA	1.74E-02	NA	1.66E-02	NA
Rb-89	4.21E-12	3.84E+03	1.57E-11	1.43E+04	1.50E-11	1.36E+04
Rh-103m	2.22E+00	NA	8.27E+00	NA	7.88E+00	NA
Rh-106	4.74E-02	NA	1.77E-01	NA	1.69E-01	NA
Ru-103	2.24E+00	3.48E+00	8.37E+00	1.30E+01	7.97E+00	1.24E+01
Ru-106	4.74E-02	7.37E-02	1.77E-01	2.75E-01	1.69E-01	2.62E-01
Sb-128	7.66E+00	2.10E+01	2.86E+01	7.83E+01	2.72E+01	7.46E+01
Sb-128m	4.22E-02	NA	1.58E-01	NA	1.50E-01	NA
Sb-129	1.68E+01	1.79E+02	6.27E+01	6.68E+02	5.97E+01	6.36E+02
Sb-130	9.68E-04	6.76E+02	3.61E-03	2.52E+03	3.44E-03	2.40E+03
Sb-131	3.03E-07	2.40E+03	1.13E-06	8.96E+03	1.08E-06	8.53E+03
Sn-128	3.48E-02	3.25E+02	1.30E-01	1.21E+03	1.24E-01	1.16E+03
Sr-89	2.21E+00	2.64E+00	8.26E+00	9.86E+00	7.87E+00	9.39E+00
Sr-90	1.33E-02	2.05E-02	4.96E-02	7.65E-02	4.72E-02	7.28E-02
Sr-91	1.46E+02	5.44E+02	5.43E+02	2.03E+03	5.17E+02	1.93E+03
Sr-92	4.52E+01	1.74E+03	1.69E+02	6.49E+03	1.61E+02	6.18E+03
Tc-99	1.25E-07	NA	4.68E-07	NA	4.46E-07	NA
Tc-99m	3.40E+01	NA	1.27E+02	NA	1.21E+02	NA
Tc-101	2.63E-11	5.94E+03	9.82E-11	2.22E+04	9.35E-11	2.11E+04
Tc-104	6.84E-10	1.78E+03	2.55E-09	6.63E+03	2.43E-09	6.31E+03
Te-129	1.76E+01	NA	6.58E+01	NA	6.27E+01	NA
Te-129m	1.16E-01	NA	4.32E-01	NA	4.11E-01	NA
Te-131	9.87E-01	2.57E+03	3.68E+00	9.58E+03	3.51E+00	9.12E+03

Radionuclide	Early Phase (Total Dose)		Early Phase (Avoidable Dose)		First Year	
	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)
Te-131m	4.38E+00	7.72E+00	1.64E+01	2.88E+01	1.56E+01	2.74E+01
Te-132	3.35E+01	5.74E+01	1.25E+02	2.14E+02	1.19E+02	2.04E+02
Te-133	1.90E-02	2.82E+03	7.08E-02	1.05E+04	6.74E-02	1.00E+04
Te-133m	8.39E-02	1.39E+03	3.13E-01	5.19E+03	2.98E-01	4.94E+03
Te-134	1.41E-02	4.80E+03	5.27E-02	1.79E+04	5.01E-02	1.71E+04
Xe-131m	3.15E-03	NA	1.18E-02	NA	1.12E-02	NA
Xe-133	1.00E+01	NA	3.73E+01	NA	3.55E+01	NA
Xe-133m	6.77E-01	NA	2.53E+00	NA	2.40E+00	NA
Xe-135	1.65E+02	NA	6.16E+02	NA	5.86E+02	NA
Xe-135m	2.60E+01	NA	9.72E+01	NA	9.25E+01	NA
Y-90	1.62E-03	NA	6.03E-03	NA	5.74E-03	NA
Y-91	1.42E+00	9.86E-02	5.29E+00	3.68E-01	5.04E+00	3.50E-01
Y-91m	9.28E+01	NA	3.46E+02	NA	3.30E+02	NA
Y-92	1.81E+02	2.22E+02	6.74E+02	8.28E+02	6.42E+02	7.88E+02
Y-93	1.58E+02	5.39E+02	5.90E+02	2.01E+03	5.62E+02	1.91E+03
Y-94	3.39E-09	4.80E+03	1.27E-08	1.79E+04	1.20E-08	1.71E+04
Y-95	3.54E-19	3.15E+03	1.32E-18	1.18E+04	1.26E-18	1.12E+04
Zr-93	1.52E-07	NA	5.66E-07	NA	5.39E-07	NA
Zr-95	2.48E+00	3.48E+00	9.24E+00	1.30E+01	8.80E+00	1.24E+01
Zr-97	1.30E+02	3.33E+02	4.86E+02	1.24E+03	4.63E+02	1.18E+03

[a] Integrated Air DRLs are not decayed to an evaluation time and are therefore NA for daughter radionuclides not present in the initial mixture.

Table 5.5. HEU IND Dose Rate, Alpha, and Beta Derived Response Levels

DRL Type	Early Phase (Total Dose)	Early Phase (Avoidable Dose)	First Year
Dose Rate (mrem/h)	1.30E+01	4.84E+01	4.61E+01
Alpha Deposition ($\mu Ci_{alpha}/m^2$)	1.91E-19	7.12E-19	6.78E-19
Alpha Integrated Air ($\mu Ci_{alpha} \cdot s/m^3$)[a]	NA	NA	NA
Beta Deposition ($\mu Ci_{beta}/m^2$)	1.66E+03	6.21E+03	5.91E+03
Beta Integrated Air ($\mu Ci_{beta} \cdot s/m^3$)	6.49E+04	2.42E+05	2.31E+05

a Alpha Integrated Air DRLs are NA because the parent radionuclides in the mixture do not emit alpha particles. See FRMAC Assessment Manual, Volume 2, Method 1.3 for more discussion.

Table 5.6. WGPu IND Radionuclide-Specific Derived Response Levels

Radionuclide	Early Phase (Total Dose)		Early Phase (Avoidable Dose)		First Year	
	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)
Ba-137m	1.55E-02	NA[a]	5.65E-02	NA	5.42E-02	NA
Ba-140	1.11E+01	1.79E+01	4.04E+01	6.53E+01	3.87E+01	6.26E+01
Ba-141	1.54E-09	4.27E+03	5.61E-09	1.56E+04	5.37E-09	1.49E+04
Ba-142	1.18E-18	2.57E+03	4.29E-18	9.38E+03	4.11E-18	8.99E+03
Ce-141	3.42E+00	NA	1.25E+01	NA	1.19E+01	NA
Ce-143	6.25E+01	1.11E+02	2.28E+02	4.05E+02	2.18E+02	3.88E+02

Radionuclide	Early Phase (Total Dose)		Early Phase (Avoidable Dose)		First Year	
	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3)	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3)	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3)
Ce-144	3.54E-01	5.50E-01	1.29E+00	2.01E+00	1.24E+00	1.92E+00
Co-58	2.20E-01	2.24E-01	8.04E-01	8.16E-01	7.70E-01	7.82E-01
Co-58m	9.38E+00	3.74E+01	3.42E+01	1.37E+02	3.28E+01	1.31E+02
Cs-134	1.97E-04	NA	7.18E-04	NA	6.88E-04	NA
Cs-134m	7.41E-02	2.19E+00	2.70E-01	8.01E+00	2.59E-01	7.67E+00
Cs-135	5.10E-08	NA	1.86E-07	NA	1.78E-07	NA
Cs-137	1.64E-02	2.53E-02	5.99E-02	9.24E-02	5.74E-02	8.85E-02
Cs-138	8.77E-04	5.47E+03	3.20E-03	2.00E+04	3.07E-03	1.91E+04
I-129	3.75E-09	NA	1.37E-08	NA	1.31E-08	NA
I-131	1.09E+01	5.72E+00	3.97E+01	2.09E+01	3.80E+01	2.00E+01
I-132	3.97E+01	5.89E+01	1.45E+02	2.15E+02	1.39E+02	2.06E+02
I-133	1.42E+02	2.23E+02	5.18E+02	8.12E+02	4.96E+02	7.78E+02
I-134	6.10E-01	3.71E+03	2.23E+00	1.35E+04	2.13E+00	1.30E+04
I-135	1.53E+02	8.88E+02	5.60E+02	3.24E+03	5.36E+02	3.10E+03
La-140	2.10E+00	NA	7.65E+00	NA	7.33E+00	NA
La-141	9.42E+01	9.41E+02	3.44E+02	3.43E+03	3.30E+02	3.29E+03
La-142	6.10E+00	2.38E+03	2.23E+01	8.68E+03	2.13E+01	8.32E+03
Mn-54	2.54E-02	3.99E-02	9.26E-02	1.46E-01	8.87E-02	1.40E-01
Mn-56	6.91E+01	3.02E+03	2.52E+02	1.10E+04	2.42E+02	1.05E+04
Mo-99	5.19E+01	9.30E+01	1.89E+02	3.39E+02	1.81E+02	3.25E+02
Mo-101	1.52E-12	5.05E+03	5.54E-12	1.84E+04	5.31E-12	1.77E+04
Nb-95	1.88E-02	NA	6.84E-02	NA	6.56E-02	NA
Nb-95m	1.90E-03	NA	6.94E-03	NA	6.65E-03	NA
Nb-97	1.30E+02	NA	4.73E+02	NA	4.53E+02	NA
Nd-144	1.42E-19	NA	5.17E-19	NA	4.95E-19	NA
Pr-143	1.79E+00	NA	6.53E+00	NA	6.26E+00	NA
Pr-144	3.54E-01	NA	1.29E+00	NA	1.24E+00	NA
Pr-144m	3.46E-03	NA	1.26E-02	NA	1.21E-02	NA
Pu-239	3.10E-03	4.86E-03	1.13E-02	1.77E-02	1.08E-02	1.70E-02
Rb-89	1.74E-12	1.63E+03	6.34E-12	5.95E+03	6.07E-12	5.70E+03
Rh-103m	4.65E+00	NA	1.70E+01	NA	1.63E+01	NA
Rh-105	6.41E+01	NA	2.34E+02	NA	2.24E+02	NA
Rh-106	3.26E-01	NA	1.19E+00	NA	1.14E+00	NA
Ru-103	4.70E+00	7.48E+00	1.72E+01	2.73E+01	1.64E+01	2.62E+01
Ru-105	1.08E+02	1.11E+03	3.93E+02	4.04E+03	3.76E+02	3.87E+03
Ru-106	3.26E-01	5.05E-01	1.19E+00	1.84E+00	1.14E+00	1.77E+00
Sb-128	1.29E+01	3.71E+01	4.70E+01	1.35E+02	4.51E+01	1.30E+02
Sb-128m	6.83E-02	NA	2.49E-01	NA	2.39E-01	NA
Sb-129	2.87E+01	3.15E+02	1.05E+02	1.15E+03	1.00E+02	1.10E+03
Sb-130	1.17E-03	8.40E+02	4.28E-03	3.07E+03	4.10E-03	2.94E+03
Sb-131	3.14E-07	2.54E+03	1.15E-06	9.27E+03	1.10E-06	8.88E+03
Sn-128	5.63E-02	5.28E+02	2.05E-01	1.93E+03	1.97E-01	1.84E+03
Sr-89	7.27E-02	NA	2.65E-01	NA	2.54E-01	NA
Sr-90	5.39E-03	8.29E-03	1.97E-02	3.03E-02	1.88E-02	2.90E-02
Sr-91	6.82E+01	2.61E+02	2.49E+02	9.52E+02	2.39E+02	9.13E+02
Sr-92	2.47E+01	9.77E+02	9.02E+01	3.57E+03	8.64E+01	3.42E+03
Tc-99	1.46E-07	NA	5.32E-07	NA	5.10E-07	NA
Tc-99m	3.73E+01	5.67E+00	1.36E+02	2.07E+01	1.30E+02	1.98E+01
Tc-101	3.55E-11	8.21E+03	1.30E-10	2.99E+04	1.24E-10	2.87E+04

Radionuclide	Early Phase (Total Dose)		Early Phase (Avoidable Dose)		First Year	
	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)	DRL_{Dp} (µCi/m²)	$DRL_{\tilde{A}}$ (µCi•s/m³)
Te-129	3.01E+01	NA	1.10E+02	NA	1.05E+02	NA
Te-129m	1.98E-01	NA	7.22E-01	NA	6.92E-01	NA
Te-131	2.84E+00	2.88E+03	1.04E+01	1.05E+04	9.94E+00	1.01E+04
Te-131m	1.26E+01	2.50E+01	4.61E+01	9.13E+01	4.41E+01	8.75E+01
Te-132	3.86E+01	6.78E+01	1.41E+02	2.48E+02	1.35E+02	2.37E+02
Te-133	2.90E-02	NA	1.06E-01	NA	1.01E-01	NA
Te-133m	1.28E-01	2.18E+03	4.69E-01	7.95E+03	4.49E-01	7.61E+03
Te-134	1.08E-02	3.80E+03	3.96E-02	1.39E+04	3.79E-02	1.33E+04
U-235	3.96E-15	NA	1.44E-14	NA	1.38E-14	NA
U-235m	3.10E-03	NA	1.13E-02	NA	1.08E-02	NA
Xe-131m	3.56E-03	NA	1.30E-02	NA	1.25E-02	NA
Xe-133	1.05E+01	NA	3.83E+01	NA	3.67E+01	NA
Xe-133m	7.11E-01	NA	2.59E+00	NA	2.49E+00	NA
Xe-135	1.68E+02	NA	6.12E+02	NA	5.86E+02	NA
Xe-135m	2.64E+01	NA	9.65E+01	NA	9.25E+01	NA
Y-90	6.56E-04	NA	2.39E-03	NA	2.29E-03	NA
Y-91	6.14E-01	NA	2.24E+00	NA	2.15E+00	NA
Y-91m	4.35E+01	NA	1.59E+02	NA	1.52E+02	NA
Y-92	8.79E+01	NA	3.21E+02	NA	3.07E+02	NA
Y-93	1.03E+02	3.60E+02	3.76E+02	1.31E+03	3.60E+02	1.26E+03
Y-94	2.42E-09	3.52E+03	8.84E-09	1.28E+04	8.47E-09	1.23E+04
Y-95	2.71E-19	2.46E+03	9.87E-19	8.96E+03	9.46E-19	8.59E+03
Zr-93	9.88E-08	NA	3.60E-07	NA	3.45E-07	NA
Zr-95	1.92E+00	2.75E+00	7.00E+00	1.00E+01	6.71E+00	9.62E+00
Zr-97	1.21E+02	3.15E+02	4.40E+02	1.15E+03	4.22E+02	1.10E+03

[a] Integrated Air DRLs are not decayed to an evaluation time and are therefore NA for daughter radionuclides not present in the initial mixture.

Table 5.7. WGPu IND Dose Rate, Alpha, and Beta Derived Response Levels

DRL Type	Early Phase (Total Dose)	Early Phase (Avoidable Dose)	First Year
Dose Rate (mrem/h)	1.30E+01	4.75E+01	4.55E+01
Alpha Deposition ($\mu Ci_{alpha}/m^2$)	3.10E-03	1.13E-02	1.08E-02
Alpha Integrated Air (μCi_{alpha}•s/m³)	4.86E-03	1.77E-02	1.70E-02
Beta Deposition ($\mu Ci_{beta}/m^2$)	1.60E+03	5.85E+03	5.61E+03
Beta Integrated Air (μCi_{beta}•s/m³)	6.03E+04	2.20E+05	2.11E+05

5.5.2. Worker Protection Turn-Back Limits

Table 5.8 and Table 5.9 contain worker TBLs for the representative fallout mixtures for HEU INDs and WGPu INDs, respectively. Dose Rate, Alpha, and Beta TBLs are calculated for an 8-h shift starting 12 h after the plume has passed. The TBLs are provided per rem dose limit and are appropriate for the Adult Whole Body. To scale a listed TBL for a different dose limit (in units of rem), multiply the values in the tables by the desired dose limit.

NOTE: *TBLs are not provided for during plume passage because of the inability of field instrumentation to differentiate between ground and air activity. The provided TBLs should be adjusted to instrument-specific values for field team use.*

NOTE: *The Dose Rate TBL will be most useful. The Alpha and Beta TBLs are included for completeness.*

NOTE: *Assigned protection factors (APF) for respirators are included in the tables for completeness, even though the impact of the dose from inhalation of resuspended material is expected to be so low that respirators do not provide significant total dose reduction. Therefore, it might not be advisable to use respirators for activities after the plume has passed.*

Table 5.8. HEU IND Worker Protection Turn-Back Limits for Varying Assigned Protection Factors (APF)

TBL Type	TBL per rem Dose Limit			
	APF			
	1	50	100	1000
Dose Rate (mrem/h)	1.24E+02	1.25E+02	1.25E+02	1.25E+02
Alpha (μCiα/m2)a	3.36E-18	3.37E-18	3.37E-18	3.37E-18
Beta (μCiβ/m2)	1.65E+04	1.66E+04	1.66E+04	1.66E+04

Table 5.9. WGPu IND Worker Protection Turn-Back Limits for Varying Assigned Protection Factors (APF)

TBL Type	TBL per rem Dose Limit			
	APF			
	1	50	100	1000
Dose Rate (mrem/h)	1.24E+02	1.25E+02	1.25E+02	1.25E+02
Alpha (μCiα/m2)	4.07E-02	4.09E-02	4.09E-02	4.09E-02
Beta (μCiβ/m2)	1.61E+04	1.62E+04	1.62E+04	1.62E+04

5.5.3. Ingestion Pathway

Table 5.10 and Table 5.11 include FILs and Ingestion DRLs for radionuclides in Table 5.1 and Table 5.1 that are **NOT** included in FRMAC Assessment Manual Volume 2 Appendix C, Tables 8-1 and 8-2.

Table 5.10. Ingestion Pathway – FILs, Crop DRLs, and Transfer Factors for HEU and WGPu IND Radionuclides

Radionuclide	FIL ($\mu Ci/kg_{wet}$)	Crop DRL[a] ($\mu Ci/m^2$)	Leafy TF[b] (kg_{soil}/kg_{dry})	Fruit TF[b] (kg_{soil}/kg_{dry})	Non-Leafy TF[b] (kg_{soil}/kg_{dry})	Grain TF[b] (kg_{soil}/kg_{dry})
Ba-141	3.75E+04	2.74E+17	5.0E-03	1.3E-03	5.0E-03	1.0E-03
Ba-142	1.39E+05	3.90E+26	5.0E-03	1.3E-03	5.0E-03	1.0E-03

Radionuclide	FIL (µCi/kg$_{wet}$)	Crop DRL[a] (µCi/m^2)	Leafy TF[b] (kg$_{soil}$/ kg$_{dry}$)	Fruit TF[b] (kg$_{soil}$/ kg$_{dry}$)	Non-Leafy TF[b] (kg$_{soil}$/ kg$_{dry}$)	Grain TF[b] (kg$_{soil}$/ kg$_{dry}$)
Ce-143	1.94E+01	2.49E+02	6.0E-03	1.0E-03	1.3E-02	3.1E-03
Co-58	7.34E-01	7.37E+00	1.7E-01	7.0E-03	1.1E-01	8.5E-03
Co-58m	3.86E+03	9.68E+04	1.7E-01	7.0E-03	1.1E-01	8.5E-03
Cs-134m	1.57E+04	2.75E+06	6.0E-02	1.3E-03	4.2E-02	2.9E-02
Cs-138	1.64E+04	5.03E+11	6.0E-02	1.3E-03	4.2E-02	2.9E-02
I-132[c]	6.66E+02	4.99E+04	4.0E-02	1.3E-03	4.0E-02	4.0E-02
I-134	8.27E+03	2.22E+08	4.0E-02	1.3E-03	4.0E-02	4.0E-02
La-141	5.25E+02	4.38E+04	5.7E-03	1.0E-03	1.6E-03	2.0E-05
La-142	3.13E+03	7.48E+06	5.7E-03	1.0E-03	1.6E-03	2.0E-05
Mn-54	4.07E-01	4.06E+00	4.1E-01	2.3E-02	3.1E-01	2.8E-01
Mn-56	1.24E+03	3.12E+05	4.1E-01	2.3E-02	3.1E-01	2.8E-01
Mo-101	8.26E+04	5.61E+20	5.1E-01	6.0E-02	3.2E-01	8.0E-01
Rb-89	7.10E+04	1.42E+20	6.2E-01	1.0E-01	9.0E-01	9.0E-01
Ru-105[c]	6.81E+02	4.43E+04	9.0E-02	2.0E-02	2.0E-02	3.0E-03
Sb-128	1.33E+02	3.35E+03	9.4E-05	5.4E-02	1.3E-04	1.8E-03
Sb-129	4.30E+02	2.85E+04	9.4E-05	5.4E-02	1.3E-04	1.8E-03
Sb-130	1.52E+04	4.65E+10	9.4E-05	5.4E-02	1.3E-04	1.8E-03
Sb-131	1.95E+04	5.02E+14	9.4E-05	5.4E-02	1.3E-04	1.8E-03
Sn-128	5.63E+03	2.63E+08	3.0E-02	6.0E-03	6.0E-03	6.0E-03
Sr-92	7.48E+02	1.70E+05	7.6E-01	2.7E-02	7.2E-01	1.1E-01
Tc-101	1.82E+05	1.78E+21	2.1E+02	1.5E+00	2.4E-01	7.3E-01
Tc-104[d]	3.35E+04	1.25E+17	2.1E+02	1.5E+00	2.4E-01	7.3E-01
Te-131	1.77E+04	8.25E+13	3.0E-01	3.0E-01	8.0E-04	1.0E-01
Te-133[d]	3.04E+04	6.64E+22	3.0E-01	3.0E-01	8.0E-04	1.0E-01
Te-133m	1.73E+03	1.42E+08	3.0E-01	3.0E-01	8.0E-04	1.0E-01
Te-134	1.03E+04	1.57E+10	3.0E-01	3.0E-01	8.0E-04	1.0E-01
Y-92[d]	4.25E+02	4.45E+04	2.0E-03	2.0E-03	2.0E-03	5.0E-04
Y-93	6.20E+01	1.40E+03	2.0E-03	2.0E-03	2.0E-03	5.0E-04
Y-94	3.17E+04	1.23E+17	2.0E-03	2.0E-03	2.0E-03	5.0E-04
Y-95	1.00E+05	1.11E+27	2.0E-03	2.0E-03	2.0E-03	5.0E-04
Zr-97	2.23E+01	3.66E+02	4.0E-03	1.1E-03	4.0E-03	1.0E-03

[a] Assumes crops are ready to harvest (e.g., Time to Harvest = 0). The displayed Crop DRL uses the largest Transfer Factor of the four crop types included in this table.
[b] Transfer Factors from PNNL20.
[c] Only in default WGPu IND mixture.
[d] Only in default HEU IND mixture.

Table 5.11. Ingestion Pathway – FILs, Milk and Meat DRLs, and Transfer Factors for HEU and WGPu IND Radionuclides

Radionuclide	FIL (µCi/kg$_{wet}$)	Forage TF[a] (kg$_{soil}$/ kg$_{dry}$)	Milk DRL[b] (area) (µCi/m^2)	Milk DRL[b] (mass) (µCi/kg$_{wet}$)	Milk DRL[b] (water) (µCi/l)	Milk TF[b] (d/l)	Meat DRL[c] (area) (µCi/m^2)	Meat DRL[c] (mass) (µCi/kg$_{wet}$)	Meat DRL[c] (water) (µCi/l)	Meat TF[c] (d/kg$_{wet}$)
Ba-141	3.75E+04	2.0E+00	2.63E+42	1.90E+42	1.58E+42	1.6E-04	NA[d]	NA	NA	1.4E-04
Ba-142	1.39E+05	2.0E+00	5.52E+68	3.98E+68	3.32E+68	1.6E-04	NA	NA	NA	1.4E-04
Ce-143	1.94E+01	3.7E-01	3.60E+04	2.60E+04	2.16E+04	3.3E-05	4.93E+07	3.56E+07	3.56E+07	2.0E-04
Co-58	7.34E-01	4.5E-02	1.95E+02	1.41E+02	1.17E+02	1.1E-04	5.73E+01	4.13E+01	4.13E+01	4.3E-04
Co-58m	3.86E+03	4.5E-02	1.60E+07	1.15E+07	9.62E+06	1.1E-04	9.57E+20	6.90E+20	6.90E+20	4.3E-04
Cs-134m	1.57E+04	2.5E-01	5.32E+08	3.83E+08	3.19E+08	4.6E-03	6.69E+52	4.82E+52	4.82E+52	2.2E-02
Cs-138	1.64E+04	2.5E-01	2.98E+24	2.15E+24	1.79E+24	4.6E-03	2.09E+257	1.51E+257	1.51E+257	2.2E-02
I-132[e]	6.66E+02	3.7E-03	9.43E+07	1.35E+08	1.13E+08	5.4E-03	3.37E+64	4.84E+64	4.84E+64	6.7E-03
I-134	8.27E+03	3.7E-03	5.39E+16	7.73E+16	6.44E+16	5.4E-03	1.75E+165	2.51E+165	2.51E+165	6.7E-03
La-141	5.25E+02	2.0E-02	4.41E+08	3.17E+08	2.65E+08	2.0E-05	9.74E+40	7.02E+40	7.02E+40	1.3E-04
La-142	3.13E+03	2.0E-02	6.19E+13	4.46E+13	3.72E+13	2.0E-05	4.09E+98	2.95E+98	2.95E+98	1.3E-04
Mn-54	4.07E-01	6.4E-01	2.87E+02	2.07E+02	1.72E+02	4.1E-05	1.96E+01	1.42E+01	1.42E+01	6.0E-04
Mn-56	1.24E+03	6.4E-01	1.39E+10	1.00E+10	8.36E+09	4.1E-05	2.44E+59	1.76E+59	1.76E+59	6.0E-04
Mo-101	8.26E+04	5.4E+00	6.93E+50	5.00E+50	4.17E+50	1.1E-03	NA	NA	NA	1.0E-03
Rb-89	7.10E+04	2.6E-01	1.42E+48	1.02E+48	8.51E+47	1.2E-02	NA	NA	NA	1.0E-02
Ru-105[e]	6.81E+02	2.0E-03	5.77E+08	4.16E+08	3.46E+08	9.4E-06	3.08E+35	2.22E+35	2.22E+35	3.3E-03
Sb-128	1.33E+02	2.0E+00	1.61E+06	1.16E+06	9.69E+05	3.8E-05	1.33E+19	9.61E+18	9.61E+18	1.2E-03
Sb-129	4.30E+02	2.0E+00	9.48E+07	6.84E+07	5.70E+07	3.8E-05	1.04E+36	7.48E+35	7.48E+35	1.2E-03
Sb-130	1.52E+04	2.0E+00	3.33E+23	2.40E+23	2.00E+23	3.8E-05	3.49E+219	2.52E+219	2.52E+219	1.2E-03
Sb-131	1.95E+04	2.0E+00	2.53E+35	1.83E+35	1.52E+35	3.8E-05	NA	NA	NA	1.2E-03
Sn-128	5.63E+03	9.2E-02	1.65E+16	1.19E+16	9.93E+15	1.0E-03	2.46E+146	1.77E+146	1.77E+146	8.0E-02
Sr-92	7.48E+02	1.3E+00	1.97E+08	1.42E+08	1.18E+08	1.3E-03	1.47E+57	1.06E+57	1.06E+57	1.3E-03
Tc-101	1.82E+05	7.6E+01	2.26E+53	1.66E+53	1.39E+53	1.4E-04	NA	NA	NA	1.0E-04
Tc-104[f]	3.35E+04	7.6E+01	2.29E+42	1.69E+42	1.41E+42	1.4E-04	NA	NA	NA	1.0E-04
Te-131	1.77E+04	1.0E+00	1.53E+32	1.10E+32	9.20E+31	3.4E-04	NA	NA	NA	7.0E-03
Te-133[f]	3.04E+04	1.0E+00	2.69E+58	1.94E+58	1.62E+58	3.4E-04	NA	NA	NA	7.0E-03
Te-133m	1.73E+03	1.0E+00	8.03E+16	5.79E+16	4.82E+16	3.4E-04	2.61E+156	1.88E+156	1.88E+156	7.0E-03
Te-134	1.03E+04	1.0E+00	3.13E+21	2.26E+21	1.88E+21	3.4E-04	6.80E+206	4.90E+206	4.90E+206	7.0E-03
Y-92[f]	4.25E+02	5.0E-03	7.06E+08	5.09E+08	4.24E+08	2.0E-05	7.39E+43	5.32E+43	5.32E+43	1.0E-03
Y-93	6.20E+01	5.0E-03	1.04E+06	7.49E+05	6.24E+05	2.0E-05	1.19E+17	8.57E+16	8.57E+16	1.0E-03
Y-94	3.17E+04	5.0E-03	2.70E+42	1.95E+42	1.62E+42	2.0E-05	NA	NA	NA	1.0E-03

Radionuclide	FIL (µCi/kg$_{wet}$)	Forage TF[a] (kg$_{soil}$/ kg$_{dry}$)	Milk DRL[b] (area) (µCi/m^2)	Milk DRL[b] (mass) (µCi/kg$_{wet}$)	Milk DRL[b] (water) (µCi/l)	Milk TF[b] (d/l)	Meat DRL[c] (area) (µCi/m^2)	Meat DRL[c] (mass) (µCi/kg$_{wet}$)	Meat DRL[c] (water) (µCi/l)	Meat TF[c] (d/kg$_{wet}$)
Y-95	1.00E+05	5.0E-03	1.95E+71	1.40E+71	1.17E+71	2.0E-05	NA	NA	NA	1.0E-03
Zr-97	2.23E+01	1.0E-02	7.93E+05	5.72E+05	4.76E+05	3.6E-06	1.34E+14	9.64E+13	9.64E+13	1.2E-06

[a] Forage Transfer Factors from IAEA10 for available elements. Transfer Factors for elements not covered by IAEA10 were inferred using the methodology described in PNNL03.
[b] Values for Cow's Milk ready to harvest (e.g., Time to Grazing and Time to Harvest = 0). Transfer factors from PNNL20.
[c] Values for Beef ready to harvest (e.g., Time to Grazing and Time to Harvest = 0). Transfer factors from PNNL20.
[d] Radionuclides with a very short half-life are shown as NA and are unlikely to cause an ingestion concern.
[e] Only in default WGPu IND mixture.
[f] Only in default HEU IND mixture.

5.6. References

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6. SCENARIO 6: NUCLEAR WEAPON INCIDENT

6.1. Introduction

Incidents[6] involving nuclear weapons (NW) may be categorized into four general categories:

1. No detonation/no release: the NW is being carried and the carrier (aircraft or vehicle) sustains damage resulting in a fire or explosion, but the weapon survives essentially intact, without having detonated the high explosives.
2. HEVR: the high explosives in the NW detonate or undergo a high-explosive violent reaction (HEVR), resulting in 100% aerosolization of the special nuclear materials being dispersed into the environment (LANL95). Detonation or HEVR of the main charge high explosive may or may not result in some nuclear yield. Nuclear yield is extremely unlikely due to the nuclear safety design of U.S. weapons. U.S. weapon design is referred to as “one-point safe,” which means there is less than one chance in a million of producing a nuclear yield equivalent to more than four pounds of trinitrotoluene (TNT) equivalent when the high explosive is initiated at any single point.
3. Fire: the NW is burned in a fully engulfing fuel or propellent fire. While this type of event may result in dispersal of radioactive material, only 1% of the special nuclear material is expected to be aerosolized, of which 5% would be respirable (LANL95).
4. Mechanical disassembly: this includes the possibility of damage to the weapon’s nuclear explosive package. Mechanical disassembly of the nuclear explosive package could be expected to result in only localized dispersal of radioactive materials.

Yield-producing incidents involving non-U.S. NWs are covered under Section 5.

The two primary NW incident types of concern for consequence management are the second and third types, in which an NW undergoes a high-explosive detonation or HEVR, or is burned in a fully engulfing fire with resulting dispersal of radioactive material. Weapons-grade plutonium isotopes, americium, uranium isotopes, and tritium present the radiological hazards from a damaged NW. Pu-239 is expected to deliver the major portion of the radiation dose following an NW incident involving a high-explosive detonation or HEVR without nuclear yield. Tritium and uranium could also be dispersed, but with less radiological consequence.

In the unlikely event that there is a one-point detonation of the NW resulting in a yield of four pounds TNT equivalent, the dispersed radioactive material would also contain on the order of several thousand curies of fission products. Groundshine from the fission products would then become a major contributor to worker dose, and measures would need to be applied to protect survey and sampling team members. There would be no indication that the NW detonation included a small nuclear yield other than the increased dose rates around the NW and in the downwind hazard area.

[6] Note, this scenario is described as an “incident” according to DOD Directive 3150.08, *DoD Response to Nuclear Weapon and Radiological Material Incidents*, which states that all NW incidents will be treated as being due to hostile incident until such times as they are determined to be an accident.

The scene of an NW incident will be divided into two regions because of national security concerns. The on-site area (region nearest the incident scene ~770 m radius) will be secured to protect classified NW recovery operations and components that may be scattered in the area (DOD13). This area will be called either the National Security Area (NSA) if under the control of the Department of Energy (DOE) National Nuclear Security Agency (NNSA), or the National Defense Area (NDA) if under control of the Department of Defense (DOD). The NNSA's Accident Response Group (ARG), together with their DOD counterparts, are responsible for conducting NSA/NDA operations until the NW has been recovered (DOD13). The off-site area is everything beyond the NSA/NDA. FRMAC is responsible for assessment activities both inside and outside of the NSA/NDA, unless directed otherwise. However, monitoring and sampling teams will not likely be given access to the NSA/NDA until the NW has been recovered, due to security concerns. Thus, this pre-assessed scenario is focused on activities beyond the NSA/NDA.

This pre-assessed scenario is based on defaults and methods as specified in the May 2023 version of the FRMAC Assessment Manual, Volume 2 (SNL23) and may need to be updated to reflect future changes. Default results were calculated using Turbo FRMAC 2021.

6.2. Scenario-Specific Concerns

The Assessment Scientist should be prepared to address the following questions to support protective action decisions:

1. **Should the population be evacuated or sheltered?**
   Evacuation or sheltering in place are early phase protective actions. These actions should be considered in areas where projected dose exceeds the corresponding Protective Action Guide (PAG). In the case of an NW incident, it is possible that a significant dispersal of uranium may occur with or without a significant dispersal of plutonium. Since uranium is normally far less of a radiological hazard than plutonium due to the Adult Whole Body inhalation dose coefficient being up to 16 times higher for Pu-239 than for U-235, protective actions such as evacuation and sheltering based on plutonium are not likely to be appropriate for releases of uranium. The ARG Home Team can provide information on whether there has been a release of plutonium based on early DOD or ARG alpha readings.
2. **Should the population be relocated?**
   Relocation is an intermediate phase protective action. Relocation should be considered in areas where projected dose exceeds the corresponding PAG.
3. **What are the likely exposure pathways?**
   During plume passage, inhalation is expected to be the dominant pathway. Following plume passage, the primary exposure pathway is internal dose from inhalation of resuspended material, inadvertent ingestion, and consumption of contaminated foods. Due to the high inhalation dose coefficient for plutonium, recommendations to fix ground contamination should be considered early. Note, inadvertent ingestion is not included in typical FRMAC ingestion calculations and should be addressed separately if expected to exceed 10% of the appropriate EPA PAG for the time phase of interest. A method for projecting dose from inadvertent soil ingestion is provided in FRMAC Assessment Manual, Volume 2, see Method 3.7.

4. **Should potassium iodide (KI) be administered?**
   KI administration is not appropriate because iodine radionuclides are not included in NWs. Diethylenetriamine pentaacetate (DTPA) can be used to help remove plutonium from the body but is most effective if administered within 24 hours of intake.[7] Contact Radiation Emergency Assistance Center/Training Site (REAC/TS) for advice regarding DTPA administration.

5. **Do workers conducting monitoring and sampling activities outside of the NSA/NDA need protective equipment?**
   Use of respiratory protection may be advised to minimize intakes of radioactive materials due to resuspension. Because Pu-239 is primarily an internal exposure hazard, a prolonged exposure time due to slower work wearing respiratory protection should not cause a significant increase in external dose. The need for PPE for contamination control should also be evaluated. FRMAC Monitoring and Sampling Manual, Volume 1 provides default guidance for PPE and respiratory protection for FRMAC field teams (FRMAC19). For NW incidents specifically, the Nuclear Weapons Accident Response Procedures (NARP) (DOD13) also provide guidance on when to consider respiratory protection. If there has been any nuclear yield, the need for respiratory protection and PPE should be reexamined.

6. **What values should be used for measurements?**
   Dose rates are frequently used for DRLs and worker turn-back guidance. However, for an NW incident, dose rates from dispersed Pu-239 are likely to be too low to be useful for informing protective action decisions. Therefore, alpha and low-energy X-ray measurements should be used instead. Note that Am-241 is a useful marker radionuclide from weapons-grade plutonium. Am-241 in-growth can be estimated based on the age of the plutonium. This information would be available through the ARG Home Team.

Answers to the following questions are dependent on the circumstances of the event to which you are responding (e.g., radionuclide mixture, deposition, weather conditions, etc.):

- When can the evacuated population be allowed to return?
- What is the potential economic/infrastructure impact?
- Can foodstuffs grown in the contaminated area be consumed?
- Can foodstuffs be grown in the impacted area in the future?

6.3. Data Needs and Sources

The following sections describe the default assumptions to use for an NW incident scenario until event-specific information is known.

6.3.1. Time Phase

Use FRMAC default time phases and evaluation time as specified in FRMAC Assessment Manual, Volume 2, Table 2-3.

[7] https://www.cdc.gov/nceh/radiation/emergencies/dtpa.htm

ACTION — Determine whether to include Plume Pathways (i.e., Total Dose or Avoidable Dose)

6.3.2. Mixture

The actual ratios of isotopic components of weapons-grade plutonium will not be available in the early stages of an incident. Table 6.1 includes mixture information for weapons-grade plutonium at year 0 (LLNL20) that can be aged to the appropriate age of the NW involved in the incident. If age is unknown, use 30 years by default, as this would be a representative age of plutonium in the current stockpile. The 0-year-old mixture aged to 30 years is provided in Table 6.2 and is used for the Default Results in Section 6.5. Am-241 is included in the 30-year-old mixture because it contributes significantly to total dose and is also a useful marker radionuclide for measurements.

Note that relative value by mass and activity are provided for the radionuclides in Table 6.1 and Table 6.2. This is acceptable in the case of DRL calculations, for which the relative concentrations of the radionuclides in the mixture are important. It is recommended that relative value by activity is used in Turbo FRMAC, as activity is requested in calculations by default.

Table 6.1. 0-Year-Old Weapons-Grade Plutonium Mixture

Radionuclide	Relative Value by Mass	Relative Value by Activity
Pu-238	4.00E-04	1.01E-02
Pu-239	0.933	8.58E-02
Pu-240	6.00E-02	2.02E-02
Pu-241	5.80E-03	0.884
Pu-242	4.00E-04	2.32E-06

Table 6.2. 30-Year-Old Weapons-Grade Plutonium Mixture

Radionuclide	Relative Value by Mass	Relative Value by Activity
Pu-238	3.16E-04	2.32E-02
Pu-239	0.932	0.249
Pu-240	5.98E-02	5.86E-02
Pu-241	1.37E-03	0.606
Pu-242	4.00E-04	6.75E-06
Am-241	4.30E-03	6.34E-02

ACTION — Request weapon age and ARG measurement data from ARG Home Team. Note, monitoring equipment used by ARG might vary and ARG prioritizes measurements to support Health & Safety activities for ARG responders on-site

ACTION Review available data and work with Monitoring & Sampling to determine what radiation type(s) and/or radionuclide(s) have been detected, relative activity ratios, and instruments being used

6.3.3. Protective Action Guides

Use FRMAC default PAGs unless instructed otherwise by Decision Makers. The PAGs are located in FRMAC Assessment Manual, Volume 2, Table 2-1.

6.4. Technical Caveats

6.4.1. Inhalation Pathway

The LCT is Type S for a high-explosive detonation or HEVR and Type M for a fuel fire. Type S is specified in ICRP Publication 68 (ICRP94) for insoluble oxides of plutonium. Type M is recommended at formation temperatures below 1000 °C (ANS19). Default results are provided in Section 6.5 for both Type S and Type M.

Since the Am-241 is assumed to have "grown-in" to the plutonium matrix, the Am-241 is assumed to have the same lung solubility characteristics as the plutonium. It is also assumed that this Am-241 has the same systemic retention and excretion characteristics as the "parent" plutonium (DOD13).

Note that the NARP uses ICRP 30 and specifies that Pu-239 is assumed to have Class Y (very insoluble) lung solubility characteristics and to have a particle size distribution of 1-µm Activity Median Aerodynamic Diameter (AMAD) (DOD13).

Special PSDs have been determined for NW source terms and should be used to estimate the dose from plume inhalation. Contact the Consequence Management Home Team (CMHT) to obtain realistic PSD information. The FRMAC default PSD is used to estimate the dose from inhalation of resuspended material.

ACTION Coordinate with the ARG Accident Site Health Group Supervisor to recommend the use of current ICRP models for dose assessment

ACTION Work with NARAC to ensure consistent source term assumptions, including LCT and PSD

ACTION Work with Health & Safety to evaluate the need for respirators, turn-back limits, stay times, etc.

ACTION Request that the field teams perform resuspension measurements to support dose projections

6.4.2. Field Measurements

Dose rates from dispersed Pu-239 are likely to be too low to be useful. Therefore, field measurements are likely to come from handheld alpha survey meters and Field Instruments for Detection of Low Energy Radiation (FIDLERs). Note that Am-241 is a useful marker radionuclide from weapons-grade plutonium.

Many in-field measurements (e.g., FIDLER surveys) and several rapid-assessment bioassay measurements (e.g., lung counts) depend upon the roughly 60-keV gamma ray emitted by Am-241. Since this americium serves as a tracer or "marker" for the presence of all plutonium activity in the mixture, interpretation of the results of such measurements will depend greatly upon the ratio of Am-241 to other radionuclides in the mixture. The ratio of plutonium-to americium activity changes dramatically with time (after the plutonium was originally processed). Therefore, knowledge, or at least an estimate of, the "age" of the plutonium mixture is critically important for interpreting such results. Table 6.3 provides ratios of Am-241 to other radionuclides in a weapons-grade plutonium mixture as a function of age.

Table 6.3. Activity Relative to Am-241 in Weapons-Grade Plutonium

Radionuclide	1-year-old	5-year-old	15-year-old	30-year-old	50-year-old
Pu-238	7.25	1.55	0.601	0.365	0.269
Pu-239	62.0	13.7	5.75	3.93	3.39
Pu-240	14.6	3.22	1.35	0.923	0.794
Pu-241	609	111	28.7	9.52	3.12
Pu-242	1.68E-03	3.70E-04	1.55E-04	1.06E-04	9.17E-05
Am-241	1.00	1.00	1.00	1.00	1.00
Pu-239 + Pu240	76.6	16.9	7.10	4.86	4.18
Total Alpha	84.9	19.5	8.70	6.22	5.45

6.4.3. Ingestion Pathway

The FDA provides DILs for radionuclides expected to deliver the major portion of the dose from ingestion during the first year following an incident.

ACTION	Don't forget that FDA provides DILs for grouped radionuclides (Pu-238 + Pu-239 + Am-241)

6.5. Default Results

6.5.1. Public Protection Derived Response Levels

Table 6.4 and Table 6.5 contain DRLs for the 30-year-old Type S weapons-grade plutonium mixture in Table 6.2. Table 6.6 and Table 6.7 contain DRLs for the 30-year-old Type M weapons-grade plutonium mixture in Table 6.2. The DRLs for the Early Phase (Total Dose) time phase, including the plume, use a high-explosive detonation PSD for Type S and a fire PSD for Type M. The DRLs are appropriate for the Adult Whole Body. Am-241 results are included as a useful marker radionuclide.

Table 6.4. NW Incident Radionuclide-Specific Derived Response Levels, Type S

Radionuclide	Early Phase (Total Dose)		Early Phase (Avoidable Dose)		First Year	
	DRL_{Dp} ($\mu Ci/m^2$)	$DRL_{\tilde{A}}$ ($\mu Ci•s/m^3$)	DRL_{Dp} ($\mu Ci/m^2$)	$DRL_{\tilde{A}}$ ($\mu Ci•s/m^3$)	DRL_{Dp} ($\mu Ci/m^2$)	$DRL_{\tilde{A}}$ ($\mu Ci•s/m^3$)
Pu-238	2.76E-02	9.21E+00	1.31E+00	4.36E+02	6.29E-01	2.10E+02
Pu-239	2.96E-01	9.86E+01	1.40E+01	4.67E+03	6.73E+00	2.24E+03
Pu-240	6.96E-02	2.32E+01	3.30E+00	1.10E+03	1.59E+00	5.29E+02
Pu-241	7.20E-01	2.40E+02	3.41E+01	1.14E+04	1.64E+01	5.47E+03
Pu-242	8.00E-06	2.67E-03	3.79E-04	1.26E-01	1.82E-04	6.07E-02
Am-241	7.54E-02	2.52E+01	3.57E+00	1.19E+03	1.72E+00	5.73E+02

Table 6.5. NW Incident Dose Rate, Alpha, and Beta Derived Response Levels, Type S

DRL Type	Early Phase (Total Dose)	Early Phase (Avoidable Dose)	First Year
Dose Rate (mrem/h)	1.96E-05	9.28E-04	4.46E-04
Alpha Deposition ($\mu Ci_{alpha}/m^2$)	4.68E-01	2.22E+01	1.07E+01
Alpha Integrated Air ($\mu Ci_{alpha}•s/m^3$)	1.56E+02	7.40E+03	3.56E+03
Beta Deposition ($\mu Ci_{beta}/m^2$)	2.64E-08	1.25E-06	6.02E-07
Beta Integrated Air ($\mu Ci_{beta}•s/m^3$)[a]	NA	NA	NA
[a] Beta Integrated Air DRLs are NA because the parent radionuclides in the NW mixture emit beta particles with average energies less than the instrument threshold. See FRMAC Assessment Manual, Volume 2, Method 1.4 Beta DRL for more discussion.			

Table 6.6. NW Incident Radionuclide-Specific Derived Response Levels, Type M

Radionuclide	Early Phase (Total Dose)		Early Phase (Avoidable Dose)		First Year	
	DRL_{Dp} ($\mu Ci/m^2$)	$DRL_{\tilde{A}}$ ($\mu Ci•s/m^3$)	DRL_{Dp} ($\mu Ci/m^2$)	$DRL_{\tilde{A}}$ ($\mu Ci•s/m^3$)	DRL_{Dp} ($\mu Ci/m^2$)	$DRL_{\tilde{A}}$ ($\mu Ci•s/m^3$)
Pu-238	2.00E-02	6.67E+00	4.25E-01	1.42E+02	2.05E-01	6.83E+01
Pu-239	2.15E-01	7.15E+01	4.57E+00	1.52E+03	2.20E+00	7.32E+02
Pu-240	5.05E-02	1.68E+01	1.07E+00	3.58E+02	5.17E-01	1.72E+02
Pu-241	5.22E-01	1.74E+02	1.11E+01	3.71E+03	5.34E+00	1.78E+03
Pu-242	5.82E-06	1.93E-03	1.24E-04	4.11E-02	5.95E-05	1.98E-02
Am-241	5.46E-02	1.82E+01	1.16E+00	3.88E+02	5.59E-01	1.87E+02

Table 6.7. NW Incident Dose Rate, Alpha, and Beta Derived Response Levels, Type M

DRL Type	Early Phase (Total Dose)	Early Phase (Avoidable Dose)	First Year
Dose Rate (mrem/h)	1.42E-05	3.02E-04	1.45E-04
Alpha Deposition ($\mu Ci_{alpha}/m^2$)	3.40E-01	7.23E+00	3.48E+00
Alpha Integrated Air ($\mu Ci_{alpha}•s/m^3$)	1.13E+02	2.41E+03	1.16E+03
Beta Deposition ($\mu Ci_{beta}/m^2$)	1.92E-08	4.08E-07	1.96E-07
Beta Integrated Air ($\mu Ci_{beta}•s/m^3$)[a]	NA	NA	NA
[a] Beta Integrated Air DRLs are NA because the parent radionuclides in the NW mixture emit beta particles with average energies less than the instrument threshold. See FRMAC Assessment Manual, Volume 2, Method 1.4 Beta DRL for more discussion.			

6.5.2. Worker Protection Turn-Back Limits

Table 6.8 and Table 6.9 contain worker TBLs for the 30-year-old weapons-grade plutonium mixture in Table 6.2 for Type S and Type M, respectively. Dose Rate, Alpha, and Beta TBLs are calculated for an 8-h shift starting 12 h after the plume has passed. The TBLs are provided per rem dose limit and are appropriate for the Adult Whole Body. To scale a listed TBL for a different dose limit (in units of rem), multiply the values in the tables by the desired dose limit.

> ***NOTE:*** *TBLs are not provided for during plume passage because of the inability of field instrumentation to differentiate between ground and air activity. The provided TBLs should be adjusted to instrument-specific values for field team use.*

> ***NOTE:*** *Dose rates from dispersed Pu-239 are likely to be too low to be a useful TBL but are included for completeness.*

Table 6.8. NW Incident Worker Protection Turn-Back Limits for Varying Assigned Protection Factors (APF), Type S

TBL Type	TBL per rem Dose Limit			
	APF			
	1	50	100	1000
Dose Rate (mrem/h)	5.77E-03	2.88E-01	5.74E-01	5.52E+00
Alpha (μCiα/m2)	1.38E+02	6.90E+03	1.38E+04	1.32E+05
Beta (μCiβ/m2)	1.03E-05	5.14E-04	1.03E-03	9.85E-03

Table 6.9. NW Incident Worker Protection Turn-Back Limits for Varying Assigned Protection Factors (APF), Type M

TBL Type	TBL per rem Dose Limit			
	APF			
	1	50	100	1000
Dose Rate (mrem/h)	1.88E-03	9.39E-02	1.88E-01	1.85E+00
Alpha (μCiα/m2)	4.50E+01	2.25E+03	4.49E+03	4.43E+04
Beta (μCiβ/m2)	3.36E-06	1.68E-04	3.35E-04	3.31E-03

6.5.3. Ingestion Pathway

Table 6.10 and Table 6.11 include FILs and Ingestion DRLs for radionuclides in Table 6.2 that are **NOT** included in FRMAC Assessment Manual Volume 2, Appendix C, Tables 8-1 and 8-2.

Table 6.10. Ingestion Pathway – FILs, Crop DRLs, and Transfer Factors for NW Incident Radionuclides

Radionuclide	FIL (µCi/kg_{wet})	Crop DRL[a] (µCi/m^2)	Leafy TF[b] (kg_{soil}/kg_{dry})	Fruit TF[b] (kg_{soil}/kg_{dry})	Non-Leafy TF[b] (kg_{soil}/kg_{dry})	Grain TF[b] (kg_{soil}/kg_{dry})
Pu-240	5.80E-04	5.80E-03	8.3E-05	4.5E-05	6.5E-05	9.5E-06
Pu-242	6.10E-04	6.09E-03	8.3E-05	4.5E-05	6.5E-05	9.5E-06

[a] Assumes crops are ready to harvest (e.g., Time to Harvest = 0). The displayed Crop DRL uses the largest Transfer Factor of the four crop types included in this table.
[b] Transfer Factors from PNNL20.

Table 6.11. Ingestion Pathway – FILs, Milk and Meat DRLs, and Transfer Factors for NW Incident Radionuclides

Radionuclide	FIL (µCi/kg_{wet})	Forage TF[a] (kg_{soil}/kg_{dry})	Milk DRL[b] (area) (µCi/m^2)	Milk DRL[b] (mass) (µCi/kg_{wet})	Milk DRL[b] (water) (µCi/l)	Milk TF[b] (d/l)	Meat DRL[c] (area) (µCi/m^2)	Meat DRL[c] (mass) (µCi/kg_{wet})	Meat DRL[c] (water) (µCi/l)	Meat TF[c] (d/kg_{wet})
Pu-240	5.80E-04	5.5E-04	1.67E+00	1.21E+00	1.01E+00	1.0E-05	1.46E+01	1.05E+01	1.05E+01	1.1E-06
Pu-242	6.10E-04	5.5E-04	1.76E+00	1.27E+00	1.06E+00	1.0E-05	1.54E+01	1.11E+01	1.11E+01	1.1E-06

[a] Forage Transfer Factors from IAEA10 for available elements. Transfer Factors for elements not covered by IAEA10 were inferred using the methodology described in PNNL03.
[b] Values for Cow's Milk ready to harvest (e.g., Time to Grazing and Time to Harvest = 0). Transfer factors from PNNL20.
[c] Values for Beef ready to harvest (e.g., Time to Grazing and Time to Harvest =0). Transfer factors from PNNL20.

6.6. References

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FRMAC19 Federal Radiological Monitoring and Assessment Center*, Monitoring and Sampling Manual Volume 1, Revision 3 Monitoring Division Operations, Monitoring Division Operations,* April 2019.

IAEA10 *Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments,* IAEA Technical Report Series No. 472, International Atomic Energy Agency, Vienna, Austria, 2010.

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LANL95 *Characterization of Plutonium Aerosols for Various Accident Scenarios by an Expert Panel*, LA-CP-95-55, Los Alamos National Laboratory, Los Alamos, NM, March 1995.

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7. SCENARIO 7: RADIOISOTOPE THERMOELECTRIC GENERATOR ACCIDENT

7.1. Introduction

Radioisotope power systems can be used by spacecraft as sources of heat and/or electrical power. Radioisotope power systems used in spacecraft consist of radioisotope thermoelectric generators (RTGs) and radioisotope heater units (RHUs). Because of mission power and longevity requirements, U.S. mission planners have relied exclusively on the use of RTGs. The most commonly used radionuclide fuel for RTGs is Pu-238, due to its relatively high heat-to-mass ratio and long half-life of 87.7 years. The nominal content of an RTG is about 60,000 Ci of plutonium dioxide (PuO_2) in ceramic form (SNL19). Figure 7.1 provides an example of the components of an RTG.

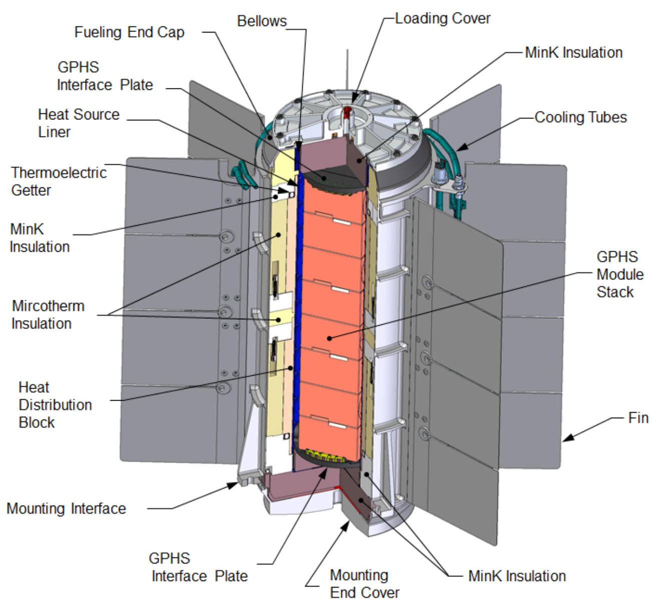

Figure 7.1. Components of an RTG (SNL19)

There is the potential for an accident during the launch that may be severe enough to release the radioactive fuel from the radioisotope power systems to the environment. These accidents include an early launch accident, an orbital decay resulting in reentry to the earth's atmosphere, and reentry at higher than orbital velocities during a fly-by maneuver for deep space missions.

RTGs are designed to contain their fuel under accident conditions; however, releases may occur due to impact with concrete, steel, or other hard objects (e.g., rock) following a launch or re-entry accident. An inadvertent re-entry represents the most severe accident environment to which RTGs could be subjected and would lead to a range of fuel end states that include intact or damaged modules, intact graphite impact shells, and fuel released at high altitude in both particulate and vapor form.

This pre-assessed scenario is based on defaults and methods as specified in the May 2023 version of the Federal Radiological Monitoring and Assessment Center (FRMAC) Assessment Manual, Volume 2 (SNL23) and may need to be updated to reflect future changes. Default results were calculated using Turbo FRMAC 2021.

7.2. Scenario-Specific Concerns

The Assessment Scientist should be prepared to address the following questions to support protective action decisions:

1. **Should the population be evacuated or sheltered?**
   Because the time and area of impact of an RTG accident cannot be accurately predicted, evacuation of populations will usually not be conducted prior to launch. Sheltering of the public is the most likely initial protective action because of the low probability of dispersal of Pu-238 and the likelihood that affected area will be of limited size.

   Although the occurrence of an RTG accident cannot be predicted, RTG launches are planned events and it is likely that Brevard County and the State of Florida have plans prepared in case of an early launch accident. An orbital reentry could impact areas outside of Florida that do not have plans in place for this specific type of accident.

2. **What are the likely exposure pathways?**
   During plume passage, inhalation is expected to be the dominant pathway. Following plume passage, the primary exposure pathway is internal dose from inhalation of resuspended material, inadvertent ingestion, and consumption of contaminated foods. Note, inadvertent ingestion is not included in typical FRMAC ingestion calculations and should be addressed separately if expected to exceed 10% of the appropriate EPA PAG for the time phase of interest. A method for projecting dose from inadvertent soil ingestion is provided in FRMAC Assessment Manual, Volume 2, see Method 3.7.

3. **Should potassium iodide (KI) be administered?**
   KI administration is not appropriate because iodine radionuclides are not included in RTG fuel.

4. **Should the population be relocated?**
   Relocation is an intermediate phase protective action. Relocation should be considered in areas where projected dose exceeds the corresponding PAG.

5. **Do emergency workers need protective equipment?**
   Use of respiratory protection may be advised to minimize intake of radioactive materials due to resuspension. Because Pu-238 is primarily an internal exposure hazard, a prolonged exposure time due to slower work wearing respiratory protection should not cause a significant increase in external dose. The need for PPE for contamination control should also be evaluated. FRMAC Monitoring and Sampling Manual, Volume 1 provides default guidance for PPE for FRMAC field teams (FRMAC19).

6. **What values should be used for measurements?**
   Dose rates are frequently used for DRLs and worker turn-back guidance. However, for an RTG accident, dose rates from dispersed Pu-238 are likely to be too low to be useful for informing protective action decisions. Therefore, alpha and low-energy X-ray measurements should be used instead.

7. **What should field teams expect to encounter in the field?**
   Accident scenarios are likely to cause the Pu-238 RTG source material to fracture into a range of particle sizes from respirable particles (<10-20 µm) to chunks that are large enough to see. Field monitoring personnel near the release point should be aware of the potential to encounter thermally hot chunks of source material and take the appropriate action (e.g., stay away, mark GPS coordinates, contact Monitoring & Sampling and Assessment Managers). Field monitoring personnel should also be aware that Pu-238 emits neutrons, due to spontaneous fission and alpha-neutron reactions in the fuel.
8. **Should roads be closed?**
   The answer to this question is event-specific, but the Assessment Scientist should be aware that there is a significant amount of commerce that occurs along I-95 and US-1, due to the large agriculture industry in Florida. Note also that NASA launches attract many spectators that could be on road shoulders.

Answers to the following questions are dependent on the circumstances of the event to which you are responding (e.g., radionuclide mixture, deposition, weather conditions, etc.):

- When can the evacuated population be allowed to return?
- What is the potential economic/infrastructure impact?
- Can foodstuffs grown in the contaminated area be consumed?
- Can foodstuffs be grown in the impacted area in the future?

7.3. Data Needs and Sources

The following sections describe the default assumptions to use for an RTG scenario until event-specific information is known.

7.3.1. Time Phase

Use FRMAC default time phases and evaluation time as specified in FRMAC Assessment Manual, Volume 2, Table 2-3.

ACTION	Determine whether to include Plume Pathways (i.e., Total Dose or Avoidable Dose)

7.3.2. Mixture

Table 7.1 includes mixture information for an RTG, based on the inventory for the Mars 2020 RTG launch (LANL18). No release fractions are applied. Instead, it is assumed that the entire inventory is released. The mixture in Table 7.1 is applicable at the Release Time and should be entered in Turbo FRMAC as an Integrated Air Concentration with equilibrium set to OFF. Note that Integrated Air Concentration units are different than the activity units provided in Table 7.1. This is acceptable in the case of DRL calculations, for which the relative concentrations of the radionuclides in the mixture are important.

> ***NOTE**: Dose will be dominated by exposure to Pu-238 because it comprises the majority (>99%) of the total RTG activity. Other plutonium isotopes and daughter products are included in the assumed RTG mixture for completeness.*

Table 7.1. RTG Mixture

Radionuclide	Activity (Ci)
Pu-238	5.86E+04
Pu-241	3.48E+02
Pu-239	3.28E+01
Am-241	2.95E+01
Pu-240	2.66E+01
Pu-236	1.80E-02
Pu-242	1.30E-02

ACTION Review available data and work with Monitoring & Sampling to determine what radiation type(s) and/or radionuclide(s) have been detected, relative activity ratios, and instruments being used

7.3.3. *Protective Action Guides*

Use FRMAC default PAGs unless instructed otherwise by Decision Makers. The PAGs are located in FRMAC Assessment Manual, Volume 2, Table 2-1.

7.4. Technical Caveats

7.4.1. *Inhalation Pathway*

Table 7.2 contains PSDs that should be used for the plume inhalation pathway, depending on the phase of the mission. The PSDs are derived from the Mars 2020 Nuclear Risk Assessment (SNL19). The PSDs should be entered as Uniform distributions in terms of Activity Median Aerodynamic Diameter (AMAD).

> ***NOTE****: The particle size bins in Table 7.2 appear irregular because they have been converted from physical diameters using bin-specific particle densities and consolidated into fewer bins.*

Table 7.2. Particle Size Distributions by Mission Phase

Mission Phase	Phase Timing	Minimum Diameter (µm AMAD)	Maximum Diameter (µm AMAD)	Fraction of Aerosolized Material
Prelaunch	~1 week before launch to just before engine ignition	0.02	9.8	0.35
		14	65	0.01
		67	143	0.64
Early Launch	Engine ignition to ~12 minutes after launch	0.02	9.8	0.16
		14	67	0.41
		65	140	0.43
Orbital Reentry	~12 minutes to ~1 hour after launch	0.03	14	0.90
		14	67	0.09
		67	143	0.01

The FRMAC default PSD for resuspension is used to estimate the dose from inhalation of resuspended material, unless monitoring and sampling data indicate an alternate PSD is appropriate. Use the ICRP Recommended LCT as specified in ICRP Publication 72 (ICRP96).

ACTION	Work with the Kennedy Space Center Radiological Control Center (RADCC) to determine when the launch anomaly occurred and select the PSD for the relevant mission phase

ACTION	Work with NARAC to ensure consistent source term assumptions, including LCT and PSD

ACTION	Work with Health & Safety to evaluate the need for respirators, turn-back limits, stay times, etc.

ACTION	Request that the field teams perform resuspension measurements to support dose projections

7.4.2. Field Measurements

Dose rates from dispersed Pu-238 are likely to be too low to be useful. Therefore, field measurements are likely to come from handheld alpha survey meters, Field Instruments for Detection of Low Energy Radiation (FIDLERs), and Environmental Continuous Air Monitors (ECAMs).

ACTION	ECAMs will be prepositioned for an RTG launch. Be prepared to compare ECAM data to the Integrated Air Alpha DRL

ACTION	ECAMs only collect particles up to 20 µm AMAD. Be prepared to correct ECAM integrated air concentration data for particles greater than 20 µm AMAD using the available PSD information

7.4.3. Ingestion Pathway

The FDA provides DILs for radionuclides expected to deliver the major portion of the dose from ingestion during the first year following an accident. Note that FRMAC has used FILs with alternate ingestion assumptions in preparation for RTG launches (e.g., in 2011 and 2020).

ACTION	Don't forget that FDA provides DILs for grouped radionuclides (Pu-238 + Pu-239 + Am-241)

ACTION	Consult with Advisory Team to get approval to use the Pu-238-only DIL rather than the grouped DIL, or to use the Pu-238 FIL (and other alternate ingestion assumptions)

Various crops, livestock, and animal products are produced year-round in Florida. Agricultural statistics are maintained by the Florida Department of Agriculture and Consumer Services , the University of Florida Agricultural Extension Service, and the U.S. Department of Agriculture. These statistics are a good source of data, such as crop types grown, growing seasons, etc. The Assessment Scientist should consult the agricultural organizations of the impacted area for a reentry scenario.

7.5. Default Results

7.5.1. Public Protection Derived Response Levels

Table 7.3 and Table 7.4 contain DRLs for the Early Phase (Total Dose) time phase for the RTG mixture specified in Table 7.1 and the PSDs in Table 7.2. The DRLs are appropriate for the Adult Whole Body.

Table 7.3. RTG Radionuclide-Specific Derived Response Levels for Early Phase (Total Dose) by Mission Phase

Radionuclide	Prelaunch		Early Launch		Orbital Reentry	
	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3)	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3)	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3)
Am-241	7.35E-05	2.45E-02	1.15E-04	3.83E-02	3.29E-05	1.10E-02
Pu-236	4.48E-08	1.49E-05	7.00E-08	2.34E-05	2.01E-08	6.69E-06
Pu-238	1.46E-01	4.87E+01	2.28E-01	7.60E+01	6.53E-02	2.18E+01
Pu-239	8.17E-05	2.72E-02	1.28E-04	4.25E-02	3.65E-05	1.22E-02
Pu-240	6.63E-05	2.21E-02	1.03E-04	3.45E-02	2.96E-05	9.88E-03
Pu-241	8.67E-04	2.89E-01	1.35E-03	4.51E-01	3.88E-04	1.29E-01
Pu-242	3.24E-08	1.08E-05	5.06E-08	1.69E-05	1.45E-08	4.83E-06

Table 7.4. RTG Dose Rate, Alpha, and Beta Derived Response Levels for Early Phase (Total Dose) by Mission Phase

DRL Type	Prelaunch	Early Launch	Orbital Reentry
Dose Rate (mrem/h)	9.73E-07	1.52E-06	4.35E-07
Alpha Deposition (µCi_{alpha}/m^2)	1.46E-01	2.28E-01	6.54E-02
Alpha Integrated Air (µCi_{alpha}•s/m^3)	4.87E+01	7.61E+01	2.18E+01
Beta Deposition (µCi_{beta}/m^2)	3.18E-11	4.97E-11	1.42E-11
Beta Integrated Air (µCi_{beta}•s/m^3) [a]	NA	NA	NA

[a] Beta Integrated Air DRLs are NA because the parent radionuclides in the RTG mixture emit beta particles with average energies less than the instrument threshold. See FRMAC Assessment Manual, Volume 2, Method 1.4 Beta DRL for more discussion.

Table 7.5 and Table 7.6 contain DRLs for the Early Phase (Avoidable Dose) and First Year default time phases for the RTG mixture specified in Table 7.1. These DRLs are not phase-dependent because they do not include plume inhalation dose, which requires a phase-dependent PSD (Table 7.2). The DRLs are appropriate for the Adult Whole Body.

Table 7.5. RTG Radionuclide-Specific Derived Response Levels for Early Phase (Avoidable Dose) and First Year

Radionuclide	Early Phase (Avoidable Dose)		First Year	
	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3)	DRL_{Dp} (µCi/m^2)	$DRL_{\tilde{A}}$ (µCi•s/m^3)
Am-241	3.93E-03	1.31E+00	1.89E-03	6.31E-01
Pu-236	2.40E-06	8.00E-04	1.15E-06	3.85E-04
Pu-238	7.81E+00	2.60E+03	3.76E+00	1.25E+03
Pu-239	4.37E-03	1.46E+00	2.10E-03	7.01E-01
Pu-240	3.54E-03	1.18E+00	1.71E-03	5.69E-01
Pu-241	4.64E-02	1.55E+01	2.23E-02	7.44E+00
Pu-242	1.73E-06	5.77E-04	8.34E-07	2.78E-04

Table 7.6. RTG Dose Rate, Alpha, and Beta Derived Response Levels for Early Phase (Avoidable Dose) and First Year

DRL Type	Early Phase (Avoidable Dose)	First Year
Dose Rate (mrem/h)	5.20E-05	2.51E-05
Alpha Deposition (µCi$_{alpha}$/m^2)	7.82E+00	3.76E+00
Alpha Integrated Air (µCi$_{alpha}$•s/m^3)	2.61E+03	1.25E+03
Beta Deposition (µCi$_{beta}$/m^2)	1.70E-09	8.19E-10
Beta Integrated Air (µCi$_{beta}$•s/m^3)[a]	NA	NA

[a] Beta Integrated Air DRLs are NA because the parent radionuclides in the RTG mixture emit beta particles with average energies less than the instrument threshold. See FRMAC Assessment Manual, Volume 2, Method 1.4 Beta DRL for more discussion.

7.5.2. *Worker Protection Turn-Back Limits*

Table 7.7 contains worker TBLs for the RTG mixture specified in Table 7.1. Dose Rate, Alpha, and Beta TBLs are calculated for an 8-h shift starting 12 h after the plume has passed. The TBLs are provided per rem dose limit and are appropriate for the Adult Whole Body. To scale a listed TBL for a different dose limit (in units of rem), multiply the values in the tables by the desired dose limit.

> ***NOTE****: TBLs are not provided for during plume passage because of the inability of field instrumentation to differentiate between ground and air activity. The provided TBLs should be adjusted to instrument-specific values for field team use.*

> ***NOTE****: Dose rates from dispersed Pu-238 are likely to be too low to be a useful TBL but are included for completeness.*

Table 7.7. RTG Turn-Back Limits for Varying Assigned Protection Factors (APF)

TBL Type	TBL per rem Effective Dose Limit			
	APF			
	1	50	100	1000
Dose Rate (mrem/h)	3.2E-04	1.6E-02	3.2E-02	3.2E-01
Alpha (μCiα/m2)	4.9E+01	2.4E+03	4.9E+03	4.9E+04
Beta (μCiβ/m2)	2.1E-07	1.1E-05	2.1E-05	2.1E-04

7.5.3. Ingestion Pathway

Table 7.8 and Table 7.9 include FILs and Ingestion DRLs for radionuclides in Table 7.1 that are **NOT** included in FRMAC Assessment Manual, Volume 2, Appendix C, Tables 8-1 and 8-2.

> ***NOTE:*** *Ingestion dose will be dominated by exposure to Pu-238 because it comprises the majority of the total RTG activity. Ingestion values for other radionuclides in the assumed RTG mixture are included below for completeness.*

Table 7.8. Ingestion Pathway – FILs, Crop DRLs, and Transfer Factors for RTG Radionuclides

Radionuclide	FIL (µCi/kg_{wet})	Crop DRL[a] (µCi/m^2)	Leafy TF[b] (kg_{soil}/kg_{dry})	Fruit TF[b] (kg_{soil}/kg_{dry})	Non-Leafy TF[b] (kg_{soil}/kg_{dry})	Grain TF[b] (kg_{soil}/kg_{dry})
Pu-236	2.03E-03	2.03E-02	8.3E-05	4.5E-05	6.5E-05	9.5E-06
Pu-240	5.80E-04	5.80E-03	8.3E-05	4.5E-05	6.5E-05	9.5E-06
Pu-242	6.10E-04	6.09E-03	8.3E-05	4.5E-05	6.5E-05	9.5E-06

[a] Assumes crops are ready to harvest (e.g., Time to Harvest = 0). The displayed Crop DRL uses the largest Transfer Factor of the four crop types included in this table.
[b] Transfer Factors from PNNL20.

Table 7.9. Ingestion Pathway – FILs, Milk and Meat DRLs, and Transfer Factors for RTG Radionuclides

Radionuclide	FIL (µCi/kg_{wet})	Forage TF[a] (kg_{soil}/kg_{dry})	Milk DRL[b] (area) (µCi/m^2)	Milk DRL[b] (mass) (µCi/kg_{wet})	Milk DRL[b] (water) (µCi/l)	Milk TF[b] (d/l)	Meat DRL[c] (area) (µCi/m^2)	Meat DRL[c] (mass) (µCi/kg_{wet})	Meat DRL[c] (water) (µCi/l)	Meat TF[c] (d/kg_{wet})
Pu-236	2.03E-03	5.5E-04	5.86E+00	4.22E+00	3.52E+00	1.0E-05	5.18E+01	3.74E+01	3.74E+01	1.1E-06
Pu-240	5.80E-04	5.5E-04	1.67E+00	1.21E+00	1.01E+00	1.0E-05	1.46E+01	1.05E+01	1.05E+01	1.1E-06
Pu-242	6.10E-04	5.5E-04	1.76E+00	1.27E+00	1.06E+00	1.0E-05	1.54E+01	1.11E+01	1.11E+01	1.1E-06

[a] Forage Transfer Factors from IAEA10 for available elements. Transfer Factors for elements not covered by IAEA10 were inferred using the methodology described in PNNL03.
[b] Values for Cow's Milk ready to harvest (e.g., Time to Grazing and Time to Harvest = 0). Transfer factors from PNNL20.
[c] Values for Beef ready to harvest (e.g., Time to Grazing and Time to Harvest = 0). Transfer factors from PNNL20.

7.6. References

FRMAC19 Federal Radiological Monitoring and Assessment Center*, Monitoring and Sampling Manual Volume 1, Revision 3 Monitoring Division Operations, Monitoring Division Operations,* April 2019.

IAEA10 *Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments,* IAEA Technical Report Series No. 472, International Atomic Energy Agency, Vienna, Austria, 2010.

ICRP96 *Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 5 Compilation of Ingestion and Inhalation Dose Coefficients*, ICRP Publication 72, International Commission on Radiological Protection, Ottawa, Ontario, Canada, 1996.

LANL18 "Mars 2020 MMRTG Fuel Inventory and Assay," Communication to U.S. DOE, December 2018.

PNNL03 *A Compendium of Transfer Factors for Agricultural and Animal Products*, PNNL-13421, Pacific Northwest National Laboratory, Richland, WA, 2003.

PNNL20 *Transfer Factors for the FRMAC Assessment Manual and Turbo FRMAC to Improve Radiological Dose Assessment*, PNNL-27926 Rev 1, Pacific Northwest National Laboratory, Richland, WA, 2020.

SNL19 *Nuclear Risk Assessment 2019 Update for the Mars 2020 Mission Environmental Impact Statement*, SAND2019-11148, Sandia National Laboratories, Albuquerque, NM, September 2019.

SNL23 *FRMAC Assessment Manual, Volume 2, Overview and Methods*, SAND2023-04457 R, Sandia National Laboratories, Albuquerque, NM, May 2023.

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APPENDIX A. CHANGE HISTORY

The May 2023 FRMAC Assessment Manual, Volume 3 contains the following changes from the previous (February 2010) version:

1. Updated Preface.
2. Changed the order of the scenarios.
3. Revised the content of each scenario to remove extraneous information and improve cross scenario consistency
4. Revised and renamed Nuclear Power Plant scenario (former Nuclear Power Plant Accident).
5. Revised and renamed Nuclear Fuel Fabrication scenario (formerly Nuclear Fuel Accident)
6. Revised and renamed Nuclear Fuel Accident scenario (formerly Aged Fission Product Accident).
7. Revised and renamed Radiological Dispersal Device scenario (formerly Radiological Dispersal Device Accident).
8. Developed and renamed Nuclear Detonation scenario (formerly Nuclear Yield Accident).
9. Revised Radioisotope Thermoelectric Generator Accident scenario.