November 06, 2023

TP-LIC-LET-0103
Project Number 99902100

U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
ATTN: Document Control Desk

**Subject:** Transmittal of TerraPower, LLC Topical Report, "Radiological Release Consequences Methodology," Revision 0

This letter transmits the TerraPower, LLC (TerraPower) Topical Report "Radiological Release Consequences Methodology Topical Report," Revision 0 (enclosed). The report contains an overview and description of the model developed to evaluate radiological release consequences for the Natrium™ Plant[1].

TerraPower requests the NRC's review and approval of the evaluation model presented in this report for use by future applications utilizing the Natrium design.

TerraPower requests that a nominal review duration of 12 months be considered.

The report contains proprietary information and as such, it is requested that Enclosure 3 be withheld from public disclosure in accordance with 10 CFR 2.390, "Public inspections, exemptions, requests for withholding." An affidavit certifying the basis for the request to withhold Enclosure 3 from public disclosure is included as Enclosure 1. Enclosure 3 also contains ECI which can be disclosed to Foreign Nationals only in accordance with the requirements of 15 CFR 730 and 10 CFR 810, as applicable. Proprietary and ECI materials have been redacted from the report provided in Enclosure 2; redacted information is identified using [[ ]]$^{(a)(4)}$, [[ ]]$^{ECI}$, or [[ ]]$^{(a)(4),\ ECI}$.

This letter and enclosures make no new or revised regulatory commitments.

[1] Natrium is a TerraPower and GE-Hitachi technology.

If you have any questions regarding this submittal, please contact Ryan Sprengel at rsprengel@terrapower.com or (425) 324-2888.

Sincerely,

Ryan Sprengel
Director of Licensing, Natrium
TerraPower, LLC

Enclosure:
1. TerraPower, LLC Affidavit and Request for Withholding from Public Disclosure (10 CFR 2.390(a)(4))
2. TerraPower, LLC Topical Report, "Radiological Release Consequences Methodology Topical Report," Revision 0 – Non-Proprietary (Public)
3. TerraPower, LLC Topical Report, "Radiological Release Consequences Methodology Topical Report," Revision 0 – Proprietary (Non-Public)

cc: Mallecia Sutton, NRC
William Jessup, NRC
Nathan Howard, DOE
Jeff Ciocco, DOE

**ENCLOSURE 1**

**TerraPower, LLC Affidavit and Request for Withholding from Public Disclosure (10 CFR 2.390(a)(4))**

**Enclosure 1**
**TerraPower, LLC Affidavit and Request for Withholding from Public Disclosure**
**(10 CFR 2.390(a)(4))**

I, George Wilson, hereby state:

1. I am the Vice President, Regulatory Affairs and I have been authorized by TerraPower, LLC (TerraPower) to review information sought to be withheld from public disclosure in connection with the development, testing, licensing, and deployment of the Natrium™ reactor and its associated fuel, structures, systems, and components, and to apply for its withholding from public disclosure on behalf of TerraPower.

2. The information sought to be withheld, in its entirety, is contained in Enclosure 3, which accompanies this Affidavit.

3. I am making this request for withholding, and executing this Affidavit as required by 10 CFR 2.390(b)(1).

4. I have personal knowledge of the criteria and procedures utilized by TerraPower in designating information as a trade secret, privileged, or as confidential commercial or financial information that would be protected from public disclosure under 10 CFR 2.390(a)(4).

5. The information contained in Enclosure 3 accompanying this Affidavit contains non-public details of the TerraPower regulatory and developmental strategies intended to support NRC staff review.

6. Pursuant to 10 CFR 2.390(b)(4), the following is furnished for consideration by the Commission in determining whether the information in Enclosure 3 should be withheld:

    a. The information has been held in confidence by TerraPower.

    b. The information is of a type customarily held in confidence by TerraPower and not customarily disclosed to the public. TerraPower has a rational basis for determining the types of information that it customarily holds in confidence and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application and substance of that system constitute TerraPower policy and provide the rational basis required.

    c. The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR 2.390, it is received in confidence by the Commission.

    d. This information is not available in public sources.

    e. TerraPower asserts that public disclosure of this non-public information is likely to cause substantial harm to the competitive position of TerraPower, because it would enhance the ability of competitors to provide similar products and services by reducing their expenditure of resources using similar project methods, equipment, testing approach, contractors, or licensing approaches.

I declare under penalty of perjury that the foregoing is true and correct.
Executed on: November 06, 2023

George Wilson

*George Wilson*
Vice President, Regulatory Affairs
TerraPower, LLC

**ENCLOSURE 2**

**TerraPower, LLC Topical Report**
**"Radiological Release Consequences Methodology Topical Report" Revision 0**

**Non-Proprietary (Public)**

*Controlled Document - Verify Current Revision*

# TOPICAL REPORT

| | | | |
|---|---|---|---|
| **Document Number:** | TP-LIC-RPT-0005 | **Revision:** | 0 |
| **Document Title:** | Radiological Release Consequences Methodology Topical Report | | |
| **Functional Area:** | Licensing | **Engineering Discipline:** | GE-Hitachi (GEH) Safety & Licensing |
| **Effective Date:** | 11/06/2023 | **Released Date:** | 11/06/2023 |
| | | **Page:** | 1 of 42 |

**Approval**

| Title | Name | Signature | Date |
|---|---|---|---|
| Originator, Licensing Engineer | Matthew Presson | Electronically Signed in Agile | 11/06/2023 |
| Reviewer, Licensing Manager | Nick Kellenberger | Electronically Signed in Agile | 11/06/2023 |
| Approver, Director of Licensing | Ryan Sprengel | Electronically Signed in Agile | 11/06/2023 |

**Export Controlled Content: Yes ☐ No ☒**

# REVISION HISTORY

| Revision No. | Effective Date | Affected Section(s) | Description of Change(s) |
|---|---|---|---|
| 0 | 11/06/2023 | All | Initial Issue. |
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# ACRONYMS

| Acronym | Definition |
|---|---|
| AOO | Anticipated Operational Occurrence |
| APM | Adaptive Plume Mesh |
| BDBE | Beyond Design Basis Event |
| CCDF | Complementary Cumulative Distribution Function |
| CR | Control Room |
| CRH | Control Room Habitability |
| DBA | Design Basis Accident |
| DBE | Design Basis Event |
| DCF | Dose Conversion Factor |
| DF | Decontamination Factor |
| DG | Draft Regulatory Guide |
| DOE | Department of Energy |
| EAB | Exclusion Area Boundary |
| ECP | Engineering Computer Program |
| EM | Evaluation Model |
| EPRI | Electric Power Research Institute |
| EPZ | Emergency Planning Zone |
| F-C | Frequency-Consequence |
| FGR | Federal Guidance Report |
| GEH | GE-Hitachi |
| LBE | Licensing Basis Event |
| LNT | Linear No Threshold |
| LPZ | Low Population Zone |
| NEI | Nuclear Energy Institute |
| NRC | U.S. Nuclear Regulatory Commission |
| OQE | Other Quantified Event |
| PDC | Principal Design Criterion |
| PEP | Plume Exposure Pathway |
| QHO | Quantitative Health Objective |
| RAF | Ramsdell and Fosmire |
| RG | Regulatory Guide |
| RRCAT | Released Radionuclide Consequence Analysis Tool |
| SDCF | Shine Dose Conversion Factor |

| Acronym | Definition |
|---|---|
| SFR | Sodium Fast Reactor |
| SOARCA | State-of-the-Art Reactor Consequence Analyses |
| SR | Safety-Related |
| SSC | System, Structure, and Component |
| TEDE | Total Effective Dose Equivalent |
| ToR | Topical Report |
| URD | Utility Requirements Document |
| U.S. | United States |

# 1 EXECUTIVE SUMMARY

This topical report (ToR) provides three evaluation models (EMs) that will be used to determine the consequences of radiological release source terms developed for the Natrium™[1] sodium fast reactor (SFR) nuclear power plant according to TP-LIC-LET-0093, *Radiological Source Term Methodology Report* [1]. The first EM is proposed for the determination of the radiological consequences of three subcategories of licensing basis events (LBEs): anticipated operational occurrences (AOOs), design basis events (DBEs), and beyond design basis events (BDBEs), as well as other quantified events. This EM is referred to as the LBE EM and is described in Section 3. The second EM is proposed for the determination of the dose consequences of design basis accidents (DBAs). This EM is referred to as the DBA EM and is described in Section 4. The third EM is proposed for the determination of dose consequences used to demonstrate control room habitability (CRH). This EM is referred to as the CRH EM and is described in Section 5. The modifications to the LBE EM needed to determine the dose results required for the determination of the size of the plume exposure pathway (PEP) emergency planning zone (EPZ) as described in TP-LIC-LET-0060, *Topical Report: Plume Exposure Pathway Emergency Planning Zone Sizing Methodology* [2] are described in the Appendix to this ToR.

The LBE EM applies a probabilistic approach to determine the radiological consequences of a given source term considering phenomena related to the atmospheric transport of radionuclides released to the environment and the resultant radiological consequences delivered to receptors at various locations surrounding the plant. These phenomena are accounted for using models implemented in the WinMACCS version 4.1.0 code [3], referred to as MACCS in this work. The MACCS code input is developed to model radiological releases from the Natrium power plant following the U.S. Nuclear Regulatory Commission (NRC) sample problem provided with the MACCS code identified as the Point Estimate Linear No Threshold (LNT) model and the guidance of NUREG-1935, *State-of-the-Art Reactor Consequence Analyses (SOARCA) Report* [4]. The following radiological consequences are determined using MACCS for the 30-day period following the initiation of the LBE:

1. The total effective dose equivalent (TEDE) dose received by a receptor on the exclusion area boundary (EAB) considering the dose due to inhalation of airborne radionuclides, radiation shine from airborne radionuclides, radiation shine from radionuclides deposited on the ground, and radiation shine from radionuclides deposited on the skin of the receptor. This quantity is determined at the $5^{th}$ and $95^{th}$ percentile as well as the mean value.
2. The probability of exceeding 100 mrem TEDE as defined above at the site boundary.
3. The average individual risk of early fatality within 1 mile of the EAB.
4. The average individual risk of latent cancer fatalities within 10 miles of the EAB.

The above are the radiological consequences considered in the Nuclear Energy Institute NEI-18-04, *Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development* [5] LBE selection Tasks 7a and 7b. These tasks relate to the Frequency-Consequence (F-C) Target and quantitative health objectives (QHOs) which are presented in the safety analysis report. The generation of the F-C Target and QHOs is outside the scope of this report. Only the determination of the radiological consequences required to generate those criteria is described.

The DBA EM applies a deterministic approach to determine the dose consequences of a given source term. In this EM, the atmospheric transport of radionuclides released to the environment to receptor

[1] a TerraPower & GE-Hitachi technology

locations is accounted for using atmospheric dispersion factors developed separately from this work. The dose delivered to offsite receptors is calculated directly with these dispersion factors. Model parameters are developed following Regulatory Guide (RG) 1.183, *Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors* [6] and Draft Regulatory Guide (DG) 1389, *Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors* [7] as applicable to determine the following dose consequences for the 30-day period following the initiation of the DBA:

1. The highest TEDE dose received over any 2-hour period by a receptor on the EAB considering the dose due to inhalation of and radiation shine from airborne radionuclides, referred to in this work as inhalation and submersion dose.

2. The 30-day TEDE dose received by a receptor on the outer boundary of the low population zone (LPZ) also considering inhalation and submersion dose.

These are the dose consequences required to demonstrate compliance to 10 CFR 50.34, *Domestic Licensing of Production and Utilization Facilities, Contents of applications; technical information* [8] limits. All DBA dose consequences are determined conservatively assuming that only safety related systems, structures, and components are available to mitigate them.

The CRH EM applies a deterministic approach similar to the DBA EM with additional phenomena considered to determine the contamination of the control room (CR) atmosphere and the radiation shine delivered to CR receptors. Phenomena related to the contamination of the CR atmosphere are accounted for using models originally described in NUREG/CR-7220, *SNAP/RADTRAD 4.0: Description of Models and Methods* [9], referred to as RADTRAD in this work. The RADTRAD code was developed for the NRC and is maintained through the NRC sponsored Radiation Protection Computer Code Analysis and Maintenance Program. The models described for determination of the CR receptor dose due to atmospheric contamination following the release of radionuclides to the environment in the RADTRAD code are implemented equivalently in the Released Radionuclide Consequence Analysis Tool (RRCAT) code version 1.0, referred to as RRCAT in this work. The RRCAT code was developed to accept the radiological source term determined by the Radiological Source Term Methodology as input and to compute doses equivalently to the RADTRAD code. Additionally, the RRCAT code accounts for dose delivered to CR receptors due to radiation shine from various locations. The RRCAT code input is developed following RG 1.183 and DG-1389 as applicable to determine the 30-day TEDE dose received by a CR receptor considering inhalation and submersion dose as well as gamma radiation shine from airborne radionuclides external to the CR, built up on filtration equipment, and held in a compartment before release to the environment. This is the dose consequence required to demonstrate compliance with Principal Design Criterion (PDC) 19 in TP-LIC-LET-0052, *Principal Design Criteria for the Natrium Advanced Reactor* [10] limits.

While the LBE EM described in this work was developed to determine radiological consequences that are required for the safety analysis report, only slight modifications are required to determine the dose results needed for the determination of the size of the PEP EPZ. The dose results required for this evaluation are described in the Natrium PEP EPZ Sizing Methodology as:

1. The mean and 95$^{th}$ percentile TEDE dose delivered to a receptor at the PEP EPZ boundary over the 4-day period following the release of radionuclides to the environment.

2. The 24-hour red bone marrow acute dose delivered to a receptor at the PEP EPZ boundary and various distances beyond.

The modifications to the LBE EM required to determine these dose results are described in the Appendix. Note that the first consequence listed above will be determined for both LBE and DBA source terms. This is acceptable because the LBE EM may be applied to determine the consequences of any given radiological source term provided all input information listed in Section 3.3 for this EM is available.

# 2 INTRODUCTION

This ToR describes the EMs used to assess radiological consequences from the Natrium SFR power plant. The radiological consequences of LBEs as defined in NEI report 18-04 [5], endorsed by the NRC in RG 1.233, *Guidance for a Technology-Inclusive, Risk-informed, and Performance-Based Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light Water Reactors* [11], as well as other events are determined with the three separate EMs described here. The criteria used to determine the acceptability of radiological consequences are also presented.

In NEI 18-04, LBEs are defined as, "… event sequences considered in the design and licensing basis of the plant …" with four event types: AOO, DBE, BDBE, and DBA. The first three LBE types are determined by the frequency of the event sequence whereas a DBA is derived from a DBE by prescriptively assuming that only safety-related (SR) systems, structures, and components (SSCs) are available to mitigate dose consequences. In this ToR, DBAs, which have no associated frequency due to prescriptive analysis assumptions, are referred to explicitly while the term LBEs is used to refer to the first three event types, AOO, DBE, and BDBE, as well as other quantified events (OQEs). The term OQE is not defined in NEI 18-04 and refers to event sequences with a frequency below the lower threshold defining a BDBE.

## 2.1 Objective and Scope

The process for selecting and evaluating LBEs is described as a series of tasks in NEI 18-04 [5]. This ToR describes the EM for determining radiological consequences of LBEs that is used in part to perform Tasks 7a and 7b in Figure 3-2 of NEI 18-04. The LBE EM and associated acceptance criteria are described in Section 3. The EM for dose consequences of DBAs that may be used in part to perform NEI 18-04 Task 7d as well as the associated acceptance criteria are described in Section 4. The EM for dose consequences related to CRH, required by PDC 19 [10], as well as the associated acceptance criteria are described in Section 5. The objective of the LBE EM is to apply a probabilistic approach with quantification of uncertainties whereas the objective of the DBA and CRH EMs is to apply a deterministic approach using conservative assumptions. The regulatory requirements and guidance, inputs, computational models, and evaluation methodology are described separately for each EM. The modifications to the LBE EM required to determine the dose results required for the determination of the size of the PEP EPZ as described in the Natrium PEP EPZ Sizing Methodology [2] are described in the Appendix. Only the determination of consequences from radiological source terms is within the scope of this ToR. The generation of source terms representative of LBEs or DBAs for the Natrium power plant are described in the Radiological Source Term Methodology Report [1] and are outside the scope of this work.

# 3 LICENSING BASIS EVENT EVALUATION MODEL

## 3.1 Objective and Scope

The objective of the LBE EM is to determine, through a probabilistic approach, the radiological consequences of an LBE for which a representative source term [1] has been determined. The radiological source term treated in this EM defines the airborne radionuclides released from the Natrium power plant to the environment as the result of an LBE. Following the release of airborne radionuclides to the environment, this EM considers the transport of radionuclide plume segments through the atmosphere and determines the resultant consequences of exposure to the released radionuclides. Atmospheric dispersion is a complex process that is affected by several phenomena including but not limited to wind speed and direction, atmospheric turbulence, building wakes, plume meander, and plume buoyancy. Besides atmospheric effects, the concentration of radionuclides in the plume decreases due to deposition of radionuclides onto the ground in both wet and dry weather conditions and radioactive decay. The concentration of some radionuclides in the plume increases due to the decay of parent radionuclides and resuspension of deposited radionuclides. These phenomena are considered to determine the radionuclide concentrations that receptors are exposed to over a 30-day period following the initiation of the LBE. The following radiological consequences are then determined:

1. The TEDE dose received by a receptor on the EAB considering the dose due to inhalation of airborne radionuclides, radiation shine from airborne radionuclides, radiation shine from radionuclides deposited on the ground, and radiation shine from radionuclides deposited on the skin of the receptor. This quantity is determined at the $5^{th}$ and $95^{th}$ percentile as well as the mean value.
2. The probability of exceeding 100 mrem TEDE as defined above at the site boundary.
3. The average individual risk of early fatality within 1 mile of the EAB.
4. The average individual risk of latent cancer fatalities within 10 miles of the EAB.

## 3.2 Regulatory Requirements and Guidance

This EM may be used to determine radiological consequences as required by NEI 18-04 [5] LBE selection and evaluation Tasks 7a and 7b. The former of which, Evaluate LBEs Against F-C Target, requires that the mean, $5^{th}$, and $95^{th}$ percentile 30-day TEDE dose to a receptor at the EAB be evaluated against frequency-consequence criteria termed the F-C Target in that report. The F-C Target is a vehicle for determining the risk significance of LBEs by comparing the dose resulting from an LBE against a limit that is scaled with consideration for the frequency of the LBE. As such, the F-C Target does not represent acceptance criteria for the dose consequences of a given LBE. Task 7b, Evaluate Integrated Plant Risk against QHOs and 10 CFR 20, requires that the following risk metrics be determined considering all LBEs cumulatively:

1. The probability of exceeding 100 mrem TEDE at the site boundary per plant-year.

2. The average individual risk of early fatality within 1 mile of the EAB per plant-year.

3. The average individual risk of latent cancer fatalities within 10 miles of the EAB per plant-year.

These three QHOs are determined by summing the product of the probability or risk determined via this EM (Items 2, 3, and 4 in Section 3.1) for a given LBE and the frequency of the LBE for all LBEs considered for the Natrium power plant. Because these are quantities integrated over all LBEs, they also do not represent acceptance criteria for the radiological consequences of a given LBE. The generation of the F-C Target and QHOs is outside the scope of this report. Only the determination of the radiological consequences required to generate those quantities is considered in this EM.

## 3.3 Evaluation Model Inputs

This EM is limited to the determination of the radiological consequences listed in Section 3.1 from a source term. As such, several items, including the determination of the radiological source term, are outside the scope of this report. Items that are used in this EM but developed separately are listed in Table 3-1. Note that the radiological source term analyzed is comprised of several individual inputs to this EM, all of which are listed.

**Table 3-1: Listing of Licensing Basis Event Evaluation Model Inputs**

| Input Number | Description |
|---|---|
| 3.1 | The time-dependent, nuclide-specific release of airborne radionuclides to the environment, referred to in this work as the release matrix, from a given location within the Natrium power plant. If an LBE results in releases from several locations, all release-specific inputs in this table must be provided for all locations. This input is release specific. |
| 3.2 | The total inventory of all radionuclides considered in each release matrix available at the beginning of the event sequence. This input is release specific. |
| 3.3 | The element-specific aerosol particle size distribution of all radionuclides considered in each release matrix input to this EM. This input is release specific. |
| 3.4 | The time-dependent rate of release of the sensible heat of the plume containing airborne radionuclides for each release matrix input to this EM. This quantity is release specific but not nuclide specific. |
| 3.5 | The physical description of the building or building complex from which radionuclides are released to the environment including the height, length, width, and angle of the building or building complex relative to north. This input is release specific, but multiple releases may be specified for the same building in a given radiological source term. |
| 3.6 | The location within the building or building complex considered from which radionuclides are released to the environment. This input is release specific. |
| 3.7 | Meteorological data including wind speed and direction, stability category, rain rate, and mixing height that is representative of weather conditions at the Natrium power plant over a period of 365 days. |

## 3.4 Computational Model

The determination of radiological consequences is performed using WinMACCS version 4.1.0 as described in the SAND2021-11535, *MACCS Theory Manual* [12], SAND2022-7112, *MACCS (MELCOR Accident Consequence Code System) User Guide – Version 4.0, Revision 1* [13], and the MACCS user guide supplement [3]. WinMACCS is a Windows-based interface and framework for performing consequence analysis. MACCS is used for calculating health and economic consequences from a release of radioactive materials into the atmosphere. For simplicity, the combined functions of MACCS and WinMACCS are referred to as MACCS in this work. MACCS was developed by Sandia National Laboratories for the NRC and has a diverse user base including the NRC, the U.S. Department of Energy (DOE), various research organizations, nuclear power plant applicants and licensees, as well as international regulators and technical support organizations.

The MACCS code input utilized for modeling the Natrium SFR generally follows the NRC sample MACCS model provided with the MACCS code identified as the Point Estimate LNT model. The NRC LNT model highlights NRC current practices, as considered in the SOARCA Report [4]. Adaptation of site modeling used in the SOARCA analysis is considered representative of the Natrium LBE radiological consequences. The main categories of MACCS model choices and parameters are GENERAL, ATMOS, EARLY, CHRONC, DOSE COEFFICIENTS, and COMIDA2. Because this EM only considers the 30-day period following the initiation of an LBE, the MACCS computational modules CHRONC (region specific data on agriculture and economic factors for calculating long-term effects and economic costs) and COMIDA2 (the food model option for ingestion exposure) are not utilized. Because no dose conversion factors (DCFs) are modified from the values in the data file used in this EM, the DOSE COEFFICIENTS (the option to modify values in the DCF file) MACCS computational module is also not utilized.

The following sections document how the MACCS code is used to determine the radiological consequences of an LBE source term. First, the adaption of the first two inputs in Table 3-1 to the input format of the MACCS code is described in Section 3.5. Then the other MACCS input selections that define the computational model utilized in this EM are developed from the remaining inputs in Table 3-1, the NRC LNT example, and SOARCA guidance in Section 3.6. Finally, the methodology for handling uncertain parameters is described in Section 3.7. Throughout, discussion of the MACCS code considers only one release matrix input to this EM. If multiple releases are specified, multiple executions of MACCS are required and the LBE radiological consequences are computed as the sum of the consequences from each release.

## 3.5 Adaption of Release Matrix to MACCS

The release matrix, Table 3-1 Item 3.1, input to this EM is generated according to the Radiological Source Term Methodology Report [1]. The MACCS code requires the initial radionuclide inventory, equivalent to Table 3-1 Item 3.2, and release fractions derived from the release matrix. The release matrix input data is specified to the MACCS code as release fractions for each chemical group. Therefore, to couple the release matrix to the MACCS code while preserving the fidelity of the radionuclide release profile, each radionuclide is treated as its own chemical group. The approach to determine MACCS plume release timing and fractions from the release matrix is discussed in Sections 3.5.2 and 3.5.3, respectively.

Other considerations for coupling the release matrix to version 4.1.0 of the MACCS code include the limitation of 150 on the number of trackable radionuclides and the restriction of the radionuclide progeny daughtering chains to a length of five. The approach to identify insignificant, trailing radionuclide releases to the environment and truncate the release matrix is discussed in Section 3.5.1. Note that these approaches can be utilized regardless of what method is leveraged to generate the release matrix.

3.5.1 Isotope Sensitivity Method

The release matrix input to this EM may include an arbitrary number of radionuclides. To quantify the relative importance of modeling a given radionuclide to accurately determine dose due to inhalation of airborne radionuclides, radiation shine from the airborne radionuclides, and radiation shine from radionuclides deposited on the ground, the radionuclide dose sensitivity is defined for the $i^{th}$ radionuclide as:

[[

]][(a)(4)]

To account for dose due to inhalation, cloud shine, and ground shine, the following DCFs are used, respectively:

- The product of the effective inhalation DCF from Table 2.1 in Federal Guidance Report (FGR) 11, *EPA-520/1-88-020, Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion* [14], and the offsite breathing rate of 3.5E-4 $m^3$/sec recommended in RG 1.183 [6] for the calculation of dose consequences from a nuclear reactor accident.
- The effective air submersion DCF from Table III.1 in FGR 12, *EPA-402-R-93-081, External Exposure to Radionuclides in Air, Water, and Soil* [15].
- The effective shine from contaminated ground surface DCF from FGR 12 Table III.3.

[[

]][a)(4)

The radionuclides are first screened by selecting the radionuclides that [[

]][a)(4) for further evaluation. Next, Equation 3-1 is evaluated using [[

]][a)(4) as defined above. Then all radionuclides are ranked by the computed dose sensitivity. To account for the effects of radioactive decay and the buildup of progeny radionuclides, the process described above is repeated for several radionuclide inventories each representing the initial inventory after some period less than the 30-day event duration has elapsed. The ranking of radionuclides based on isotope sensitivity results is then averaged across all inventories considered. The number of top ranked radionuclides required to account for at least [[ ]][a)(4) of the dose sensitivity is determined as the number of radionuclides in the sum of radionuclide dose sensitivities computed for each inventory starting with the top ranked and proceeding in descending order that results in a total not less than [[ ]][a)(4) for each inventory. The lesser of this number and 150, the maximum number of trackable radionuclides in the MACCS code, is then the number of radionuclides considered in the remainder of this EM. All radionuclides besides the number of top ranked radionuclides considered are truncated from the release matrix and initial inventory.

After truncation, the initial radionuclide inventory is input into MACCS via the Radionuclides form which specifies the name, chemical group, and inventory of each of the radionuclides treated in the MACCS calculation. The names of the top ranked radionuclides correspond to those in the DCF file associated with the project, described in Section 3.6.1, and the inventory of each is input to this EM, Table 3-1 Item 3.2. To preserve the fidelity of the nuclide-specific release matrix, each radionuclide is treated as its own chemical group leading to a unique chemical group number for each. This results in the number of chemical groups matching the number of radionuclides in the initial inventory.

#### 3.5.1.1 Pseudostable Radionuclides

Decay chains are automatically terminated when the decay product is a stable isotope. In some cases, it is desirable to terminate a decay chain with a decay product that is not stable. This is commonly done when the decay product has a very long half-life or contributes very little to the overall dose. Terminating a decay chain in this way is done by adding the radionuclide to the pseudostable isotope list input to MACCS.

A MACCS trial run without pseudostable nuclides specified is executed to determine which decay chains were incomplete and not acceptable to MACCS. Any nuclides that are identified as an intermediate decay product between two modeled nuclides should be added via the Radionuclides form described in Section 3.5.1 if there are less than 150 nuclides already modeled. The pseudostable nuclides needed to terminate decay chains identified by the MACCS trial run are then input to the MACCS code as pseudostable nuclides. Radionuclides cannot be input in both the initial inventory and pseudostable nuclide fields.

3.5.1.2 General Isotope Sensitivity Results

The methodology described in Sections 3.5.1 and 3.5.1.1 was applied to Natrium-specific core radionuclide inventories composed of nearly [[ ]]$^{(a)(4)}$ isotopes to determine a set of important radionuclides applicable to any LBE source term that is representative of release from the Natrium reactor core. Additionally, isotopes described as important in two Sandia National Laboratories reports, SAND2021-11703, *Preliminary Radioisotope Screening for Off-site Consequence Assessment of Advanced Non-LWR Systems* [17] and SAND2022-12018, *Quantitative Assessment for Advanced Reactor Radioisotope Screening Utilizing a Heat Pipe Reactor Inventory* [18], concerning the screening of isotopes for technologies including SFRs were also reviewed for inclusion in this representative, important isotope set. This additional review was intended to capture isotopes that were found to be important in other SFR isotope sensitivity evaluations including activation products, (e.g., activated sodium and tritium). Together, this evaluation of the core inventory and additional review results in a set of isotopes that are sufficient to capture the radiological consequences from source terms determined for core damage events. If a source term is input to this EM that represents a significantly different core inventory or effective release fractions than the ones analyzed here, the methodology described in Sections 3.5.1 and 3.5.1.1 will be applied to the input source term to develop an applicable set of important isotopes.

[[

]]$^{(a)(4)}$

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]](a)(4)

***Not Confidential***

*Controlled Document - Verify Current Revision*

**Table 3-2: SFR Core Damage Effective Release Fractions**

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**Table 3-3: Natrium Release Isotopes Selected for MACCS Calculations**

| Release Isotopes Selected for MACCS Calculations | | | | | | | |
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| | | | | | | | ]]$^{(a)(4), ECI}$ |

**Table 3-4: Natrium Pseudostable Radionuclides Selected for MACCS Calculations**

| Pseudostable Radionuclides Selected for MACCS Calculations | | | | | | | |
|---|---|---|---|---|---|---|---|
| [[ | | | | | | | |
| | | | | | | | ]]$^{(a)(4), ECI}$ |

3.5.2 Adaptive Plume Algorithm

The adaptive plume mesh (APM) algorithm uses a novel approach to adaptively construct the plume release time intervals used to represent the time-dependent, nuclide-specific release matrix in the MACCS code. The goal is to [[

]]$^{(a)(4)}$ This is a complex task because the release matrix may include a large number of timesteps discretizing the release of radionuclides to the environment while

version 4.1.0 of the MACCS code can only model up to 500 plume segments. As a result, some consolidation in time of the values provided in the release matrix is required. [[

]]$^{(a)(4)}$

3.5.3 Release Fraction Computation

The MACCS code calculates the release to the environment using the radionuclide inventory and release fractions of that inventory. Because the MACCS code tracks the decay of the radionuclide inventory with consideration for progeny produced by radioactive decay, the determination of release fractions requires a full progeny calculation of the radionuclide inventory. The radionuclide inventory as a function of time is:

$$\vec{R}_{inv}(t) = e^{t\boldsymbol{\Lambda}}\vec{R}_{inv}(0), \tag{3-3}$$

where, $\vec{R}_{inv}(t)$ is the vector of radionuclide inventories at time $t$ and $\boldsymbol{\Lambda}$ is the decay matrix containing terms for both rate of loss due to decay and the rate of gain due to the decay of parent radionuclides. The amount of a radionuclide released to the environment over the duration of a plume interval may be computed [[ ]]$^{(a)(4)}$ using the interpolant of the release matrix [[ ]]$^{(a)(4)}$. The release fractions for each radionuclide in a plume are then computed and input into the MACCS code by taking the ratio of the amount of that radionuclide released in the plume segment and the inventory of that radionuclide present at the beginning of the plume segment release calculated by evaluating Equation 3-3 at the start time of the segment considered.

3.6 MACCS Model Parameters

This section describes the MACCS input selections that define the computational model used to determine radiological consequences in this EM; however, selections for all possible inputs are not explicitly listed. Due to the applicability of the MACCS code to a range of applications, many possible input variables are available to the user and different combinations of input variables may be leveraged to determine radiological consequences. Only the inputs required to define an acceptable computational model are described here.

3.6.1 Data File Specifications

Two external data files are input to MACCS. The first is the meteorological data file input to this EM, Table 3-1 Item 3.7. A meteorological data file based on the Electric Power Research Institute (EPRI) 3002003129, *Advanced Nuclear Technology: Advanced Light Water Reactor Utility Requirements Document (URD)* [19] may be used if shown to be conservatively representative of the plant location considered. Characteristics of 91 U.S. reactor sites tabulated in NUREG/CR-2239, *Technical Guidance for Siting Criteria Development*, [20] were used to develop the URD site meteorological database. Atmospheric dispersion factors determined following guidance in RG 1.145, *Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants* [21] for the 0-2 hour averaging period resulting from use of this database are estimated to be greater than the values for 80 to 90% of U.S. operating sites. Therefore, this database conservatively represents the consequences of most potential sites.

The second data file is the DCF file which must include all DCF values required to calculate the radiological consequences listed in Section 3.1 for all radionuclides specified in the release matrix. These DCF values should be based upon those reported in FGR 11 [14], FGR 12 [15], and FGR 13, *EPA-402-R-99-001, Cancer Risk Coefficients for Environmental Exposure to Radionuclides* [22]. One acceptable file is the "FGR13GyEquiv_RevA.inp" file SAND2019-13422R, *FGR 13 Dose Conversion Factor Files* [23] distributed with the MACCS code. It is the most complete and current DCF file available, is recommended for most consequence analyses in the MACCS user guide [13], and contains values which are consistent with those used in the SOARCA project [4].

### 3.6.2 Atmospheric Dispersion

The transport and dispersion of airborne radionuclides through the atmosphere is affected by several phenomena. These phenomena include weather, wind speed and direction, atmospheric turbulence, building wakes, plume meander, and plume buoyancy. During transport, airborne radionuclides are also deposited on the ground. The MACCS input selections made to define the computation models applied to capture these phenomena and justification for these selections is provided in this section.

The plume of radionuclides released to the environment is modeled as a Gaussian plume. This is a typical model applied to plume transport and is consistent with other modeling decisions discussed in this section. Plume meander is accounted for with the Ramsdell and Fosmire (RAF) model which was integrated into MACCS to increase the nearfield capabilities. These are described in more detail in SAND2021-6924, *Implementation of Additional Models into the MACCS Code for Nearfield Consequence Analysis* [24]. The RAF model accounts for both building wake effects and low wind speed plume meander. The NRC has endorsed this model for offsite dispersion out to distances of 1,200 meters (RG 1.249, *Use of ARCON Methodology for Calculation of Accident-Related Offsite Atmospheric Dispersion Factors* [25]). Given that the EAB is expected to be within this distance, the RAF model is selected. If the EAB is modeled at a distance exceeding 1,200 meters, this selection will be re-justified or changed. To model building wake effects, the exterior dimensions of the building or building complex from which radionuclides are released to the environment as well as the orientation of that structure relative to north are specified as input to this EM, Table 3-1 Item 3.5. Note that the selection of the RAF model requires that the release be modeled as a point source as recommended in the MACCS user guide [13]. The dispersion parameters specified for this model are described in Section 3.6.2.1.

The buoyancy flux is an important value that MACCS uses to calculate the plume liftoff, plume trajectory, and the final amount of plume rise. This quantity is specified to be modeled from the sensible heat release rate input to this EM, Table 3-1 Item 3.4. If a sensible heat release rate is not input, a constant value of [[ ]](a)(4) may be conservatively assumed. This value was determined by assuming [[

]](a)(4) The assumed low leakage rate and temperature difference used to compute this value yield a low sensible heat release rate which results in a conservatively low amount of plume rise.

3.6.2.1 Dispersion Parameters

Plume dispersion during downwind transport is modeled using a Gaussian plume model. The crosswind and vertical extent of plume segments is expressed in terms of the crosswind ($\sigma_y$) and vertical ($\sigma_z$) standard deviations of the normal concentration distributions that characterize a Gaussian plume. Dispersion parameters are supplied in the form of a lookup-table based on the selection of the plume meander model for nearfield evaluations and the recommendation in SAND2021-6924 [24] that the Eimutis and Konicek parameterization of the Pasquill-Gifford diffusion curves, implemented via lookup-table, be used. This is consistent with the NRC LNT example distributed with the MACCS code. The $\sigma_y$ and $\sigma_z$ values for various distances and stability classes in the Eimutis and Konicek dispersion lookup-table used in this EM are taken from the MACCS input file provided in Section D.1 of SAND2021-6924. Consistent with the NRC LNT example distributed with the MACCS code, long-range crosswind dispersion is modeled as a function of time.

3.6.2.2 Weather Sampling

Random samples of weather data taken from the meteorological data file specified in Section 3.6.1 are used to compute radiological consequences. Through many weather trials, probabilistic radiological consequences capturing the inherent uncertainty in the weather assumed in the 30-day period following the initiation of the LBE may be determined. How these weather trials are sampled is specified with several MACCS input selections as described in this section.

Internally, the MACCS code defines weather bins to represent rain conditions at different distance intervals downwind from the accident site together with 16 bins for initial conditions organized by stability class and wind speed. The total number of bins is equal to the number of rain distance intervals (NRNINT) times one plus the number of rain intensity breakpoints (NRINTN) plus 16 ($NRNINT \times (NRINTN + 1) + 16$). The following rain distances are used in this EM as recommended in NUREG-1150, *Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants* [26] and consistent with the NRC LNT example distributed with the MACCS code: 3.22 km, 5.63 km, 11.27 km, 20.92 km, and 32.19 km. The following rain intensity breakpoints are used in this EM also as recommended in NUREG-1150 and consistent with the NRC LNT example: 2 mm/hr, 4 mm/hr, and 6 mm/hr. From these values, the number of weather bins is calculated to be 36.

The number of weather sequences to be sampled from each weather bin is specified as nonuniform. This nonuniform bin sampling scheme allows the user to directly specify the number of weather sequences to sample from each weather bin. The number of samples to be taken from each bin is determined by a trial execution of the MACCS code resulting in the weather frequency for each bin being output. The number of samples to be taken from each of the 36 weather bins is then computed as the product of the weather frequency for that bin and the total number of weather sequences being sampled. These values will vary depending on the meteorological data file used in this EM.

After a weather sequence is sampled, additional MACCS inputs must be specified to determine the effect of the sequence on the plume. Wind shift, the physical phenomena of the plume direction changing after release due to changes in the direction of wind, is included in the computational model. Wind rotation, a numerical convenience for acquiring more information out of a set of results without significantly increasing the computational time, is not included.

### 3.6.3 Plume Deposition

As the plume of airborne radionuclides travels through the atmosphere, some radionuclides are deposited on the ground. The resultant radiation shine from the radionuclides deposited on the ground is accounted for when determining radiological consequences. Because noble gases do not form aerosols and are highly inert, they are assumed to remain suspended in the air without deposition. [[

]]$^{(a)(4)}$ In dry conditions, deposition modeling is dependent on the deposition velocity, a radionuclide-specific value input depending on the size of the radionuclide aerosol, Table 3-1 Item 3.3. Deposition in wet conditions is only modeled intermittently according to the weather trial considered and is modeled identically for all non-noble gas radionuclides. [[

]]$^{(a)(4)}$

After deposition, radionuclides may become resuspended. This is modeled in the MACCS code with a resuspension coefficient and resuspension coefficient half-life. The concentration in the air due to resuspension is then computed as the product of the ground concentration, the resuspension coefficient, and a reduction factor determined from the time elapsed since deposition and the half-life as specified in Equation 3-27 in the MACCS user guide [13]. Consistent with the NRC LNT example MACCS model distributed with the MACCS code, the resuspension coefficient and resuspension coefficient half-life are specified as 1E-4 $m^{-1}$ and 1.82E5 sec, respectively.

### 3.6.4 Plant Area

Several aspects of the area surrounding the plant are specified to MACCS including the population distribution. To ensure the radiological consequences relating to areas outside of the EAB, Section 3.1 Items 3 and 4, are determined conservatively, the land surrounding the plant is assumed to be entirely inhabited by a population distributed uniformly beginning at the EAB and extending at least to the furthest distance at which consequences are determined.

### 3.6.5 Protective Actions

Generally, no credit is taken for protective actions to ensure a conservative determination of radiological consequences. Because the MACCS code provides the user several options to specify how to model protective actions, this broad modeling decision affects several input selections. These selections are:

- No credit taken for the ingestion of potassium iodide
- No general or keyhole evacuation model considered
- The dose after which people are relocated at the normal or hot spot relocation times specified as an unphysically high value such as 1E10 Sv to ensure that no relocation is modeled

### 3.6.6 Dosimetry

The MACCS code offers numerous options for calculating radiological consequences of radionuclide releases and only the input parameters used to determine the consequences listed in Section 3.1 are described here. Consistent with the NRC LNT example MACCS model distributed with the MACCS code, dose is computed with the LNT model. Radiological consequences are modeled in the MACCS code in terms of organs of risk. These are organs for which DCFs are provided in the DCF data file prepended with either “A” to denote an acute dose or “L” to denote a lifetime dose. The organs of risk considered in this EM are listed in Table 3-5.

**Table 3-5: Listing of Organs of Risk for MACCS Calculations**

| Organs of Risk | | | |
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The average risk of individual early fatality is computed considering the acute (prepended with an “A”) organs of risk from Table 3-5. The risk of early fatality is computed using the hazard function, given by Equation 3-35 of the MACCS user guide [13], which requires factors for each organ considered. The alpha and beta factors of the hazard function as well as the threshold dose below which the risk of fatality is zero given in the MACCS user guide are listed for all organs considered in this EM for early fatality in Table 3-6.

**Table 3-6: Early Fatality Parameters for MACCS Calculations**

| Organ Name | Alpha Factor (Sv) | Beta Factor | Threshold (Gy) |
|---|---|---|---|
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The average risk of individual latent cancer fatalities is computed considering the lifetime (prepended with a “L”) organs of risk from Table 3-5 except for L-ICRP60ED which is only used for TEDE dose calculations. The MACCS code is capable of computing latent cancer fatality risk with a linear-quadratic model. The quadratic portion of this model is disabled by specifying a linear factor of one, a quadratic factor of zero, and a dose limit for the linear-quadratic relationship of zero for all organs. The risk of latent cancer fatality is then computed from the fraction of the population that is susceptible to the latent cancer, the lifetime risk factor for a cancer fatality, and the dose and dose-rate effectiveness factor. The values for these parameters are taken from the NRC LNT example MACCS model distributed with the MACCS code and are listed in Table 3-7.

**Table 3-7: Latent Cancer Fatality Parameters for MACCS Calculations**

| Organ Name | Fraction of Population Susceptible to Cancer | Lifetime Fatality Risk Factor (1/Sv) | Dose Effectiveness Factor |
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3.6.7 Radiological Consequences

Two radiological consequence output options are used in this EM to determine the four radiological consequences listed in Section 3.1. These represent one set of MACCS outputs that are acceptable for determining radiological consequences. As noted in Section 3.6, the MACCS code includes many input options. This is especially true of the EARLY module output specification which includes several user options that can be leveraged in different ways to achieve equally valid results.

The first output option specified is the peak dose. This output is calculated as the maximum average dose over a fine grid element for all fine grid elements within a radial interval. When the radial interval is centered on the EAB, this output is equivalent to the highest 30-day TEDE dose received by any receptor on the EAB. The target organ is specified as L-ICRP60ED from Table 3-5 so that the TEDE dose is calculated for the whole body rather than a specific organ, the inner and outer radii of the radial interval are specified as centered on the EAB, and the complementary cumulative distribution function (CCDF) reporting option is selected. The 5$^{th}$ percentile TEDE dose value may be extracted from the CCDF which contains doses for a range of probabilities spanning from near zero to near one. The mean and 95$^{th}$ percentile TEDE dose values are reported directly by MACCS separately from the CCDF. If the site boundary is not coincident with the EAB, a second peak dose value must be specified identically to the first peak dose value but with a radial interval centered on the site boundary. The probability of exceeding 100 mrem at the site boundary may be deduced from the CCDF of this result or the first peak dose value if the EAB and site boundary are coincident.

The second output option specified is the population-weighted risk. This output is calculated as the number of cases of a health effect within a region and divided by the total population of that region. Two values are specified to be output. The first is the total early fatality health effect specified over a radial interval with an inner radius equal to or less than the EAB and an outer radius equal to or greater than the EAB plus one mile. The total early fatality health effect is the cumulative early fatality risk of each organ listed in Table 3-6 so this value is equivalent to the average individual risk of early fatality within one mile of the EAB. The second output value is the total cancer fatality health effect specified over a radial interval from an inner radius equal to or less than the EAB to an outer radius greater than or equal to the EAB plus 10 miles. The total cancer fatality health effect is the cumulative latent cancer fatality risk of each organ listed in Table 3-7 so this value is equivalent to the average individual risk of latent cancer fatalities within 10 miles of the EAB.

## 3.7 MACCS Analysis Uncertainty Methodology

While applicable values for a number of MACCS parameters or acceptable methods to determine these values were presented in Sections 3.5 and 3.6, robust justification for some MACCS inputs may not be available. Additionally, values input to this EM, Table 3-1, may have associated uncertainties. This section presents an acceptable methodology for determining the sensitivity of radiological consequences to these values as well as an acceptable treatment of the uncertainty of these values.

### 3.7.1 Parameter Sensitivity

An analysis is performed to determine the sensitivity of radiological consequences to parameters with some associated uncertainty. One acceptable method to perform this analysis is direct manipulation of parameters of interest. Nominal values for all required parameters are input into the MACCS code so that it may be executed, and radiological consequences may be computed. See Section 3.6.7 for detail on the code outputs that constitute radiological consequences. Then, a parameter of interest is repeatedly perturbed to different values within the range of the uncertainty surrounding the nominal value of that parameter and MACCS is repeatedly executed. The resulting radiological consequences may then be studied as a function of the perturbed parameter and the sensitivity of consequences to the parameter may be determined.

Both peak dose and population-weighted risk MACCS outputs should be considered when determining parameter sensitivity as only one of these output types may be sensitive to the studied parameter. If radiological consequences are found to be relatively insensitive to the parameter, (i.e., variation of the parameter does not significantly affect either peak dose or population-weighted risk MACCS outputs), a single nominal value may be assumed when determining the final radiological consequences produced by application of this EM. If the parameter does significantly affect either radiological consequence output, the treatment described in Section 3.7.2 is applied.

### 3.7.2 Uncertain Parameter Treatment

For uncertain parameters that contribute significantly to radiological consequences, two acceptable approaches are described. First, although it should be avoided if possible as the objective of this EM is to provide a probabilistic radiological consequence assessment, values that conservatively bound the uncertainty surrounding parameters may be prescribed. This approach may require multiple executions with the parameter value selected separately for each consequence if the parameter affects peak dose and population-weighted risk MACCS outputs differently. Generally, the second approach should be pursued.

The second acceptable treatment of uncertain parameters is randomly sampling values for uncertain inputs from a probability distribution. Many parameters may be sampled using Monte Carlo techniques to generate the inputs for a single MACCS execution. The values of uncertain inputs are repeatedly sampled and MACCS is repeatedly executed to generate many radiological consequence samples. [[

]]$^{(a)(4)}$ Care should be taken when extracting final results from the sampled set because a single MACCS execution outputs 5th percentile, mean, and 95$^{th}$ percentile results due to the weather sequence random sampling described in Section 3.6.2.2. [[

]]$^{(a)(4)}$ Additionally, the MACCS code includes post-processing capabilities that may be utilized to determine the mean, 5$^{th}$ and, 95$^{th}$ percentile results of the sampled set. These QHO and dose results represent the final determination of this EM.

The treatment of uncertainty with regards to the source term input, Table 3-1 Item 3.1, will be expected to follow one of the above methods depending on the treatment of uncertainty utilized in the development of the source term [1]. If the treatment of uncertainty in the development of the source term input requires a different approach from the two described above, it will be described and justified at the time of application.

# 4 DESIGN BASIS ACCIDENT EVALUATION MODEL

## 4.1 Objective and Scope

The objective of the DBA EM is to determine, through a conservative, deterministic approach, the dose consequences of a DBA for which a representative source term has been determined. The source terms analyzed in this EM are derived from the DBEs analyzed by the LBE EM described in Section 3 by only taking credit for SR SSCs to mitigate dose consequences. Explicit treatment of atmospheric transport from the point of release of radionuclides to receptor locations is not considered in this EM. Instead, atmospheric dispersion factors are determined externally and input to this EM. These factors allow the direct computation of radionuclide concentrations in the environment that receptors are exposed to over a 30-day period. The following dose consequences are then determined:

1. The highest TEDE dose received over any 2-hour period by a receptor on the EAB considering the dose due to inhalation of and radiation shine from airborne radionuclides, referred to in this work as inhalation and submersion dose.

2. The 30-day TEDE dose received by a receptor on the outer boundary of the LPZ also considering inhalation and submersion dose.

## 4.2 Regulatory Requirements and Guidance

This EM may be used to determine dose consequences as required by NEI 18-04 [5] LBE selection and evaluation Task 7d. The NEI 18-04 task, Perform Deterministic Safety Analyses Against 10 CFR 50.34, states that the dose consequences of DBAs are determined using conservative assumptions and compared with 10 CFR 50.34 [8] dose criteria. The criteria from 10 CFR 50.34 that are applicable to this EM are as follows:

1. Per 10 CFR 50.34(a)(1)(ii)(D)(1), “An individual located at any point on the boundary of the exclusion area for any 2-hour period following the onset of the postulated fission product release, would not receive a radiation dose in excess of 25 rem total effective dose equivalent (TEDE).” This criterion is equivalent to limiting the dose consequence described in Section 4.1 Item 1 to 25 rem.

2. Per 10 CFR 50.34(a)(1)(ii)(D)(2), “An individual located at any point on the outer boundary of the low population zone, who is exposed to the radioactive cloud resulting from the postulated fission product release (during the entire period of its passage) would not receive a radiation dose in excess of 25 rem total effective dose equivalent (TEDE).” This criterion is equivalent to limiting the dose consequence described in Section 4.1 Item 2 to 25 rem.

These limits are applicable to each DBA for which dose consequences are determined with this EM and as such, constitute the acceptance criteria for the dose consequences of a DBA.

The dose consequences calculated for DBAs in this EM align with traditional deterministic safety analyses of DBAs typically performed by license applications not following NEI 18-04 guidance. Because of this, there are several regulatory guides that, while not directly applicable to the Natrium SFR technology, inform acceptable approaches to determining dose results. Throughout this EM, the guidance of RG 1.183 [6] and the proposed revision to this RG, DG 1389 [7], is used as applicable.

## 4.3 Evaluation Model Inputs

This EM is limited to the determination of dose consequences listed in Section 4.1 from a source term. As such, several items, including the determination of the radiological source term and atmospheric dispersion factors, are outside the scope of this report. Items that are used in this EM but developed separately are listed in Table 4-1.

**Table 4-1: Listing of Design Basis Accident Evaluation Model Inputs**

| Input Number | Description |
|---|---|
| 4.1 | The time-dependent, nuclide-specific release of airborne radionuclides to the environment, referred to in this work as the release matrix, from a given location within the Natrium power plant. If a DBA results in releases from several locations, all release specific inputs in this table must be provided for all locations. This input is release specific. |
| 4.2 | Atmospheric dispersion factors ($\chi/Q$ factors) corresponding to the location of the release and the most limiting location on the EAB. The 0-2 hour averaging period factor must be included. This input is release specific. |
| 4.3 | $\chi/Q$ factors corresponding to the location of the release and the most limiting location on the outer boundary of the LPZ. The 0-2, 2-8, 8-24, 24-96, and 96-720 hour averaging period factors must be included. This input is release specific. |

## 4.4 Computational Model

With the release matrix and $\chi/Q$ factors for the EAB and LPZ locations, Table 4-1 Items 4.1, 4.2, and 4.3, the inhalation and submersion doses delivered to receptors on the EAB or boundary of the LPZ may be computed directly using Equations 7 and 8 from RG 1.195, *Methods and Assumptions for Evaluating Radiological Consequences of Design Basis Accidents at Light-Water Nuclear Power Reactors* [28] and DCFs consistent with the dose quantity computed. This calculation may be performed by the SNAP/RADTRAD code version 4.0 [9], referred to as RADTRAD in this work, which is maintained as part of the NRC sponsored Radiation Protection Computer Code Analysis and Maintenance Program. The RADTRAD code was developed for the NRC to assess the dose delivered to receptors at the EAB, LPZ, and in the CR for various DBAs starting from the release of radionuclides in some compartment of the plant being analyzed.

The implementation of the RADTRAD code is explained in detail in NUREG/CR-7220, SNAP/RADTRAD 4.0: *Description of Models and Methods*. The RADTRAD code first computes the radionuclide release to the environment at a given timestep by modeling several complex physical phenomena to account for transport of radionuclides from the release location within

some plant compartment to the environment. The dose delivered to offsite (EAB and LPZ) receptors is then computed directly as the product of the integrated radionuclide release, the $\chi/Q$ factor, the DCF consistent with the dose quantity computed, and, only for the inhalation dose, the receptor breathing rate as specified in Equations 4-45 and 4-47 in NUREG/CR-7220.

The RADTRAD code is not used in this EM because the release matrix is input, Table 4-1 Item 4.1, not calculated. The release matrix may contain many radionuclides released over many timesteps. As a result, it is not possible to input these releases into the RADTRAD code without significant loss of resolution in either the number of radionuclides tracked or the time dependence of the release. For this reason, the RRCAT code version 1.0, which can compute offsite receptor inhalation and submersion doses equivalently to the algorithm used in RADTRAD described above, was developed. Following the guidance in RG 1.183 [6], the RRCAT code is input with effective dose equivalent DCFs from FGR 12 Table III.1 [15] to compute submersion dose and committed effective dose equivalent DCFs from FGR 11 Table 2.1 [14] to compute inhalation dose. For consistency with the application of FGR 12 DCFs, half-life and decay progeny information input to RRCAT is taken from FGR 12 Table A.1.

## 4.5 Atmospheric Dispersion

To calculate dose consequences for any receptor, $\chi/Q$ factors must be specified for the location of the receptor. For the LPZ receptor, a set of $\chi/Q$ factors are input corresponding to averaging periods of 0-2, 2-8, 8-24, 24-96, and 96-720 hours. In accordance with DG-1389 [7] guidance and to ensure that the most limiting release in the release matrix corresponds to the most limiting $\chi/Q$ factors, the 0-2 hour $\chi/Q$ factor is applied to the 2-hour period in which the limiting release to the environment occurs. The period of limiting release to the environment, referred to in this work as the limiting release period, is defined in this EM as the release period that results in the highest 2-hour TEDE dose to the receptor at the EAB. This period is determined by a trial execution of the RRCAT code wherein only the EAB receptor is specified with a constant $\chi/Q$ factor of the 0-2 hour averaging period, Table 4-1 Item 4.2, and a constant breathing rate of 3.5E-4 $m^3$/sec for the duration of the accident.

For the LPZ receptor, $\chi/Q$ factors are structured around this limiting release period consistent with DG-1389 guidance. First the 0-2 hour $\chi/Q$ factor is applied to the limiting release period. Next, the 2-8-hour factor is applied for half of the duration of the factor (three hours) before the limiting release period and half after. If the beginning of the accident is reached before the factor can be applied to the duration preceding the limiting release period, the remainder of the duration of the factor should be applied after the limiting release period. This process is repeated for the remaining $\chi/Q$ factors to define the entire 30-day accident duration.

## 4.6 Offsite Dose Consequences

To compute dose consequences for the receptor at the EAB, the 0-2 hour averaging period $\chi/Q$ factor, Table 4-1 Item 4.2, and a breathing rate of 3.5E-4 $m^3$/sec, the most limiting breathing rate recommended for offsite dose analyses in RG 1.183 [6], are specified. Note that these

specifications are identical to those used in the trial RRCAT execution used to determine the limiting period of release described in Section 4.5. To compute dose consequences for the receptor on the outer boundary of the LPZ, the LPZ $\chi/Q$ factors, Table 4-1 Item 4.3, structured following the methodology presented in Section 4.5, are specified. In addition, breathing rates of 3.5E-4 $m^3$/sec, 1.8E-4 $m^3$/sec, and 2.3E-4 $m^3$/sec corresponding to the first 8 hours, the following 16 hours, and the remainder of the accident duration are specified as recommended in RG 1.183. These specifications as well as the release matrix, Table 4-1 Item 4.1, are then input into the RRCAT code which may then be executed to determine dose consequences 1 and 2 from Section 4.1.

# 5 CONTROL ROOM HABITABILITY EVALUATION MODEL

## 5.1 Objective and Scope

The objective of the CRH EM is to determine, through a conservative, deterministic approach, the dose consequences required to demonstrate habitability in the CR. The source terms analyzed in this EM include DBEs, a subset of LBEs, as well as the major accident source term. The development of these source terms [1] and identification of the major accident source term are outside the scope of this EM. Only the methodology applied to determine the dose consequences of these inputs is described. Similar to the DBA EM described in Section 4, atmospheric transport is accounted for using atmospheric dispersion factors. Several phenomena in addition to atmospheric transport are considered in this EM to determine dose delivered to receptors in the CR during the event duration. These include the flow of radionuclides into the CR considering both air flow and filtration, the change in radionuclide concentration in the CR due to radioactive decay and production of progeny radionuclides and shine dose from several sources. Considering these phenomena, the 30-day TEDE dose received by a CR receptor considering inhalation and submersion dose as well as gamma radiation shine from airborne radionuclides external to the CR, built up on filtration equipment, and held in a compartment before release to the environment, is determined.

## 5.2 Regulatory Requirements and Guidance

The CRH EM is used to determine dose consequences as required by PDC-19 [10]. The language of PDC-19 relating to CR radiological habitability is, “Adequate radiation protection shall be provided to permit access and occupancy of the control room under accident conditions without personnel receiving radiation exposures in excess of 5 rem total effective dose equivalent, as defined in § 50.2 for the duration of the accident.” This criterion is equivalent to limiting the dose consequence described in Section 5.1 to 5 rem. This limit is applicable to each source term for which dose consequences are determined with this EM and as such, constitutes acceptance criterion for CRH. Throughout this EM, the guidance of RG 1.183 [6] and the proposed revision to this RG, DG-1389 [7], is used as applicable.

## 5.3 Evaluation Model Inputs

This EM is limited to the determination of the dose consequence described in Section 5.1 from a source term. As such, several items, including the determination of the radiological source term and atmospheric dispersion factors, are outside the scope of this report. Items that are used in

this EM but developed separately are listed in Table 5-1. Note that the radiological source term analyzed is comprised of several individual inputs to this EM, all of which are listed.

**Table 5-1: Listing of Control Room Habitability Evaluation Model Inputs**

| Input Number | Description |
|---|---|
| 5.1 | The time-dependent, nuclide-specific release of airborne radionuclides to the environment, referred to in this work as the release matrix, from a given location within the Natrium power plant. If an event results in releases from several locations, all release-specific inputs in this table must be provided for all locations. This input is release specific. |
| 5.2 | The specification of radionuclides in the release matrix as either entirely aerosols or entirely vapors. If both aerosols and vapors are released, two release matrices must be specified, each containing entirely aerosol or vapor release information. This input is release specific. |
| 5.3 | The physical description of the compartment from which radionuclides are released to the environment, referred to in this work as the final compartment, including the dimensions, the regions occupied by equipment, and the orientation of the compartment relative to the CR. This input is release specific, but multiple releases may be specified for the same compartment in a given radiological source term. |
| 5.4 | The time-dependent leakage rate from the final compartment to the environment. This input is release specific. |
| 5.5 | $\chi/Q$ factors corresponding to the location of the release and the air intake location of the CR. If there are multiple air intake locations, factors must be provided for each. The 0-2, 2-8, 8-24, 24-96, and 96-720-hour averaging period factors must be included. This input is release specific. |
| 5.6 | The physical description of the CR including the dimensions and the regions occupied by equipment. |
| 5.7 | The description of the CR heating, ventilation, and air conditioning system including all air flow paths and in-leakage from the environment and all filtration equipment. |

## 5.4 Computational Model

With the release matrix and $\chi/Q$ factors for the CR air intake location, Table 5-1 Items 5.1 and 5.5, the inhalation and submersion doses delivered to a receptor standing outside the CR may be computed as described in the DBA EM in Section 4. However, more effort is required to compute the inhalation and submersion doses delivered to receptors inside the CR because the time dependent radionuclide concentration in the CR must be determined considering air flow rates, filtration equipment, radioactive decay, and the production of progeny radionuclides. This calculation is performed by the RRCAT code which implements equivalent mathematical models to the RADTRAD code for the calculation of CR dose consequences.

As described in Section 4.4, the RADTRAD code models several complex phenomena to determine the radionuclide release to the environment, which is an input to this EM, Table 5-1 Item 5.1. Next, the RADTRAD code relates the release to the environment to the concentration

outside the CR using $\chi/Q$ factors. Then, two matrix equations are solved to compute the radionuclide concentration in the CR. The first is the transport equation, Equation 4-6 in NUREG/CR-7220 [9], which considers the removal of radionuclides due to exhaust to the environment or the filtration of air being recirculated as well as the gain of radionuclides due to all, possibly filtered, air flowing into the CR from the environment. The second is the decay equation, Equation 4-10 in NUREG/CR-7220, which considers the removal of radionuclides due to radioactive decay and gain of radionuclides produced by the decay of parent radionuclides. These two equations are solved alternatively by numerically evaluating the analytical matrix exponential solutions. Using this algorithm to compute CR radionuclide concentrations, the inhalation and submersion doses delivered to CR receptors are computed as the product of the integrated radionuclide concentration in the CR, the DCF, the occupancy factor, and either the breathing rate for inhalation dose or the inverse of the Murphy-Campe geometric factor (Murphy, K.G. and Campe, K.M., *Nuclear Power Plant Control Room Ventilation System Design for Meeting General Criterion 19, 13th AEC Air Cleaning Conference* [29], for the submersion dose as specified in Equations 4-48 and 4-50 in NUREG/CR-7220.

Consistent with the DBA EM, the RADTRAD code is not used in this EM because the release matrix input, Table 5-1 Item 5.1, is incompatible with it. Instead, the RRCAT code, which can compute CR receptor inhalation and submersion doses equivalently to the algorithm used in RADTRAD described above, is used. The algorithm implemented is identical to the one described for RADTRAD with minor exceptions including that the transport and decay equations formed and solved separately in RADTRAD are instead formed and solved as one equation which considers the same phenomena. Following the guidance in RG 1.183 [6], the RRCAT code is input with effective dose equivalent DCFs from FGR 12 Table III.1 [15] to compute submersion dose and committed effective dose equivalent DCFs from FGR 11 Table 2.1 [14] to compute inhalation dose. For consistency with the application of FGR 12 DCFs, half-life and decay progeny information input to RRCAT is taken from FGR 12 Table A.1.

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A deficiency of the RRCAT code compared to the RADTRAD code is the limited handling of the chemical form of released radionuclides. The RADTRAD code allows users to specify filtration efficiencies for different chemical forms of airborne radionuclides. The chemical forms of the radionuclides are then tracked, and the corresponding filtration efficiency is applied when evaluating the transport equation. The RRCAT code does not track the chemical forms of radionuclides. As a result, if radionuclides are released in both aerosol and vapor form, two release matrices, each containing only the releases of one form, are required as specified in Table 5-1 Item 5.2. The code is then executed twice, once with each release matrix and corresponding filtration efficiencies input. Note that consistent with RADTRAD, noble gases are conservatively assumed to not be filtered. An additional deficiency of the RRCAT code is that only one set of $\chi/Q$ factors are allowed to be specified for the CR air intake location. If there are CR air intake locations sufficiently separated such that different $\chi/Q$ factors are specified for each location, multiple RRCAT executions are again required. One execution per air intake location is needed. Finally, the RRCAT code only computes dose consequences for a single release matrix at a time. If multiple release matrices are specified, multiple RRCAT executions are again required. The following sections document how the RRCAT code is leveraged to determine the dose consequences for a source term. Throughout, discussion of the RRCAT code considers only one set of CR $\chi/Q$ factors and one release matrix containing a single chemical form. If this is not the case, multiple executions of RRCAT are required and the dose consequences are computed as the sum of independent dose results. [[

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## 5.5 Shine Dose

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## 5.6 Control Room Dose Consequences

To compute the dose consequences for the CR receptor, the limiting release period is determined with a trial execution of RRCAT as described in Section 4.5 with some constant $\chi/Q$ factor in place of the EAB 0-2 hour $\chi/Q$ factor. The CR $\chi/Q$ factors, Table 5-1 Item 5.5, are then structured following the methodology described for the LPZ receptor Section 4.5. A constant breathing rate of 3.5E-4 $m^3$/sec, as recommended by RG 1.183 [6], is also specified. Additionally, the free volume of the CR, deduced from Table 5-1 Item 5.6, is specified as well as occupancy factors of 1, 0.6, and 0.4 corresponding to the first 24 hours, the following 72 hours, and the remainder of the accident duration as recommended in RG 1.183. Finally, the air flow paths into, out of, or recirculating within the CR, Table 5-1 Item 5.7, are specified as well as the efficiency with which radionuclides are filtered from the air flow path. Filtration efficiencies are determined from the description of the filtration equipment associated with the air flow path, Table 5-1 Item 5.7, and the chemical form of the release matrix, Table 5-1 Item 5.2. These specifications as well as the release matrix, Table 5-1 Item 5.1, [[

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## 5.7 Uncertainty Treatment

This EM is applied to DBE and the major accident source terms to demonstrate CRH. Given that the Natrium CR is classified as non-safety-related with special treatment, SSCs with the same classification may be credited to mitigate dose consequences in this EM. Uncertainty related to the behavior of these SSCs, and other EM inputs, is accounted for with bounding conservative assumptions consistent with the intent of this EM to provide a deterministic dose assessment; however, effort should be made to avoid the arbitrary “stacking” of conservative assumptions that lack physical meaning. Note that conservative assumptions made relating to non-safety-related with special treatment SSC operation should bound realistically expected behavior of the SSC not the availability of the SSC as it is credited in this EM.

# 6 CONCLUSIONS ON EVALUATION MODELS

The proposed EMs provide both probabilistic and deterministic methodologies for evaluating the radiological consequences of LBE and DBA source terms. The probabilistic LBE EM utilizes the MACCS code [3] following the NRC LNT example and SOARCA [4] guidance as applicable. This EM will be utilized to determine the radiological consequences of LBEs that are required to be evaluated by NEI 18-04 [5] LBE selection and evaluation Tasks 7a and 7b relating to the F-C Target and QHOs, respectively. The deterministic DBA EM utilizes the mathematical models of the RADTRAD code [9], implemented equivalently in the RRCAT code, and follows RG 1.183 [6] and DG-1389 [7] guidance as applicable to determine offsite dose consequences. The offsite dose consequences determined by the DBA EM may be used to demonstrate compliance with 10 CFR 50.34 [8] dose criteria in accordance with NEI 18-04 LBE selection and evaluation Task 7d. The deterministic CRH EM utilizes the RRCAT code and follows RG 1.183 and DG-1389 guidance as applicable and determines CR dose consequences. The CR dose consequences determined by the CRH EM may be used to demonstrate compliance with the radiological habitability requirements set forth in PDC-19 [10]. In the LBE and CRH EMs, a methodology to address uncertainty associated with model inputs or parameters which applies either a probabilistic or deterministic approach in accordance with the objective of the EM is proposed.

The LBE EM changes required to determine dose consequences to inform the sizing of the PEP EPZ as described in the Natrium PEP EPZ Sizing Methodology ToR [2] are described in the Appendix. The LBE EM may be applied to determine the consequences of any given radiological source term provided all input information listed for the EM is available. This allows the determination of dose consequences of DBA source terms using the modified LBE EM as required by the PEP EPZ sizing analysis.

## 6.1 Computational Model Updates

Several computer codes, MACCS, RRCAT, [[ ]]$^{(a)(4)}$, implement aspects of the methodology described in this ToR. These codes are controlled in accordance with a quality assurance program which complies with 10 CFR 50 Appendix B [32], as engineering computer programs (ECPs). Corrections, changes, and improvements to these ECPs that do not fundamentally alter the modeling capabilities required for the radiological consequence EM in which they are used may be made without prior NRC review and approval. Some examples include changes in the numerical methods to improve efficiency, the addition or enhancement of features that support effective code input/output and automation, or the porting to a new computer platform. Changes which do alter the modeling capabilities required for a given radiological consequence EM and result in increased radiological consequences also may be made without NRC review and approval. Additionally, other computer codes which equivalently implement aspects of the methodology described in this ToR may be used in place of those listed provided they are also controlled by a quality assurance program.

# 7 REFERENCES

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| 17 | SAND2021-11703, "*Preliminary Radioisotope Screening for Off-site Consequence Assessment of Advanced Non-LWR Systems*," Sandia National Laboratories, 2021. |
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| 25 | RG 1.249, Rev.0, "*Use of ARCON Methodology for Calculation of Accident-Related Offsite Atmospheric Dispersion Factors*," NRC, 2023. |
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| 30 | [[ ]]$^{(a)(4)}$ |
| 31 | [[ ]]$^{(a)(4)}$ |
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## APPENDIX - ADAPTATION OF LICENSING BASIS EVENT EVALUATION MODEL TO EMERGENCY PLANNING ZONE SIZING

The PEP EPZ sizing methodology for the Natrium power plant is described in a separate ToR [2] which describes the radiological consequence acceptance criteria for evaluating the EPZ sizing.

The methodology referred to in the PEP EPZ ToR is the licensing basis event EM described in Section 3 of this ToR. Only minor changes to the MACCS code inputs described in Section 3 are needed to produce the two dose consequences evaluated for PEP EPZ sizing: the mean and 95th percentile 4-day TEDE dose at the PEP EPZ boundary, and the 1-day red bone marrow acute dose results at the PEP EPZ boundary as well as various distances beyond.

To output TEDE dose results at the PEP EPZ boundary as required by PEP EPZ sizing methodology, the evaluation duration is reduced from the 30 days considered in the LBE EM to 4 days. Then, the peak dose output option is used. As noted in Section 3.6.7 of this ToR, this output is calculated as the maximum average dose over a fine grid element for all fine grid elements within a radial interval. As such, when the target organ is specified as L-ICRP60ED resulting in TEDE dose being calculated and the inner and outer radii of the radial interval are specified as centered on the PEP EPZ boundary, the resulting output is equivalent to the 4-day TEDE dose at the PEP EPZ boundary.

To output the acute red bone marrow dose results at several distances as required by PEP EPZ sizing methodology, the evaluation duration is reduced from the 30 days considered in the LBE EM to 1 day. Then, the peak dose output option is used again. When the peak dose target organ is specified as A-RED MARR, the 24-hour red bone marrow effective acute dose is computed. For the PEP EPZ boundary and all distances beyond it which are considered in the PEP EPZ sizing analysis, a peak dose value with a target organ of A-RED MARR, inner and outer radii values which are centered on the distance considered, and the CCDF reporting option selected is specified.

With the changes to the MACCS input made as described above, code execution results in the dose consequences required for the PEP EPZ sizing analysis. If uncertain input parameter sampling is used as described in Section 3.7.2 of this ToR, mean and 95th percentile results should be extracted as described for the 30-day TEDE dose in that section.

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