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Turbo FRMAC Implementation of IAEA Radiological Assessment Methodologies for Nuclear and Radiological Emergencies

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ABSTRACT

This report documents the findings of an assessment of the Turbo FRMAC software's ability to implement International Atomic Energy Agency (IAEA) guidance for calculating Operational Intervention Levels (OIL) 1 & 2 for nuclear and radiological emergencies. The IAEA OIL and U.S. Federal Radiological Monitoring and Assessment Center (FRMAC) Derived Response Level methodology and implementation in respective tools were compared, as demonstrated through benchmarking activities for a nuclear power plant source term and potential radionuclides of concern for radiological dispersal devices. This comparison revealed some shortcomings in Turbo FRMAC's ability to perform IAEA OIL calculations and resulted in recommended software modifications to be considered for future development.

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

This report provides a comparison of the International Atomic Energy Agency (IAEA) Operational Intervention Level (OIL) and U.S. Federal Radiological Monitoring and Assessment Center (FRMAC) Derived Response Level (DRL). The goal of this work is to evaluate the ability of the Turbo FRMAC© software to calculate IAEA OILs, as part of IAEA Coordinated Research Project (CRP) J15002 on the "Effective use of dose projection tools in the preparedness and response to nuclear and radiological emergencies." This report specifically addresses IAEA OIL1 and OIL2 and the FRMAC Public Protection DRL.

The IAEA defines OILs as "operational criteria that allow the prompt implementation of protective actions and other response actions on the basis of monitoring results that are readily available during a nuclear or radiological emergency." OILs are pre-established values that are to be revised "as appropriate, in the course of a nuclear or radiological emergency, with account taken of the prevailing conditions as they evolve." Default OILs are used to allow for decisions to be taken quickly, and to account for the limited information typically available at the start of an emergency. The basis for the default OILs for LWR accidents is provided in IAEA EPR-NPP-OILs 2017. The methodology used to derive the default OILs can also be used to calculate an incident-specific OIL.

FRMAC uses an OIL-like quantity called a DRL, which is a level of radioactivity in an environmental medium that would be expected to produce a dose equal to the corresponding protective action guide. DRLs are not pre-established values like OILs; they are calculated for a given scenario using default dosimetric methodology established in the FRMAC Assessment Manual. At a minimum, incident-specific source term information is used to calculate DRLs, and additional information is used to tailor other inputs as it becomes available during a response.

The IAEA provides an Excel-based tool to perform OIL calculations, while the U.S. calculates DRLs using a software called Turbo FRMAC. A detailed comparison of IAEA Excel Tool and Turbo FRMAC assumptions and features is included in this report. Additionally, the IAEA Excel tool and Turbo FRMAC were both used to calculate OILs in order to assess Turbo FRMAC's ability to perform these calculations and better understand the IAEA OIL methodology. The scenarios considered in this benchmarking activity were a nuclear power plant source term and a few radionuclides of concern for potential use in a radiological dispersal device (RDD): Am-241, Cs-137, and Sr-90.

The feature comparison and benchmarking activity concluded that Turbo FRMAC is a far more flexible tool for calculating OIL-like quantities than the IAEA Excel tool due to its built-in radiological database and ability to handle dose calculations for custom exposure periods and any mixture of radionuclides. However, the Turbo FRMAC DRL calculation does not include the exposure pathways for external exposure to resuspended material (i.e., airshine) and inadvertent soil ingestion, nor does it calculate dose to the fetus. These are exposure pathways and receptors included in IAEA OIL calculations. Turbo FRMAC can best emulate an OIL for groundshine exposure scenarios where the adult is the primary receptor of interest (e.g., Cs-137 RDD). However, Turbo FRMAC cannot adequately calculate OILs according to IAEA guidance for scenarios where infant or fetus dose is most restrictive, or where inadvertent soil ingestion dose is significant. This finding will be used to motivate future development work for Turbo FRMAC to make it a more useful tool for the international response community, as well as better enable U.S. assessment of international incidents.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
Am-241	americium-241
AMAD	activity median aerodynamic diameter
Ba-137m	metastable barium-137
CRP	coordinated research project
Cs-137	cesium-137
DCFPAK	Dose Coefficient File Package
DRL	derived response level
EPA	U.S. Environmental Protection Agency
EPR	emergency preparedness and response
FGR	federal guidance report
FRMAC	Federal Radiological Monitoring and Assessment Center
GC	generic criteria
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
LWR	light water reactor
NCRP	National Council on Radiation Protection Measurements
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
OIL	operational intervention level
PAG	protective action guide
RASCAL	Radiological Assessment System for Consequence Analysis
RCM	research coordination meeting
RDD	radiological dispersal device
SNL	Sandia National Laboratories
Sr-90	strontium-90
SOARCA	State-of-the-Art Reactor Consequence Analyses
Y-90	yttrium-90

1. INTRODUCTION

In January 2020, the International Atomic Energy Agency (IAEA) held the first Research Coordination Meeting (RCM) for IAEA Coordinated Research Project (CRP) J15002 on the "Effective use of dose projection tools in the preparedness and response to nuclear and radiological emergencies." The meeting participants generally support the use of dose projection models in both preparedness and response. However, there is not consensus on the appropriate use of these models soon after a nuclear or radiological incident occurs (e.g., the urgent phase). Additionally, the majority of the proposed research projects under this CRP are focused on dose projection modeling, ranging from simple to sophisticated atmospheric dispersion modeling. Only a few participants noted the use of Operational Intervention Levels (OIL) in their project, so more work is needed in this area to understand how other Member States calculate and use similar operational quantities.

The goal of the three-year CRP is to develop recommendations for the improved use of dose projection tools to support emergency planning and management at the preparedness phase and the response stage, which will in turn contribute to the improvement of the international Emergency Preparedness and Response (EPR) framework. Sandia National Laboratories (SNL) participants developed the following project objectives based on discussions with IAEA staff and participants from other Member States during the first RCM:

- Provide recommendations to improve IAEA OIL calculational methods and technical assumptions
- Provide recommendations to improve guidance on when it is appropriate to revise OILs or use pre-calculated, incident-specific OILs rather than default OILs
- Use knowledge gained through previous objectives to plan development of international calculations in Turbo FRMAC

Further review of IAEA guidance and discussion with IAEA staff and other Member States is needed to better understand how a tool like Turbo FRMAC might support operational needs during a response (e.g., calculating OILs), and what software modifications are needed to do this. This report documents the findings of SNL assessment of the Turbo FRMAC software's ability to implement IAEA guidance for calculating OILs.

2. METHODOLOGY COMPARISON

2.1. Protective Action Guidance

2.1.1. IAEA Guidance

The IAEA guidance for preparedness and response for a nuclear or radiological emergency is documented in IAEA Safety Standard Series No. GSR Part 7 [1]. This document provides generic criteria (GC), which are projected or received doses at which response actions are to be taken in a nuclear or radiological emergency. The IAEA says that Member States can adopt the IAEA's GC or develop their own "on the basis of the outcome of the justification and the optimization of their protection strategy" [2]. It is not known to the author which IAEA Member States have adopted the IAEA's GC.

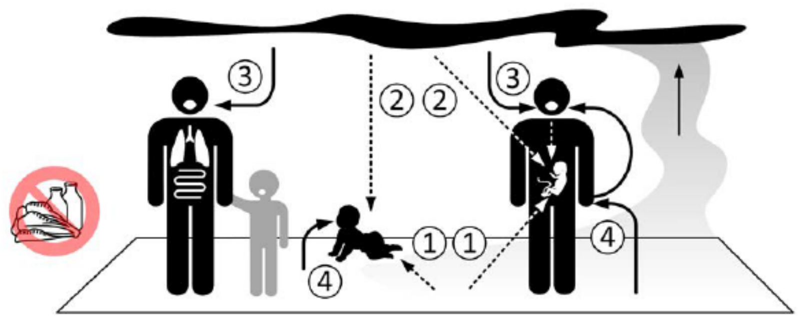
The IAEA GC are "established at doses below those at which radiation induced health effects would be expected to be observed, even in a very large exposed group composed of the most sensitive members of the public (e.g. children and pregnant women)" and as such, the IAEA warns against implementing response actions below the GC [2]. The IAEA GC for chronic exposure are

- 0.1 Sv total effective dose to the representative person in the first 7 days (urgent phase),
- 0.1 Sv total equivalent dose to the fetus in the first 7 days,
- 0.1 Sv total effective dose to the representative person in the first year (early phase), and
- 0.1 Sv total equivalent dose to the fetus in the first year,

as well as a 0.1 Sv limit for committed equivalent dose to the thyroid from radioiodine and 0.01 Sv committed effective dose to the representative person or fetus from ingestion of food, milk, and drinking water during the first year.[1] The representative person is an individual receiving a dose that is representative of the doses to the more highly exposed individuals in the population and is thus meant to be a "conservative approach: No member of the public is expected to receive a dose during an actual emergency close to that calculated for the representative person for the conditions described in the scenarios" [2]. In application, the representative person is a combination of infant and adult dosimetric characteristics. Figure 2-1 includes an overview of how the effective dose to the representative person is determined.

[1] The thyroid and ingestion GC and OILs are not addressed in this report but will be addressed in future work.

TABLE 12. EXPOSURE PATHWAYS AND PARAMETERS FOR THE 'GROUND' SCENARIO



	Exposure pathways	Effective dose to the representative person	Equivalent dose to the fetus
1	External exposure from radioactive material deposited on the ground (i.e. ground shine)	Effective dose to the infant	Equivalent dose to the fetus of the pregnant woman from external exposure to ground shine
2	External exposure from resuspended[a] radioactive material (i.e. air shine)	Effective dose to the infant	Equivalent dose to the fetus of the pregnant woman from external exposure to air shine
3	Inhalation of resuspended[a] radioactive material	Breathing rate for an adult performing light activity combined with the committed effective dose to the adult	Breathing rate for an adult (pregnant woman) performing light activity combined with the committed equivalent dose to the fetus from inhalation by the pregnant woman
4	Inadvertent ingestion of soil (e.g. from dirt on the hands)	Inadvertent ingestion rates by an infant during normal activity combined with the committed effective dose to the infant[b]	Inadvertent ingestion rates of dust and soil by an adult (pregnant woman) during normal activity combined with the committed equivalent dose to the fetus from ingestion by the pregnant woman

Figure 2-1. Overview of IAEA OIL Exposure Pathways (reproduced from IAEA EPR-NPP-OILs 2017 [2])

2.1.2. U.S. Guidance

The U.S. guidance for response to nuclear or radiological incidents is documented in the U.S. Environmental Protection Agency (EPA) Protective Action Guide (PAG) Manual [3]. The PAG Manual provides numerical PAGs for the principal protective actions available to public officials during a radiological incident. A PAG is defined as a projected dose to an individual from a release of radioactive material at which a specific protective action to reduce or avoid that dose is recommended. The PAGs are

- 0.01 to 0.05 Sv projected dose over four days,
- 0.02 Sv projected dose in the first year, and
- 0.005 Sv projected dose per year in the second and subsequent years,

as well as 0.05 Sv projected child thyroid dose from exposure to radioiodine, 0.005 Sv per year projected whole body dose or 0.05 Sv per year projected organ dose (whichever is limiting) for consumption of contaminated food products in the first year, and 0.001 Sv projected dose to infants, children, pregnant women, and nursing women and 0.005 Sv projected dose to the general population for consumption of contaminated drinking water for one year.

EPA PAGs are based on adult exposure. The basis for this is that conservative assumptions such as not accounting for occupancy and sheltering and using a particle size of 1 micron activity median aerodynamic diameter (AMAD) are conservative, and these conservatisms allow dose assessors to project whole body doses or total effective dose to a reference person, for simplicity, and then decision-makers can make protective action decisions that apply to entire communities including children, adults and the elderly. Dose assessors are encouraged to utilize realistic inputs when site- or source-specific information is available to limit the amount of conservatism built into calculations. Further into the intermediate phase when incident characteristics have been assessed, more realistic incident-specific factors may be considered by local decision makers in projecting risks and adapting mitigation measures [3].

2.2. Operational Criteria

2.2.1. IAEA Operational Intervention Level

In addition to GC, the IAEA uses OILs, which are defined as "operational criteria that allow the prompt implementation of protective actions and other response actions on the basis of monitoring results that are readily available during a nuclear or radiological emergency" [2]. OILs are pre-established values that are to be revised "as appropriate, in the course of a nuclear or radiological emergency, with account taken of the prevailing conditions as they evolve" [1]. Default OILs are used to allow for decisions to be taken quickly, and to account for the limited information typically available at the start of an emergency. The default OILs for a light water reactor (LWR) accident that correspond to the GC listed above are

- OIL1 – 1000 μSv/h during the urgent phase
- OIL2 – 100 μSv/h for the first 10 days after reactor shutdown and 25 μSv/h later than 10 days after reactor shutdown or for spent fuel, during the early phase

The basis for the default OILs for LWR accidents is provided in IAEA EPR-NPP-OILs 2017 [2]. The methodology used to derive the default OILs can also be used to calculate an incident-specific OIL. The IAEA provides an Excel-based tool [4] to perform OIL calculations. A screenshot of this tool is included as Figure 2-2.

OIL1 and OIL2 use the minimum (most restrictive) of the OIL calculated using the total effective dose to the representative person and the OIL calculated using the total equivalent dose to the fetus. OIL1 and OIL2 are ambient dose equivalent rates measured 1 m above ground. A dose rate measurement is used because it is "readily available, easy to obtain (with simple instruments and little training) and representative of the expected radionuclide mixes." EPR-NPP-OILs 2017 states that OILs for use during a plume are not provided because the release will usually be over by the time air concentration measurements are available, these measurements are difficult to take and analyze in a timely manner, and there is great variation in time and location of plume concentrations at any location during a release [2].

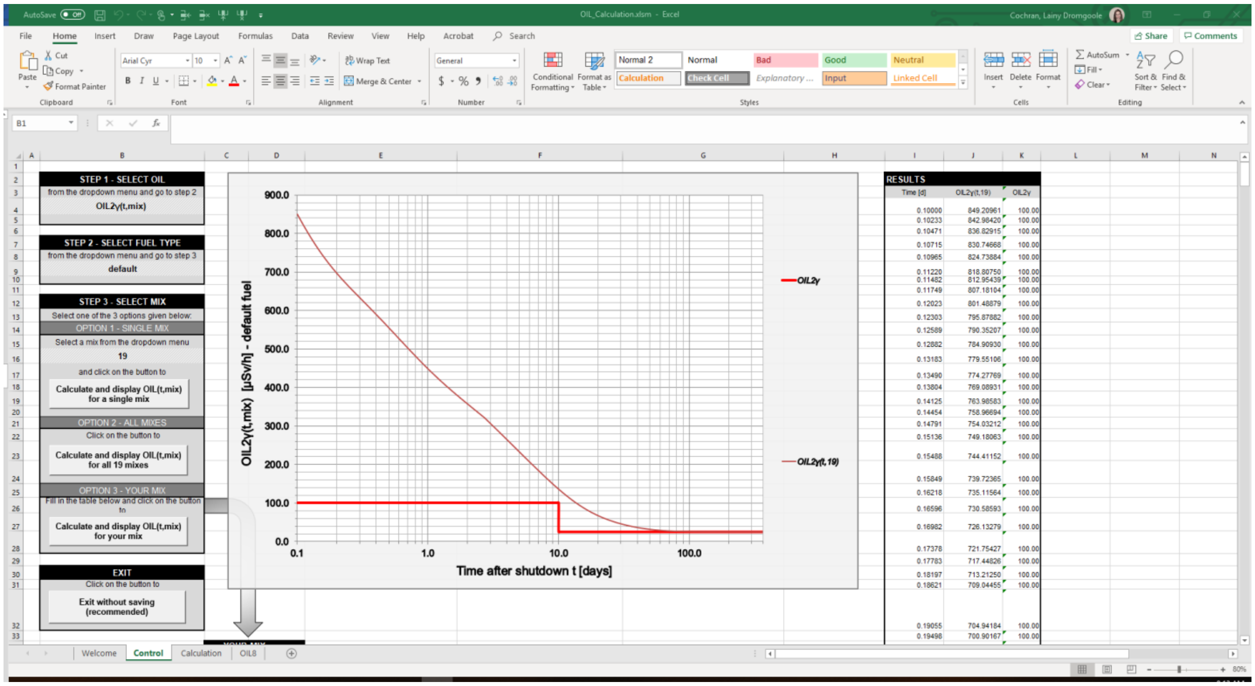


Figure 2-2. IAEA Excel Tool Screenshot

OIL1 and OIL2 include multiplicative weighting factors "to ensure that all members of the public are effectively protected and to avoid the implementation of unwarranted actions that will do more harm than good." A default weighting factor of 3 is used for OIL1 because this OIL is to be used in the first hours after an emergency is declared and "the dose actually received if response actions are implemented within the first day would be 1/3 of the dose projected for an exposure period of 7 days." OIL2 is meant to be used later when there is more time to implement response actions, so the default weighting factor for this OIL is 1.

2.2.2. FRMAC Derived Response Level

The U.S. uses an OIL-like quantity called a Derived Response Level (DRL), which is a level of radioactivity in an environmental medium that would be expected to produce a dose equal to the corresponding PAG. The Federal Radiological Monitoring and Assessment Center (FRMAC) Assessment Manual [5] provides guidance on how to calculate DRLs. DRLs are not pre-established values like OILs; they are calculated for a given scenario using default dosimetric methodology established in the FRMAC Assessment Manual. At a minimum, incident-specific source term information is used to calculate DRLs, and additional information is used to tailor other inputs as it becomes available during a response.

The Turbo FRMAC© Software [6] implements the technical methods in the FRMAC Assessment Manual. Turbo FRMAC is developed by SNL for the Department of Energy / National Nuclear Security Administration Office of Nuclear Incident Response (NA-84) and has served as the FRMAC's radiological assessment tool for over 15 years. Turbo FRMAC allows for rapid computation of important dose assessment data such as DRLs and projected doses. The software includes default input values established by the FRMAC Assessment Working Group but can easily be modified to accommodate incident-specific conditions. A screenshot of this tool is included as Figure 2-3.

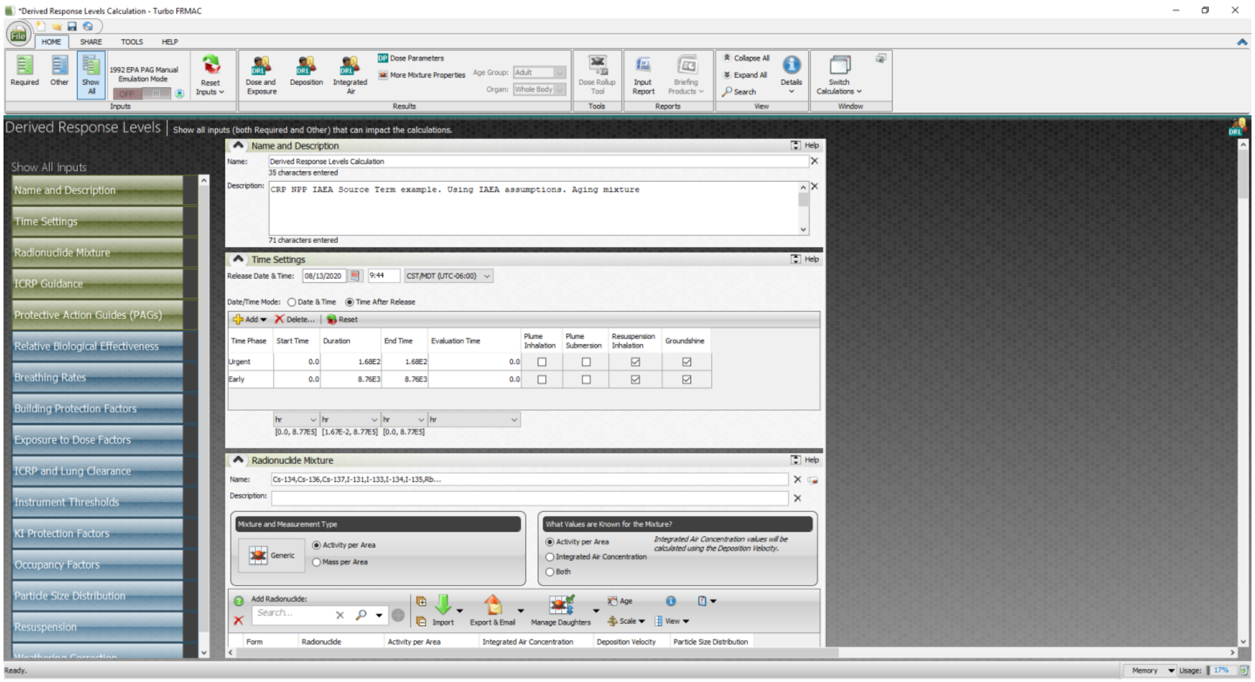


Figure 2-3. Turbo FRMAC Screenshot

Turbo FRMAC calculates Public Protection DRLs for the adult age group for various measurement types, including radionuclide-specific integrated air and deposition concentrations, alpha and beta integrated air and deposition concentrations, and dose and exposure rates. DRLs are calculated for a specific evaluation time that can be adjusted to any time after the release for comparison to measurements. The evaluation time is used to account for decay and weathering of ground measurement based DRLs (deposition and dose/exposure rates).

2.3. Technical Assumptions

The following sections describe the technical assumptions used by the IAEA to calculate OILs and by FRMAC to calculate DRLs, as well as how they are implemented in their respective tools. This assessment was performed based on those specified in EPR-NPP-OILs 2017 [2] and a version of the IAEA Excel tool dated February 13, 2017 [4], and in the 2018 version of the FRMAC Assessment Manual, Volume 1 [5] and Turbo FRMAC 2019 version 9.0.2 [6].

2.3.1. Radionuclide Inventories

IAEA: EPR-NPP-OILs 2017 is specifically written to address LWR emergencies. The IAEA Excel tool includes two LWR inventories of 38 radionuclides, one "standard fuel" and one for "high burnup fuel." The IAEA notes in EPR-NPP-OILs-2017 that "the results for both inventories only differ slightly and do not affect the final default OIL values," however both inventories are included in the Excel tool. The "standard fuel" inventory comes from IAEA-TECDOC-955 [7] and is based on the U.S. Nuclear Regulatory Commission (NRC) 1975 WASH-1400 reactor safety study [8]. The "high burnup fuel" inventory comes from the more recent NRC State-of-the-Art Reactor Consequence Analyses (SOARCA) [9]. If a user wants to use the IAEA Excel tool for a radionuclide mixture that includes radionuclides not included in the two pre-populated inventories, the user must add all the associated radiological data manually.

FRMAC: The Turbo FRMAC installer includes the Mixture Manager tool [10]. This tool provides the ability to view default mixtures of radionuclides (e.g., like those provided in the IAEA Excel tool), and create custom mixtures that can be saved for future import into Turbo FRMAC calculations. The Mixture Manager tool can support many radionuclide mixtures of any type (LWR or otherwise).

Turbo FRMAC can calculate DRLs for any mixture of radionuclides available in Dose Coefficient File Package (DCFPAK) version 4.0 [11]. This includes 1252 radionuclides for external dose coefficients and 888 radionuclides for ingestion and inhalation dose coefficients. The DCFPAK database underlying Turbo FRMAC enables the software to auto-populate all radiological data, including half-life and dose coefficients.

2.3.2. Release Fractions

IAEA: The IAEA Excel tool includes 19 sets of release fractions grouped for postulated core to contaminant release scenarios, postulated core to atmosphere release scenarios, postulated spent fuel release scenarios, and historical emergencies (Chernobyl and Fukushima). The selected release fractions are then applied to the selected inventory (standard or high burnup) and used to calculate OILs.

FRMAC: FRMAC procedure is to use an NRC-postulated source term informed by plant conditions and the RASCAL software [12] to calculate DRLs for nuclear power plant (NPP) releases. This source term includes radionuclides with release fractions applied. Any radionuclide mixture used in Turbo FRMAC calculations must already have release fractions applied. Turbo FRMAC does not include a release fraction library nor a field for entering them separately, though inventories with release fractions already applied can be stored in the Mixture Manager tool for use in Turbo FRMAC calculations.

2.3.3. Radionuclide Concentrations

IAEA: The IAEA Excel tool calculates a normalized dose per unit area for each of the provided radionuclides and then uses the relative activities of the released mixture to calculate OILs.

FRMAC: Turbo FRMAC accepts radionuclide mixtures provided in units of integrated air concentration (e.g., $Bq\text{-}s/m^3$), ground concentration (e.g., Bq/m^2), or both. If only integrated air or ground concentration is provided, deposition velocity is used to infer the other concentration, and can be assigned per radionuclide. The absolute concentrations can be used to project doses, but the relative concentrations are used to calculate DRLs. Radionuclide concentration information initially comes from source term and atmospheric dispersion models, and transitions to field measurements and laboratory analysis results as they become available.

2.3.4. Decay and In-Growth

IAEA: The IAEA Excel tool specifies progenies for 12 parent radionuclides in the provided inventories (e.g., Sr-90/Y-90, Cs-137/Ba-137m). These progenies are assumed to be in equilibrium with the parent. The IAEA Excel tool allows the user to decay the provided radionuclide inventories to a single time after reactor shutdown. In-growth is not handled.

FRMAC: Turbo FRMAC models decay and in-growth using the Bateman equations [13]. This is a very powerful capability that is necessary for accurately calculating doses from complex fission product mixtures. Additionally, Turbo FRMAC has features which allow users to very easily turn equilibrium assumptions on and off, as well as apply truncation rules in order to save computation time without significantly affecting calculated dose [14].

All radionuclide mixtures entered into Turbo FRMAC calculations must be the mixture present at the time of deposition. If the available inventory needs to be decayed, the user can easily age the mixture in the Turbo FRMAC calculation. The age feature operates similarly to the "time after reactor shutdown" field in the IAEA Excel tool.

2.3.5. Dose Limits

IAEA: The IAEA Excel tool calculates OILs using the default GC. The GC fields are editable for the predefined exposure periods.

FRMAC: Turbo FRMAC calculates DRLs using the default PAGs. The PAGs are editable should alternative dose limits be used.

2.3.6. Exposure Periods

IAEA: The IAEA Excel tool assumes an exposure period of 7 days or 1 year in accordance with the relevant GC. These exposure periods are addressed in the tool for precalculated integrated external ground dose rate weathering and resuspension factors that also consider decay for the radionuclides included in the tool. Using the tool for any other exposure period requires the user to separately integrate these factors.

FRMAC: Turbo FRMAC provides default exposure periods (also referred to as time phases) of 4 days, 1st year, 2nd year, and 50 years after a release in accordance with the relevant PAG.[2] However, doses and DRLs can be calculated for any exposure period of interest. Additionally, Turbo FRMAC can support several exposure periods in a single calculation.

2.3.7. Exposure Pathways

IAEA: The IAEA Excel tool uses four exposure pathways to calculate OIL1 and OIL2 – groundshine, inhalation of resuspended material, external exposure to resuspended material (i.e., "airshine"), and inadvertent soil ingestion. The IAEA does not include external and internal dose from exposure to a plume of radioactive material "since the response actions to protect the public from these exposure pathways needs to be triggered by the emergency classification system to be effective and not by monitoring results" [2]. All four exposure pathways are always included.

FRMAC: Turbo FRMAC Public Protection DRL and Projected Public Dose calculations can include any combination of four exposure pathways – plume submersion, plume inhalation, groundshine, and inhalation of resuspended material. Inadvertent soil ingestion dose is not included in DRL calculations but can be calculated using a separate calculation. The FRMAC Assessment Manual states that dose from this pathway should be included if it exceeds 10% of the appropriate PAG [5].

Table 2-1 provides a comparison of the exposure pathways considered by the IAEA and FRMAC.

[2] EPA removed the 50-year PAG in the 2017 PAG Manual but it is retained in Turbo FRMAC.

Table 2-1. Comparison of Exposure Pathways Considered by IAEA and FRMAC

Exposure Pathway	IAEA	FRMAC
Inhalation of plume-borne material		X
External exposure from plume submersion		X
External exposure from deposited material (groundshine)	X	X
Inhalation of resuspended material	X	X
External exposure from resuspended material	X	
Inadvertent ingestion of contaminated soil	X	Considered separately as needed

2.3.8. Dose Coefficients

IAEA: The IAEA Excel tool includes dose coefficients for the specific exposure pathways, age groups, and organs defined by the GC. These dose coefficients make inherent assumptions regarding International Commission on Radiological Protection (ICRP) recommendation basis and lung clearance type. Changes to these assumptions must be manually applied by adjusting each coefficient for each radionuclide, i.e., changes cannot be universally applied to the radionuclide mixture.

EPR-NPP-OILs 2017 references U.S. EPA Federal Guidance Report No. 12 (FGR 12) for adult external dose coefficients [15]. FGR 12 values are based on ICRP 30 tissue weighting factors for effective dose equivalent [16]. The IAEA notes that FGR 12 "uses the legacy unit 'effective dose equivalent', which is equivalent to the effective dose from external exposure."[3] Because external dose coefficients are not available for non-adult age groups, the IAEA uses a scaling factor of 1.4 for infant groundshine and submersion dose and 0.9 for fetus groundshine dose and 0.8 for fetus airshine dose.

For infant and adult inhalation and ingestion dose coefficients, EPR-NPP-OILs 2017 references IAEA GSR Part 3 [17], which includes tables of dose coefficients from ICRP Publication 119 [18]. This publication follows ICRP 60 recommendations. For fetus inhalation and ingestion dose coefficients, EPR-NPP-OILs 2017 references ICRP Publication 88 [19] and uses "the value that gives the highest embryo or fetus organ dose for both acute and chronic inhalation." This publication follows ICRP 60 recommendations. Fetus dose coefficients are not provided for all radionuclides, so the IAEA uses "the one year committed equivalent dose to the uterus of an adult" for radionuclides missing fetus dose coefficients.

FRMAC: Turbo FRMAC uses dose coefficients from the underlying DCFPAK database for the specified ICRP recommendation basis (ICRP 30 or ICRP 60 [20]) and lung clearance type. FRMAC defaults to ICRP 60 recommendations based on the EPA PAG Manual [3], however calculations can easily use ICRP 30 based dose coefficients using a single selection in the software.

[3] "Effective dose equivalent" and "effective dose" are conceptually equivalent but use different tissue weighting factors for estimating the overall health risk from uniform whole body irradiation. This means external dose estimates using FGR 12 (ICRP 30 based) dose coefficients versus newer dose coefficients based on ICRP 60 could be different.

Doses can be calculated for any of the six standard ICRP age groups if the dose coefficient data is available.[4] The standard ICRP age groups are the 3 month, 1 year, 5 year, 10 year, 15 year, and adult [21]. Dose coefficients for the fetus are not currently available in DCFPAK. Doses can be calculated for any of 33 provided organs, but DRLs are only calculated for the organs for which PAGs have historically been provided (whole body, thyroid, and skin). Additionally, age groups and organs cannot be combined in a single projected dose or DRL calculation.

2.3.9. Chemical/Physical Form

IAEA: The IAEA Excel tool does not account for modeling differences for elements that potentially exist as multiple chemical/physical forms.

FRMAC: As a default approach FRMAC considers all radionuclides to be present in the particulate physical form. However, if incident-specific information indicates that one or more radionuclides may exist in different chemical/physical forms, they can be modeled accordingly by partitioning and using the appropriate inhalation and ingestion dose coefficients. For example, Turbo FRMAC partitions the total iodine in an NPP type mixture to 45% methyl iodide, 30% iodine vapor, and 25% particulate, following NRC methodology [12]. Each form uses the appropriate dose coefficient from the DCFPAK database and can also be assigned a specific deposition velocity.

2.3.10. Lung Clearance Type

IAEA: The IAEA Excel tool inherently uses the maximum lung clearance type because of the included inhalation dose coefficients. This assumption cannot be universally changed and must be manually adjusted by changing each radionuclide-specific dose coefficient.

FRMAC: Turbo FRMAC defaults to the ICRP Recommended lung clearance type for all radionuclides, but this assumption can be universally changed for all radionuclides in a calculation or can also be specified by radionuclide.

2.3.11. Particle Size Distribution

IAEA: The IAEA Excel tool inherently assumes a monodispersed particle size of 1-micron AMAD because of the included inhalation dose coefficients. This assumption cannot be universally changed and must be manually adjusted by changing each radionuclide-specific dose coefficient. Alternate particle size distributions can somewhat be accounted for by adjusting a respirable fraction input.

FRMAC: Turbo FRMAC also defaults to a monodispersed particle size of 1-micron AMAD, but this assumption can be universally changed for all radionuclides in a calculation or can also be specified by radionuclide. The inhalation dose coefficients are then recalculated accordingly using DCFPAK [11].

2.3.12. Resuspension Factor

IAEA: The IAEA Excel tool accounts for resuspension using precalculated integrated resuspension factors for the 7-day and 1-year exposure periods. The default resuspension model is based on the National Council on Radiation Protection Measurements (NCRP) Report No. 129 method [22]

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[4] Inhalation and ingestion dose coefficients are age-specific and external (plume submersion and deposition external) dose coefficients are available for adults only. Age-specific external dose coefficients have recently been made available in U.S. EPA Federal Guidance Report No. 15 (2019) but are not yet incorporated into DCFPAK and therefore cannot be used by Turbo FRMAC at this time.

using a start value of 10^{-5} m^{-1}. Use of any other resuspension model is difficult in the tool because the tool itself does not integrate the model over the exposure period of interest.

FRMAC: Turbo FRMAC provides three time-varying resuspension models (Maxwell and Anspaugh 2011 (default) [23], NCRP 129 [22], and WASH-1400 [8]), as well as allows a constant resuspension factor. The parameters of each model are editable. Turbo FRMAC integrates the specified model over the exposure period of interest, considering decay and weathering.

2.3.13. Breathing Rates

IAEA: The IAEA Excel tool provides a single breathing rate for calculating dose from inhalation of resuspended material. The provided default is 1.2 m^3/h [24] and the input is editable.

FRMAC: Turbo FRMAC provides default breathing rates for the six standard ICRP age groups and for four activity types – sleeping, sitting, light exercise, and heavy exercise [25]. The light exercise breathing rate is used to calculate dose from inhalation of the plume. The FRMAC default for light exercise breathing rate is 1.5 m^3/h. The number of hours in a day spent performing each activity type up to 24 hours is used to calculate an activity-averaged breathing rate. The activity-averaged breathing rate is used to calculate dose from inhalation of resuspended material. The FRMAC default for activity-averaged breathing rate is 0.92 m^3/h. The age-specific and activity-specific breathing rates in Turbo FRMAC are all editable, as is the number of hours spent performing a given activity type.

2.3.14. Weathering Factor

IAEA: The IAEA Excel tool accounts for weathering using precalculated integrated weathering factors for the 7-day and 1-year exposure periods. The default weathering model is based on WASH-1400 [8]. The exponent coefficients for this model are adjustable in the tool. Use of any other weathering model is difficult in the tool because the tool itself does not integrate the model over the exposure period of interest.

FRMAC: Turbo FRMAC provides two time-varying weathering models (Anspaugh 2002 (default) [26] and WASH-1400 [8]). The parameters of both of these models are editable. Turbo FRMAC integrates the specified model over the exposure period of interest, considering decay and weathering.

2.3.15. Ground Roughness Factor

IAEA: The IAEA Excel tool assumes a ground roughness factor of 0.7 [15] to account for groundshine dose rate reduction due to ground roughness. This is an editable input.

FRMAC: Turbo FRMAC assumes a ground roughness factor of 0.82 [26] to account for groundshine dose rate reduction due to ground roughness. This is an editable input.

2.3.16. Occupancy and Sheltering

IAEA: The IAEA Excel tool assumes a default building occupancy fraction of 0.6 and a building protection factor of 0.4. These are editable inputs.

FRMAC: Default FRMAC methodology assumes that the receptor is outdoors in the contaminated area continuously during the time phase under consideration. However, Turbo FRMAC does allow users to specify what fraction of the exposure period is spent outdoors in a contaminated area versus indoors in a contaminated area (referred to as occupancy factors), as well as building protection factors for time spent indoors in a contaminated area.

2.3.17. Instrument Response

IAEA: OILs and DRLs are meant to be compared with monitoring results provided by instruments. OIL1 and OIL2 are dose rates calculated in terms of ambient dose equivalent rate 1 m above ground level for a specified time after reactor shutdown. This quantity is based on the effective dose rate to the adult from an infinite smooth plane source per unit surface activity of a given radionuclide, the ground roughness factor of 0.7, and a scaling factor of 1.4 to convert the effective dose into ambient dose equivalent "for the photon energies of concern." The scaling factor is based on ICRP 74 [27] and is an editable input.

FRMAC: Dose Rate DRLs use a similar quantity called a deposition external dose factor to relate a dose rate measurement from a survey instrument one meter above the ground to the projected dose from the deposited mixture relative to the PAG. This factor is obtained by multiplying the areal activity of each radionuclide by the associated deposition external dose coefficient modified by the ground roughness factor of 0.82 and the time-adjusted weathering factor described above. Additionally, Turbo FRMAC calculates exposure rate DRLs using an editable exposure to dose conversion factor, which is a default value of 1 mrem/mR.

It is important to note a primary difference between OILs and DRLs with respect to instrument response: IAEA uses the same relative activities in calculating both instrument response and projected dose, which is ratioed to the GC. Therefore, the OILs are calculated for the time at which the release occurs relative to reactor shutdown and are not adjusted to account for decay and in-growth after the release, which could be significant for fission product mixtures like those from nuclear power plant accidents. In other words, OILs are only calculated for an evaluation time of zero. DRLs can be calculated for any evaluation time, and therefore can reflect expected decay and in-growth effects on field measurements.

2.4. Comparison Summary

A summary of the technical assumptions described in detail in Section 2.3 is provided in Table 2-2. The implementation of these assumptions in IAEA's and FRMAC's respective tools is summarized in Table 2-3. This initial comparison work shows that Turbo FRMAC is better suited to calculate custom DRLs and doses for exposure periods and radionuclides other than those included in the IAEA Excel tool by default.

Table 2-2. Comparison of IAEA and FRMAC Default Assumptions

Input	IAEA	U.S.
Time Phase	OIL1 – Urgent (Avoidable Dose): 0-168 hours OIL2 – Early (1st Year): 0-365 days	Early Phase (Total Dose): 0-96 hours Early Phase (Avoidable Dose): 12-108 hours 1st Year: 12-8772 hours 2nd Year: 365-730 days
PAG/Generic Criteria	OIL1&2: 0.1 Sv	Early: 0.01 Sv 1st Year: 0.02 Sv 2nd Year: 0.005 Sv
Receptor	Representative Person (Adult + Infant combination) and Fetus	Adult
Dose Pathways	Groundshine, Resuspension Inhalation, Airshine, Inadvertent Soil Ingestion	Plume Inhalation, Plume Submersion, Resuspension Inhalation, Groundshine
Dosimetry Model	ICRP 30 for external and ICRP 60 for internal	ICRP 60 for external and internal
Breathing Rate	1.2 m^3/h	Plume: 1.5 m^3/h Resuspension: 0.92 m^3/h
Deposition Velocity	Only addresses ground pathways, so does not specify	Iodine: 6.5E-03 m/s Particulate: 3.0E-03 m/s Noble gases: 0 m/s
Building Protection Factors	2.5 for Groundshine	None
Exposure-to-Dose Conversion Factor	0.714 mrem/mR	1 mrem/mR
Ground Roughness Factor	0.7	0.82
Lung Clearance Type	Maximum	ICRP Recommended
Occupancy Factor	0.6 for inside, 0.4 for outside	None
Particle Size Distribution	1 µm AMAD	1 µm AMAD
Resuspension Factor	NCRP 129, Start Value = 1.00E-05 m^{-1}	Maxwell-Anspaugh 2011
Weathering Factor	WASH 1400	Anspaugh 2002

Table 2-3. Comparison of IAEA Excel Tool and Turbo FRMAC Features

Input	IAEA Excel Tool	Turbo FRMAC
Calculational output	Calculates ambient dose equivalent rate	Calculates radionuclide-specific integrated air and deposition concentrations, alpha and beta integrated air and deposition concentrations, and dose and exposure rate. Also calculates projected doses
Radionuclide inventories	Includes pre-determined list of light water reactor radionuclides	Supports any mixture of radionuclides available in DCFPAK
Release fractions	Includes 19 sets of release fractions for nuclear reactor and spent fuel accidents	Does not include release fractions. Mixtures used in calculations must already have release fractions applied
Radionuclide concentrations	Uses relative activities of released radionuclides	Allows mixtures in units of integrated air concentrations, ground concentrations, or both
Decay and in-growth	Performs decay for pre-determined list of light water reactor radionuclides. Does not handle in-growth	Models decay and in-growth for mixtures using the Bateman equations
Dose limits	Includes editable fields for generic criteria	Includes editable fields for protective action guides
Exposure periods	Assumes exposure period of 7 days or 1 year in accordance with the relevant generic criteria. This exposure period is built into precalculated integrated external ground dose rate weathering and resuspension factors	Provides default exposure periods in accordance with the relevant protective action guide, and can also calculate doses and DRLs for any user-defined exposure period of interest, including several in a single calculation
Exposure pathways	Four exposure pathways always included – groundshine, inhalation of resuspended material, external exposure to resuspended material, and inadvertent soil ingestion	Supports any combination of four exposure pathways – plume submersion, plume inhalation, groundshine, and inhalation of resuspended material
Dose coefficients	Includes dose coefficients for the specific exposure pathways, age groups, and organs defined by the generic criteria. Dose coefficients for radionuclides other than the predefined mixture must be manually added	Uses DCFPAK database to call dose coefficients for radionuclides in the specified mixture
Chemical/physical form	Does not account for modeling differences due to chemical/physical form	Allows for special dose coefficients and deposition velocities for non-particulate forms, as well as supports elemental partitioning

Input	IAEA Excel Tool	Turbo FRMAC
Lung clearance type	Inherently assumes Maximum lung clearance type based on included inhalation dose coefficients	Allows user to select lung clearance type for all or individual radionuclides in a calculation without having to provide the specific dose coefficient value
Particle size distribution	Inherently assumes 1-micron AMAD particle size based on included inhalation dose coefficients	Allows user to specify particle size distribution and calculates inhalation dose coefficient accordingly
Resuspension factor	Uses precalculated resuspension factors for the 7-days and 1-year exposure periods	Provides three time-varying and one constant resuspension model with editable parameters
Breathing rates	Includes editable field for single breathing rate	Includes editable fields for age-specific and activity-specific breathing rates
Weathering factor	Uses precalculated integrated weathering factors for the 7-day and 1-year exposure periods. Weathering model is not easily editable	Provides two time-varying weathering models with editable parameters
Ground roughness factor	Includes editable field for ground roughness factor	Includes editable field for ground roughness factor
Occupancy and sheltering	Includes editable fields for occupancy fractions and shielding factors	Includes editable fields for occupancy fractions and building protection factors
Instrument response	Includes editable field for scaling factor to convert the effective dose into ambient dose equivalent	Calculates a deposition external dose factor using the editable inputs used to calculate groundshine dose

2.5. Potential Turbo FRMAC Modifications

A Turbo FRMAC OIL calculation could be used to facilitate the revision of the default OILs to consider different underlying assumptions than those used by the IAEA. The following modifications must be made to Turbo FRMAC in order to perform exact implementation of the IAEA OIL1 and OIL2 calculations as documented in EPR-NPP-OILs 2017:

- Remove plume submersion and plume inhalation exposure pathways
- Limit evaluation time to zero
- Limit radionuclide mixture to be specified by ground concentration
- Limit radionuclide form to particulate
- Add exposure pathway for external exposure to resuspended material (i.e., airshine)
- Add exposure pathway for inadvertent soil ingestion
  - Add input for inadvertent soil ingestion intake rate
- Combine ICRP methodologies for respective exposure pathways (e.g., ICRP 30 for external and ICRP 60 for internal)[5]
- Calculate effective dose to the representative person
  - Combine infant (1 year old) and adult age groups for respective exposure pathways
  - Add a scaling factor input for converting the adult groundshine effective dose to infant
  - Add a scaling factor input for converting the adult airshine effective dose to infant
- Calculate equivalent dose to the fetus
  - Add a scaling factor input for converting the adult groundshine red marrow dose coefficient to fetus groundshine
  - Add a scaling factor input for converting the adult airshine red marrow dose coefficient to fetus airshine
  - Include fetus ingestion and inhalation dose coefficients from ICRP 88
  - Use adult uterus dose ingestion and inhalation dose coefficients for radionuclides that are not included in ICRP 88
- Add weighting factor input for each OIL
- Provide the minimum of the OIL calculated using the effective dose to the representative person and the OIL calculated using the equivalent dose to the fetus
- Limit output to dose/exposure rate
- Limit output to representative person and fetus age groups
- Limit output to total effective dose (i.e., "whole body" organ)

[5] Turbo FRMAC currently does not easily accommodate the use of two ICRP frameworks at once. The author is interested to know if the IAEA would use ICRP 60 external dose coefficients from DCFPAK, which would allow for one ICRP framework to be used.

3. BENCHMARKING STUDIES

The IAEA Excel tool and Turbo FRMAC were used to calculate custom OILs in order to assess Turbo FRMAC's ability to perform these calculations and better understand the IAEA OIL methodology. The term "custom" is used to differentiate from the default OILs provided by IAEA. An NPP source term from EPR-NPP-OILs 2017 was analyzed, as well as radionuclides of concern for potential use in a radiological dispersal device (RDD). Turbo FRMAC was used to determine the relative contribution of each exposure pathway to total dose for the representative person and the fetus. This information is difficult to derive from the IAEA Excel tool because of the way it is structured.

In addition to this analysis, Turbo FRMAC was used to calculate DRLs using IAEA assumptions where possible by manually adjusting calculation inputs. The DRLs were compared to the OILs calculated using the IAEA Excel tool in order to determine the importance of the potential modifications needed for Turbo FRMAC to calculate OILs according to IAEA guidance, as detailed in Section 2.5.

3.1. Nuclear Power Plant Release Scenario

3.1.1. NPP OIL Calculations

OIL1 and OIL2 were calculated for "Mix 1" from EPR-NPP-OILs 2017 using the IAEA Excel tool and Turbo FRMAC. Mix 1 is a postulated core to containment release scenario based on a release during the gap release phase of fuel damage for a pressurized water reactor or boiling water reactor with "standard fuel." The released activity for Mix 1, considering fuel inventory and release fraction, is shown in Table 3-1. Note, only radionuclides with non-zero released activity are shown in Table 3-1, but the IAEA includes more radionuclides in its Excel tool.

Table 3-1. Released Activity at 30 minutes After Reactor Shutdown[6]

Radionuclide	Released Activity (Bq)
Cs-134	1.39E+16
Cs-136	5.55E+15
Cs-137+	8.70E+15
I-131	1.58E+17
I-133	3.15E+17
I-134	3.52E+17
I-135	2.78E+17
Rb-86	4.81E+13

The time-dependent OIL1 and OIL2 are shown in Figure 3-1 and Figure 3-2, respectively, along with the default OILs to be used at the start of a response. The default OILs shown in Figure 3-1 and Figure 3-2 were selected by the IAEA as a bounding case considering custom OILs calculated for each of the radionuclide mixtures addressed in EPR-NPP-OILs 2017.

[6] The progeny of radionuclides marked with "+" are assumed to be in equilibrium with the parent.

The figures also show which receptor, representative person or fetus, is more restrictive at each point in time. For OIL1, the fetus is initially more restrictive until the release occurs around 40 days after reactor shutdown, at which point the representative person is more restrictive. For OIL2, the fetus is initially more restrictive than the representative though only marginally so, then the representative person is more restrictive beyond the first 12 hours.

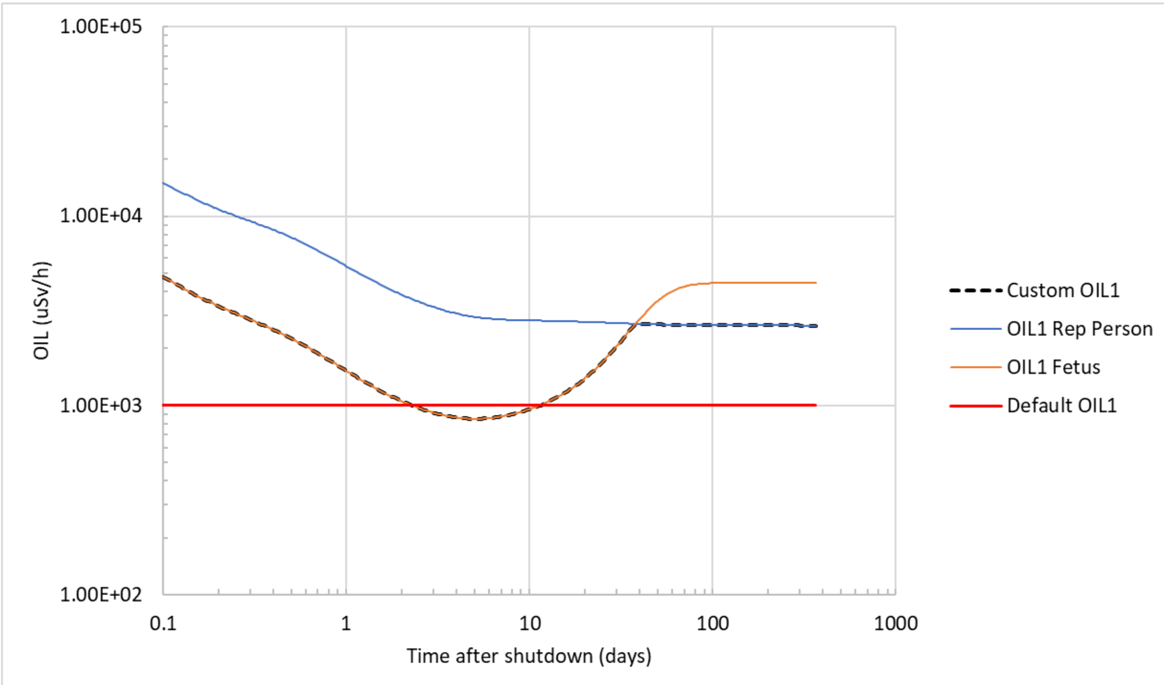

Figure 3-1. Default and Custom OIL1 for an NPP Release Scenario

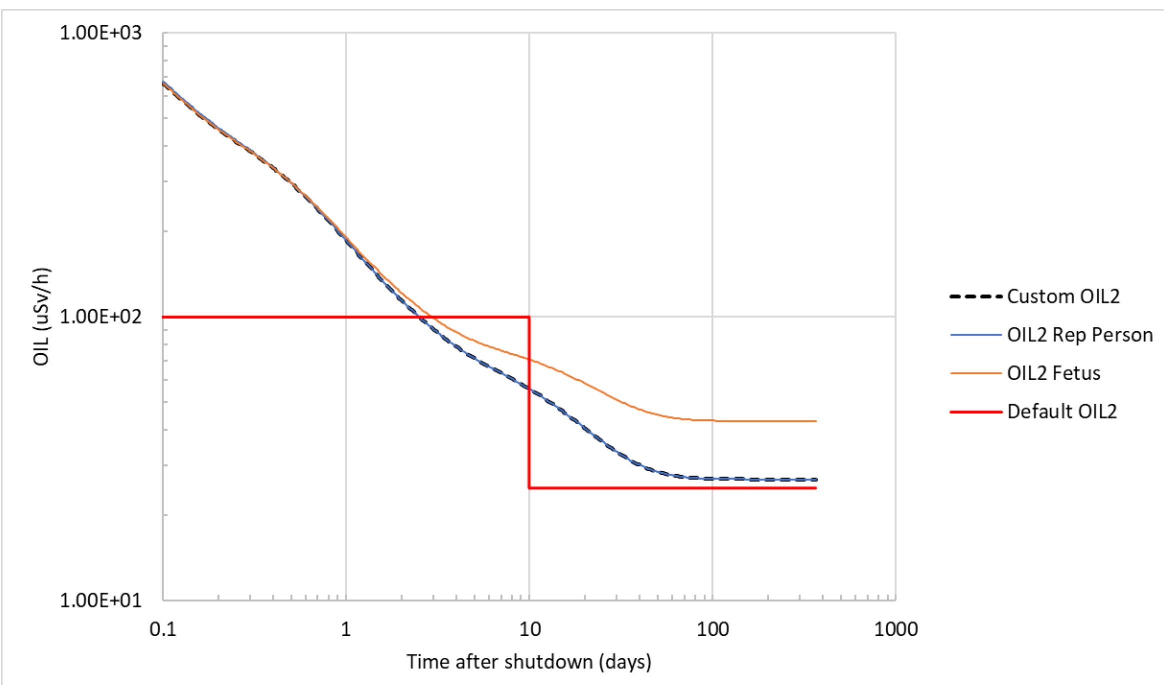

Figure 3-2. Default and Custom OIL2 for an NPP Release Scenario

Table 3-2 provides the percent of total dose contributed by each exposure pathway for the urgent (7 days) and early (first year) phases for the mixture provided in Table 3-1, applicable at 30 minutes after reactor shutdown. This information is also shown in Figure 3-3 and Figure 3-4. Groundshine drives total dose for the representative person for both phases. However, resuspension inhalation drives total dose for the fetus for the urgent phase and contributes significantly, in addition to groundshine, to total dose during the early phase. Resuspension inhalation dose to the fetus is driven by radioiodine inhalation, as iodines comprise most of the radionuclide mixture for this scenario. The inhalation dose coefficients used for the fetus are based on inhalation by the pregnant woman carrying the fetus. The IAEA uses dose coefficients from ICRP 88 [37] that are orders of magnitude larger than the dose coefficients for groundshine exposure.

Table 3-2. Exposure Pathway Contributions for an NPP Release Scenario

Phase	Receptor	Groundshine	Resuspension Inhalation	Airshine	Inadvertent Soil Ingestion
Urgent (7 days)	Representative Person	89%	2%	0%	9%
	Fetus	18%	73%	0%	9%
Early (1 year)	Representative Person	98%	1%	0%	1%
	Fetus	60%	36%	0%	4%

The IAEA states in EPR-NPP-OILs 2017 that use of newer resuspension models than the default, NCRP 129, "has little impact on the OIL values for the LWRs" [2]. Figure 3-3 and Figure 3-4 indicate the contrary, that resuspension inhalation dose could be a significant contribution to total dose and therefore choice of resuspension model is important.

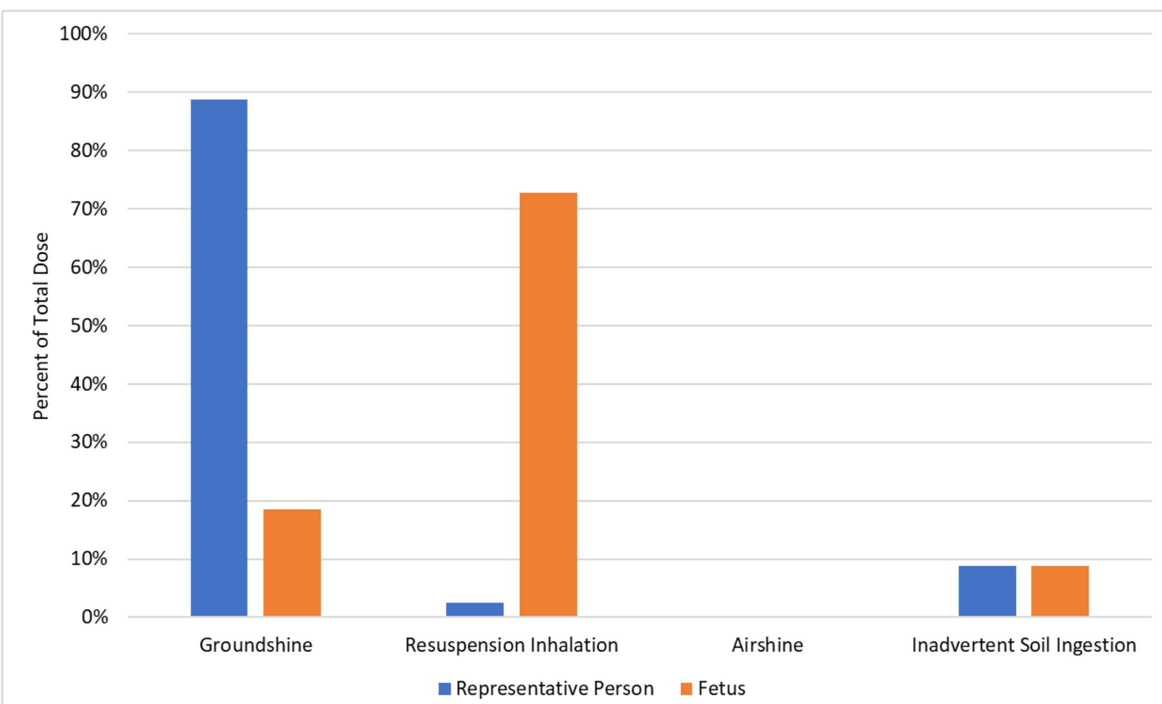

Figure 3-3. Urgent Phase Exposure Pathway Contributions for an NPP Release Scenario

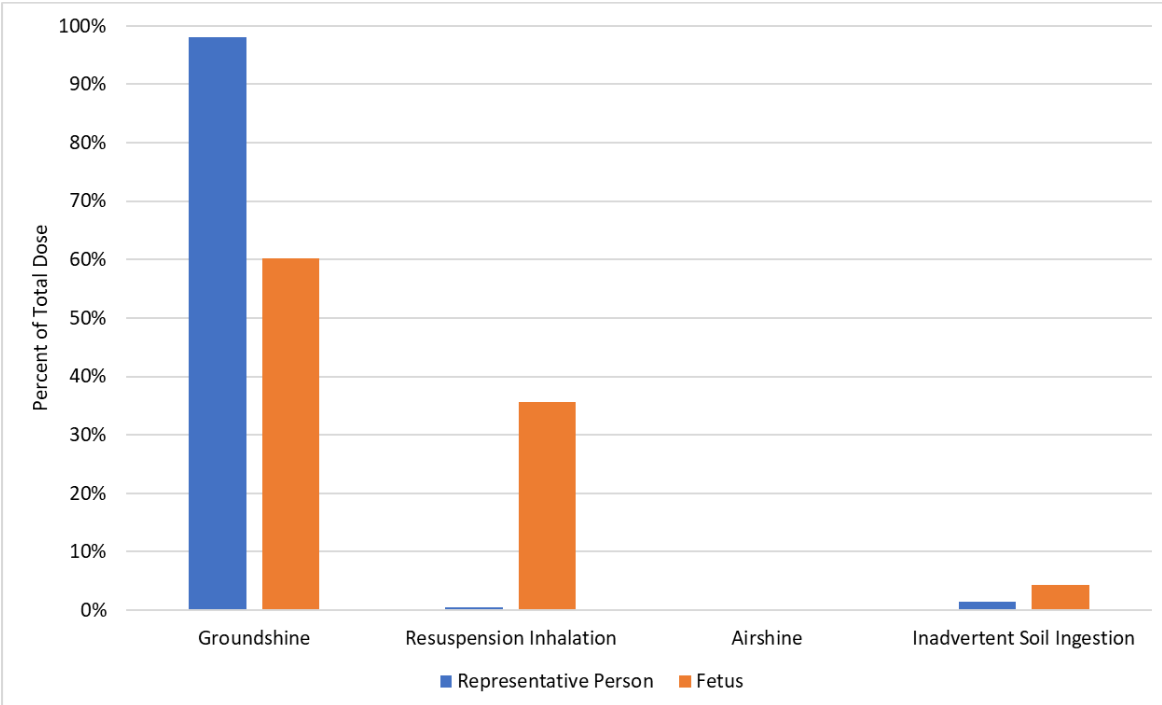

Figure 3-4. Early Phase Exposure Pathway Contributions for an NPP Release Scenario

The iodines are shorter lived than the cesiums which comprise most of the remaining activity for the mixture provided in Table 3-1. As time after shutdown increases, the iodines will decay away, leaving cesiums to contribute the majority of dose. In this case, it is expected that resuspension inhalation dose will decrease relative to groundshine. Therefore, OIL1 for the fetus initially decreases, but then increases as more time passes after reactor shutdown, as shown in Figure 3-1.

3.1.2. NPP DRL Comparison

Figure 3-5 and Figure 3-6 includes Dose Rate DRLs for urgent phase and early phase, respectively. The DRLs were calculated using Turbo FRMAC using IAEA assumptions where possible. Figure 3-6 shows that Turbo FRMAC can reasonably replicate IAEA OIL2 where most of the dose comes from groundshine, as shown in Table 3-2. The difference between the DRLs and the OILs generated using the IAEA Excel tool can be attributed to a few factors that Turbo FRMAC 2019 cannot accommodate:

- OIL1 is initially driven by fetus dose, which Turbo FRMAC cannot calculate, resulting in a larger DRL.
- IAEA includes a scaling factor of 1.4 for infant effective dose from groundshine and airshine for the representative person. Turbo FRMAC does not, resulting in a larger DRL.
- IAEA includes a scaling factor of 1.4 for instrument response. Turbo FRMAC does not, resulting in a smaller DRL.
- IAEA includes a weighting factor of 3 for OIL1. Turbo FRMAC does not, resulting in a smaller DRL by a factor of 3 when dose to the representative person drives OIL1.

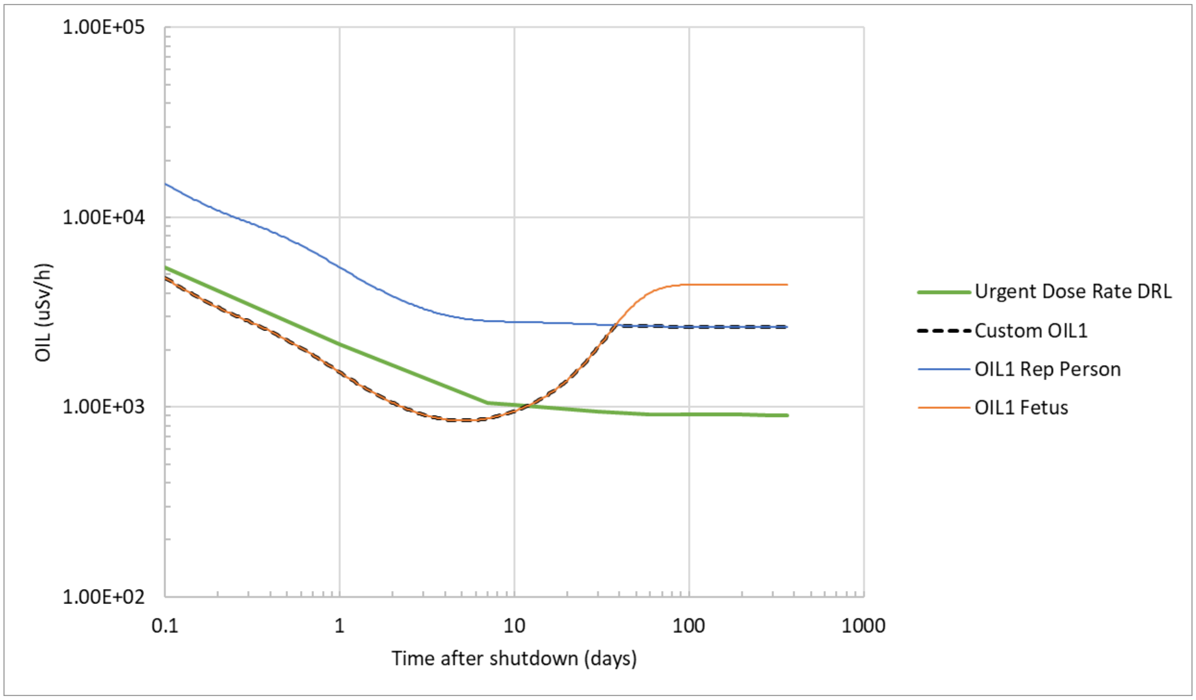

Figure 3-5. DRL and OILs for an NPP Release Scenario, Urgent Phase

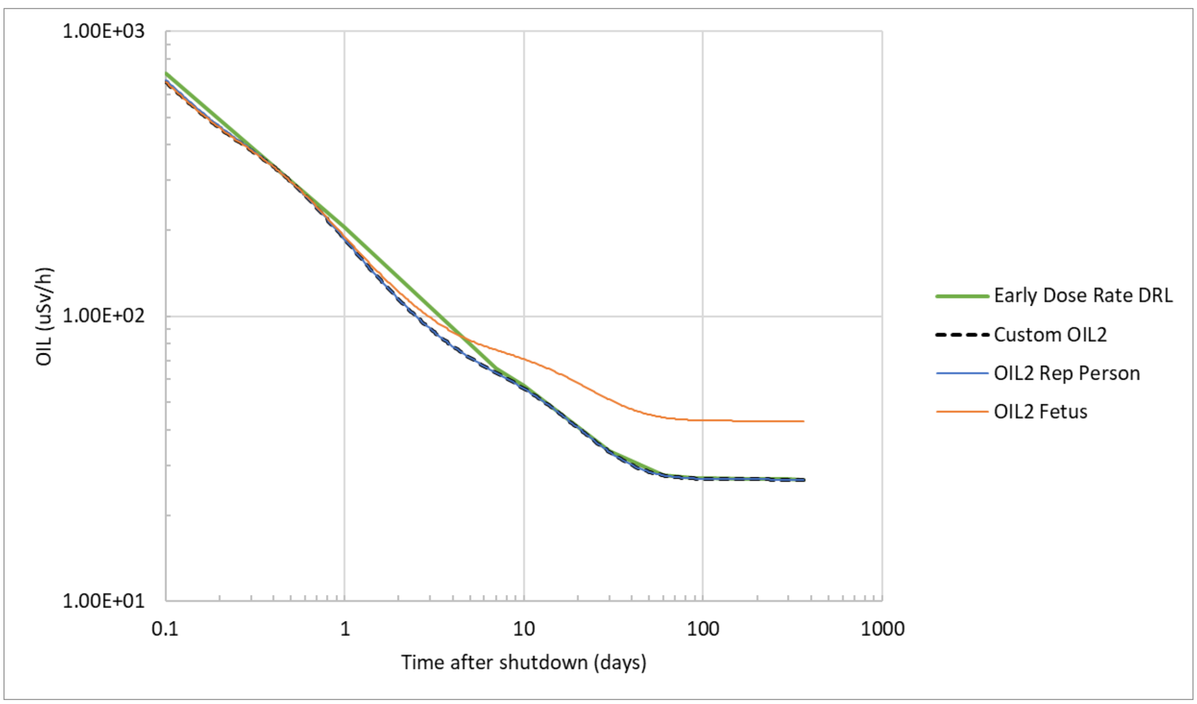

Figure 3-6. DRL and OILs for an NPP Release Scenario, Early Phase

3.2. Radiological Dispersal Device Scenario

3.2.1. RDD OIL Calculations

OIL calculations were performed for radionuclides of concern for potential use in an RDD [28]. The resulting OILs were compared to the default OILs provided for LWR accidents. The radionuclides selected were Americium-241 (Am-241) (alpha emitter), Cesium-137 (Cs-137) (beta-gamma emitter), and Strontium-90 (Sr-90) (beta emitter). These radionuclides are also already included in the IAEA Excel tool so significant modification of the tool was not needed for this analysis. The Cs-137 and Sr-90 scenarios assume Ba-137m and Y-90 progeny, respectively, are present in equilibrium.

OIL1 and OIL2 were calculated for separate releases of Am-241, Cs-137, and Sr-90 using the IAEA Excel tool and Turbo FRMAC. The OILs are shown in Table 3-3 along with the default OILs derived for LWRs. Note, the default OIL for the early phase is 100 µSv/h for the first 10 days after reactor shutdown and 25 µSv/h later than 10 days after reactor shutdown or for spent fuel, as noted in Section 2.2.1. The applicability of this two-step OIL to radiological incidents is not clear from EPR-NPP-OILs 2017 but is included here for comparison anyway.

Table 3-3. Custom and Default OILs for an RDD Scenario

Phase	Radionuclide	Custom OIL (µSv/h)	Default OIL (µSv/h)		Default/Custom	
Urgent (7 days)	Am-241	0.357	1000		2.80E+03	
	Cs-137+	2.42E+03			0.413	
	Sr-90+	33.6			29.8	
Early (1 year)	Am-241	5.05E-02	100	25	1.98E+03	4.96E+02
	Cs-137+	23.9	100	25	4.18	1.04
	Sr-90+	4.33	100	25	23.1	5.77

Table 3-4 and Table 3-5 provide the percent of total dose contributed by each exposure pathway for the representative person and the fetus, respectively. This information is also shown in Figure 3-7 through Figure 3-10.

Table 3-4. Exposure Pathway Contributions for the Representative Person for an RDD Scenario

Phase	Radionuclide	Groundshine	Resuspension Inhalation	Airshine	Inadvertent Soil Ingestion
Urgent (7 days)	Am-241	0%	100%	0%	0%
	Cs-137+	86%	13%	0%	1%
	Sr-90+	1%	88%	0%	11%
Early (1 year)	Am-241	0%	100%	0%	0%
	Cs-137+	99%	1%	0%	0%
	Sr-90+	18%	73%	0%	9%

Table 3-5. Exposure Pathway Contributions for the Fetus for an RDD Scenario

Phase	Radionuclide	Groundshine	Resuspension Inhalation	Airshine	Inadvertent Soil Ingestion
Urgent (7 days)	Am-241	0%	100%	0%	0%
	Cs-137+	98%	2%	0%	0%
	Sr-90+	1%	82%	0%	18%
Early (1 year)	Am-241	5%	95%	0%	0%
	Cs-137+	100%	0%	0%	0%
	Sr-90+	10%	74%	0%	16%

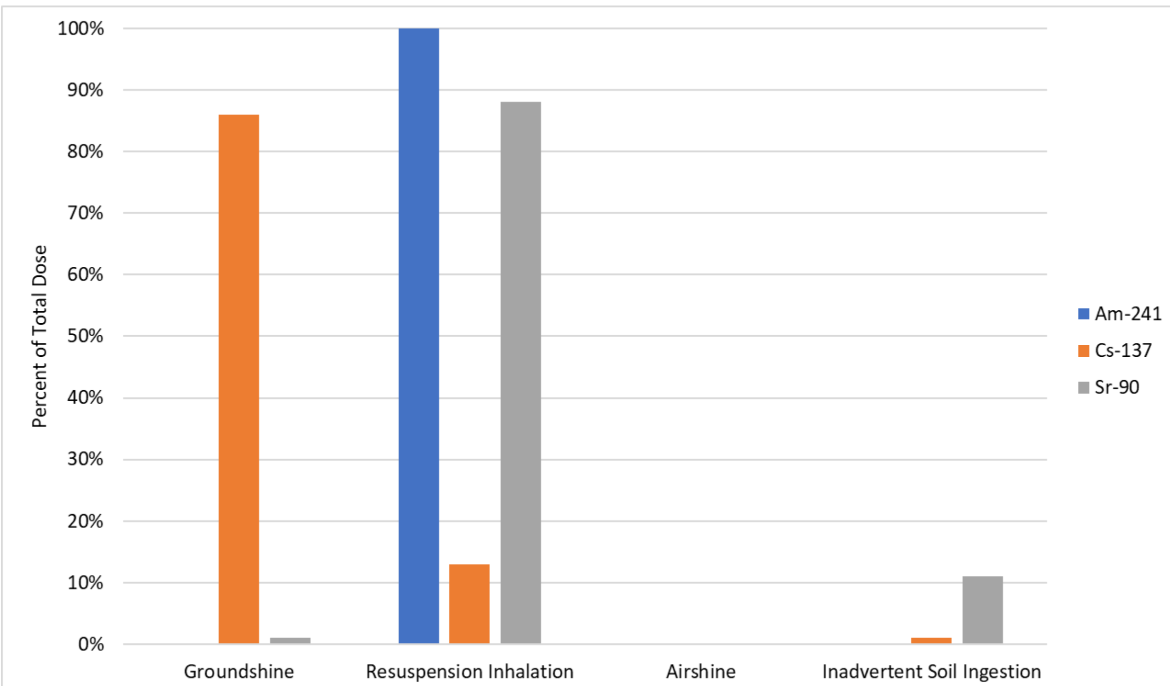

Figure 3-7. Urgent Phase Exposure Pathway Contributions for the Representative Person for an RDD Scenario

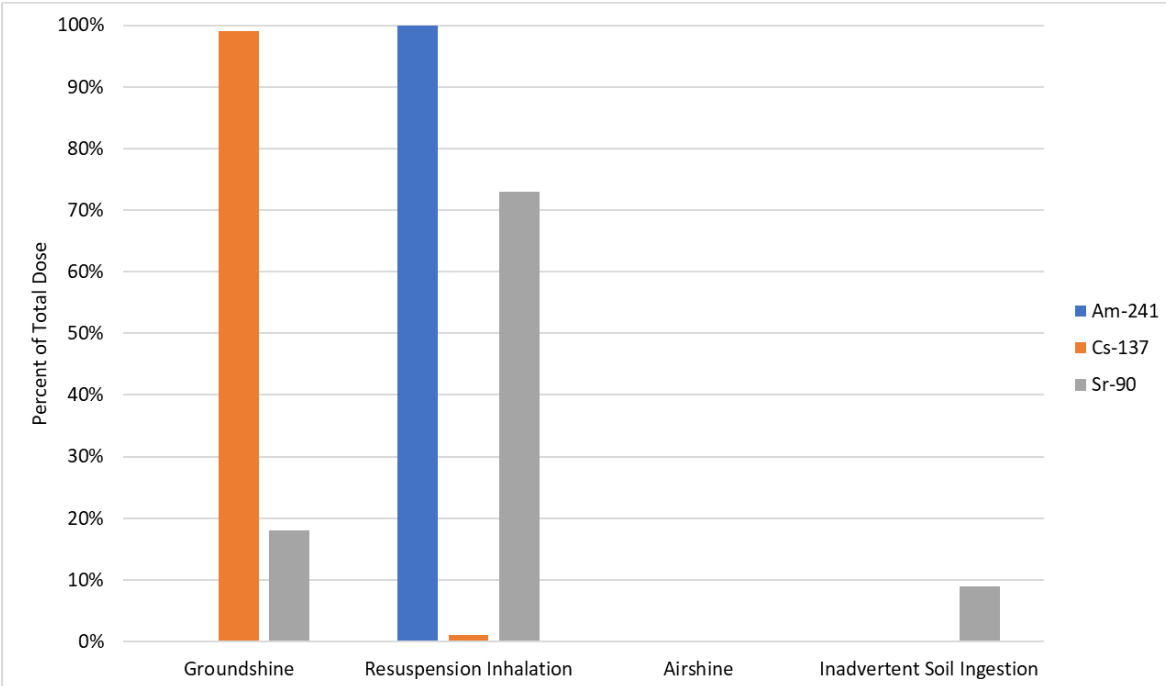

Figure 3-8. Early Phase Exposure Pathway Contributions for the Representative Person for an RDD Scenario

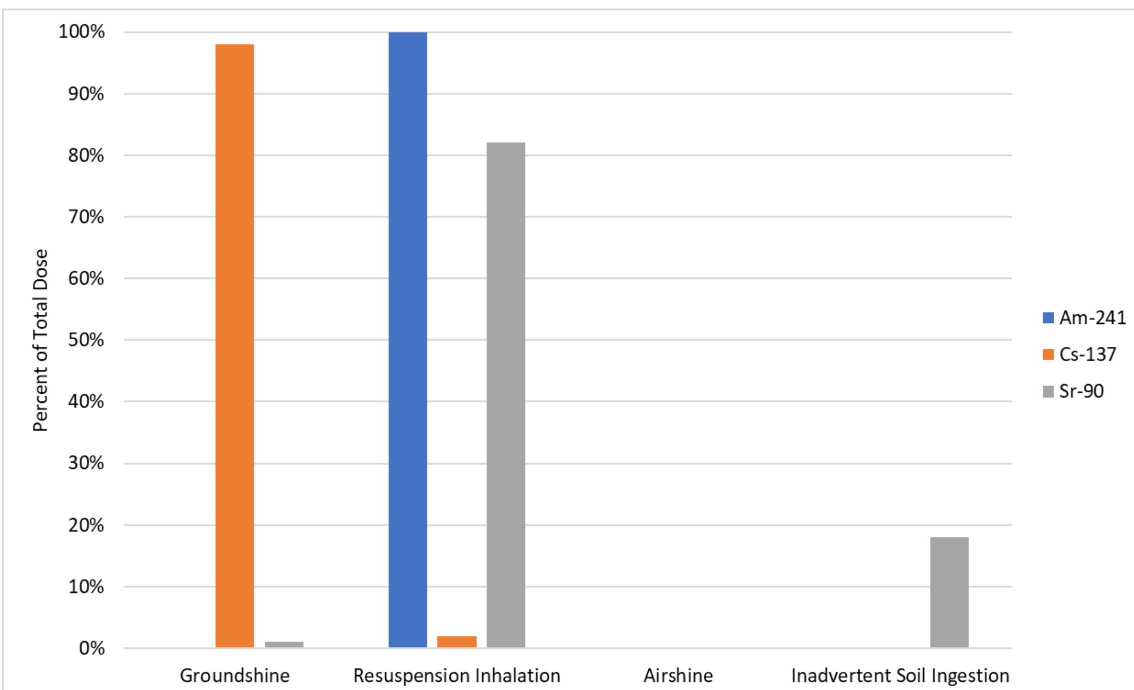

Figure 3-9. Urgent Phase Exposure Pathway Contributions for the Fetus for an RDD Scenario

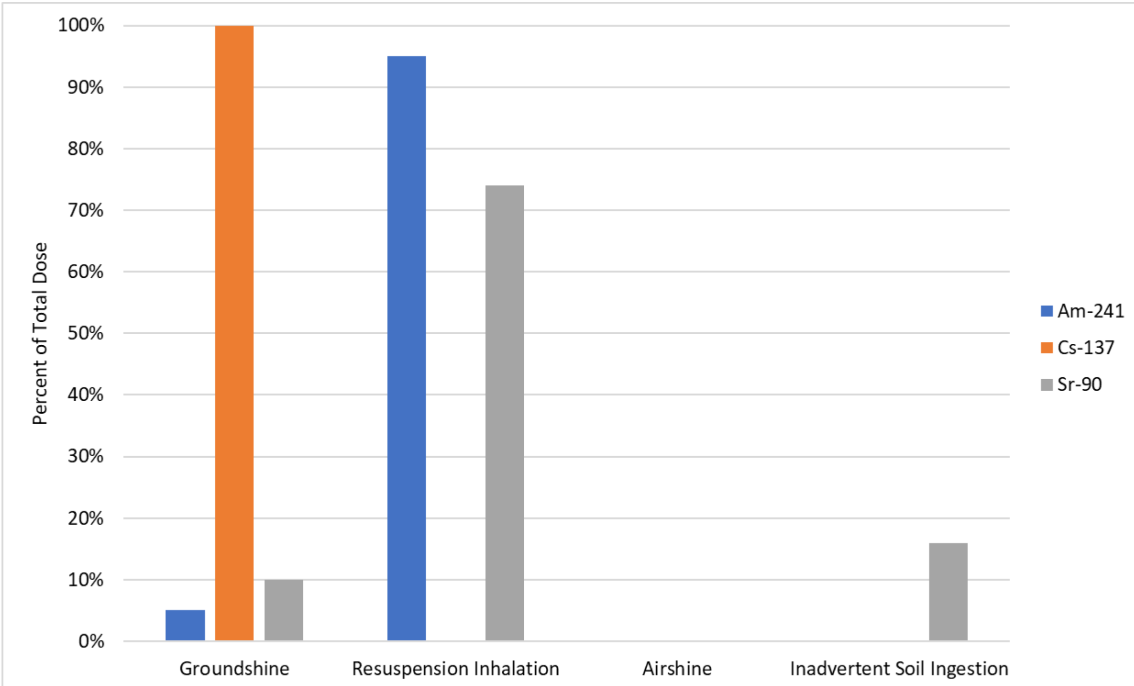

Figure 3-10. Early Phase Exposure Pathway Contributions for the Fetus for an RDD Scenario

Am-241: The dose to the representative person is more restrictive than that to the fetus. Total dose is driven by resuspension inhalation for both the representative person and the fetus. Also, the default OILs for an LWR release are over 1000 times greater than the custom OILs calculated for an Am-241 release. This demonstrates that the default LWR OILs would not be appropriate to apply for incident involving radioactive material for which internal dose is the primary exposure pathway. Additionally, the custom OILs for the Am-241 release are less than 1 μSv/h. EPR-NPP-OILs 2017 states that 1 μSv/h is "considered the lowest practical ambient dose equivalent rate to be used for ground monitoring under severe emergency conditions." For releases like Am-241 and other radionuclides with dose rates that are not easily detectable, OIL1 and OIL2 are not useful. The IAEA does not provide a methodology for calculating OILs for other measurement types such as alpha contamination.

Cs-137: The dose to the representative person is more restrictive than that to the fetus. The default OILs for an LWR release could be reasonably applied to a Cs-137 releases as the difference is within a factor of 10. This is because the primary exposure pathway for Cs-137 is groundshine, which also drives total dose for most LWR releases.

Sr-90: The dose to the representative person and the fetus are nearly the same for both urgent phase and early phase. The default OILs for an LWR release are over 20-30 times greater than the custom OILs calculated for a Sr-90 release. This is because resuspension inhalation dose is the dominant exposure pathway for Sr-90, similar to Am-241.

For each RDD scenario, airshine dose is negligible and dose from inadvertent soil ingestion is only significant for Sr-90, though contributes less than 10% of total dose for the representative person and less than 20% of total dose for the fetus.

Custom OILs are compared to the default OILs for an LWR release here, but it should be acknowledged that source term uncertainty with respect to released radionuclides and relative amount is expected to be lower for an RDD incident than for a large fission product release like that from an LWR accident. This could mean a dose assessor might have more confidence in calculation of a custom OIL for an RDD release than for an LWR release, for which default OILs are provided due to assumed uncertainty associated with the properties of a release (e.g., timing, isotopic mixture, etc.).

3.2.2. RDD DRL Comparison

Table 3-6 includes Dose Rate DRLs calculated for the urgent phase for Am-241, Cs-137, and Sr-90 independently. Time-dependent comparisons are not needed for RDD DRL calculations because there is only one parent radionuclide in the mixture and therefore relative concentrations do not rapidly change over time like for complex fission product mixtures.

Table 3-6. DRLs and OILs for an RDD Scenario

Phase	Radionuclide	OIL (µSv/h)	DRL (µSv/h)	OIL / DRL
Urgent (7 days)	Am-241	0.357	6.79E-02	5.26
	Cs-137+	2.42E+03	8.93E+02	2.71
	Sr-90+	33.6	4.68	7.17
Early (1 year)	Am-241	5.05E-02	2.90E-02	1.74
	Cs-137+	23.9	24.1	0.995
	Sr-90+	4.33	1.86	2.33

Turbo FRMAC DRLs for the urgent phase will always be low by a factor of 3 due to its inability to apply the IAEA weighting factor. Results can be manually multiplied by 3 to get closer to OIL1 as calculated by the IAEA Excel Tool. This difference aside, Turbo FRMAC DRLs are at most a factor of 2 low for the considered radionuclides.

Turbo FRMAC most closely recreates early phase OIL2 for Cs-137. This is because groundshine dose to the representative person (infant) drives the OIL. Although Turbo FRMAC lacks a scaling factor of 1.4 for infant effective dose from groundshine, this is balanced using a scaling factor of 1.4 for instrument response.

Turbo FRMAC DRLs are roughly half of the IAEA OIL for Am-241 and Sr-90 (disregarding the weighting factor of 3 for OIL1). The difference for Am-241 can be attributed to Turbo FRMAC's inability to combine ICRP 30 for the instrument response and ICRP 60 for the dose calculation. Current guidance for FRMAC Assessment Scientists is to use ICRP 30 by default for OIL-like DRL calculations because this is more accurate for the groundshine exposure driven NPP scenarios upon which IAEA guidance is based. This means Am-241 dose projections are off by both the difference between ICRP 30 and ICRP 60 dose coefficients and the scaling factor of 1.4 for instrument response. The difference for Sr-90 can be attributed to Turbo FRMAC's inability to calculate resuspension inhalation dose to the fetus as well as inadvertent soil ingestion dose for any age group. This means Sr-90 dose projections are off by this difference as well as the scaling factor of 1.4 for instrument response.

3.3. Benchmarking Summary

The Turbo FRMAC DRL calculation can best emulate an OIL for groundshine exposure scenarios where the adult is the primary receptor of interest (e.g., a Cs-137 RDD). However, Turbo FRMAC cannot adequately calculate OILs according to IAEA guidance for scenarios where infant or fetus dose is most restrictive, or where inadvertent soil ingestion dose is significant. For this reason, consideration should be given to implementing the modifications to Turbo FRMAC described in Section 2.5.

EPR-NPP-OILs 2017 states that "the general methodology presented…is generically applicable for deriving default OIL values for other reactor types or for radiological emergencies, but needs to be adapted. Additional publications addressing other reactor types and radiological emergencies may be issued by the IAEA" [2]. To the author's knowledge, no other publications have been issued at the time of writing this report. Based on the analysis presented here, further guidance from IAEA is indeed needed for non-LWR emergencies, especially for radionuclide mixtures for which groundshine is not the dominant exposure pathway.

3.4. Future Work

Additional scenarios of interest for benchmarking Turbo FRMAC and the IAEA Excel tool are an NPP release scenario that uses a different source term (e.g., radionuclides and release fraction) than those covered by the IAEA Excel tool, and an improvised nuclear device detonation scenario. Benchmarking these scenarios would require adding radionuclides and associated radiological data to the IAEA Excel tool, which is not a simple task due to the pre-integrated parameters used by the tool.

4. CONCLUSION

Turbo FRMAC is a far more flexible tool for calculating OIL-like quantities than the IAEA Excel tool due to its built-in radiological database and ability to handle dose calculations for custom exposure periods and any mixture of radionuclides. Software development is currently underway to create an IAEA "OIL-like" calculation that uses the framework for FRMAC DRL calculations but uses IAEA-specific default inputs values. This will result in a partial implementation of the IAEA methodology for OIL1 and OIL2 in Turbo FRMAC.

The results of the benchmarking show that changing input values in a normal FRMAC DRL calculation can be insufficient for implementing IAEA OIL guidance, particularly for complex fission product mixtures and mixtures for which fetus dose is significant. Further investment is needed in order to develop full OIL1 and OIL2 calculations in Turbo FRMAC that exactly implement the IAEA OIL methodology.

Initial benchmarking revealed that lack of an alternative measurement type for IAEA OILs might make use of field measurements difficult for non-NPP scenarios. Also, default LWR OILs might not be appropriate to apply for non-NPP scenarios where internal dose from resuspension inhalation is the primary exposure pathway.

Future benchmarking work planned under this CRP includes performing similar analyses for other IAEA OILs and comparing FRMAC scenario-specific DRLs to the default IAEA OILs, considering the same and organization-specific exposure periods and dose limits.

REFERENCES

[1] *Preparedness and Response for a Nuclear or Radiological Emergency*, IAEA General Safety Requirements No. GSR Part 7, International Atomic Energy Agency, Vienna, Austria, 2015.

[2] *Operational Intervention Levels for Reactor Emergencies and Methodology for Their Derivation*, IAEA EPR-NPP-OILs 2017, International Atomic Energy Agency, Vienna, Austria, 2017.

[3] *PAG Manual: Protective Action Guides and Planning Guidance for Radiological Incidents*, EPA-400/R-17/001, U.S. Environmental Protection Agency, Washington, DC, 2017.

[4] Vilar Welter, P., et al., OIL Calculation Spreadsheet, International Atomic Energy Agency, Vienna, Austria, 2017.

[5] *FRMAC Assessment Manual, Volume 1: Overview and Methods*, SAND2019-0247R, Sandia National Laboratories, Albuquerque, NM, 2018.

[6] Fulton, J., et al., Turbo FRMAC© Assessment Software Package, Sandia National Laboratories, Albuquerque, NM, 2019.

[7] *Generic Assessment Procedures for Determining Protective Actions During a Reactor Accident,* IAEA-TECDOC-955, International Atomic Energy Agency, Vienna, Austria, 1997.

[8] *Reactor Safety Study: An Assessment of the Accident Risks in U.S. Commercial Nuclear Power Plants,* NUREG-75/014 (WASH-1400), U.S. Nuclear Regulatory Commission, Washington, DC, 1975.

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

[10] Fulton, J., et al., Mixture Manager©, Sandia National Laboratories, Albuquerque, NM, 2017.

[11] Eckerman, K., et al., Dose Coefficient Factor Package, Oak Ridge National Laboratory, Oak Ridge, TN, 1996 – current version.

[12] *RASCAL 4: Deposition of Models and Methods*, NUREG-1940, U.S. Nuclear Regulatory Commission, Washington, DC, 2012.

[13] Bateman, H., "Solution of a System of Differential Equations Occurring in the Theory of Radioactive Transformations," Proc. Cambridge Phil. Soc. IS, 423, 1910.

[14] Kraus, T., Hunt, B., and Cochran, L.D., *Radioactive Decay Chain Truncation Rules for Emergency Response Radiological Assessments*, SAND2017-8519, Sandia National Laboratories, Albuquerque, NM, 2017.

[15] *External Exposure to Radionuclides in Air, Water, and Soil*, Federal Guidance Report No. 12, EPA-402-R-93-081, U.S. Environmental Protection Agency, Washington, DC, 1993.

[16] *Limits for Intakes of Radionuclides by Workers*, ICRP Publication 30, International Commission on Radiological Protection, Ottawa, Ontario, Canada, 1979.

[17] *Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards,* IAEA GSR Part 3, International Atomic Energy Agency, Vienna, Austria, 2014.

[18] *Compendium of Dose Coefficients based on ICRP Publication 60,* ICRP Publication 119, International Commission on Radiological Protection, Ottawa, Ontario, Canada, 2012.

[19] *Doses to the Embryo and Fetus from Intakes of Radionuclides by the Mother*, ICRP Publication 88, International Commission on Radiological Protection, Ottawa, Ontario, Canada, 2002.

[20] *1990 Recommendations of the International Commission on Radiological Protection*, ICRP Publication 60, International Commission on Radiological Protection, Ottawa, Ontario, Canada, 1990.

[21]*Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 1*, ICRP Publication 56, International Commission on Radiological Protection, Ottawa, Ontario, Canada, 1989.

[22]*Recommended Screening Limits for Contaminated Surface Soil and Review of Factors Relevant to Site Specific Studies,* NCRP Report No. 129, National Council on Radiation Protection and Measurements, Bethesda, MD, 1999.

[23]Maxwell, R.M., and Anspaugh, L.R., "An Improved Model for Prediction of Resuspension," *Health Physics,* Vol. 101 pp. 722-730, 2011.

[24]*Report of the Task Group on Reference Man*, ICRP Publication 23, International Commission on Radiological Protection, Ottawa, Ontario, Canada, 1975.

[25]*Human Respiratory Tract Model for Radiological Protection*, ICRP Publication 66, International Commission on Radiological Protection, Ottawa, Ontario, Canada, 1994.

[26]Anspaugh, L.R., et al., "Movement of Radionuclides in Terrestrial Ecosystems by Physical Processes," *Health Physics,* Vol. 82, pp. 670-679, 2002.

[27]*Conversion Coefficients for use in Radiological Protection against External Radiation,* ICRP Publication 74, International Commission on Radiological Protection, Ottawa, Ontario, Canada, 1996.

[28]*Categorization of Radioactive Sources,* IAEA RS-G-1.9, International Atomic Energy Agency, Vienna, Austria, 2005.

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