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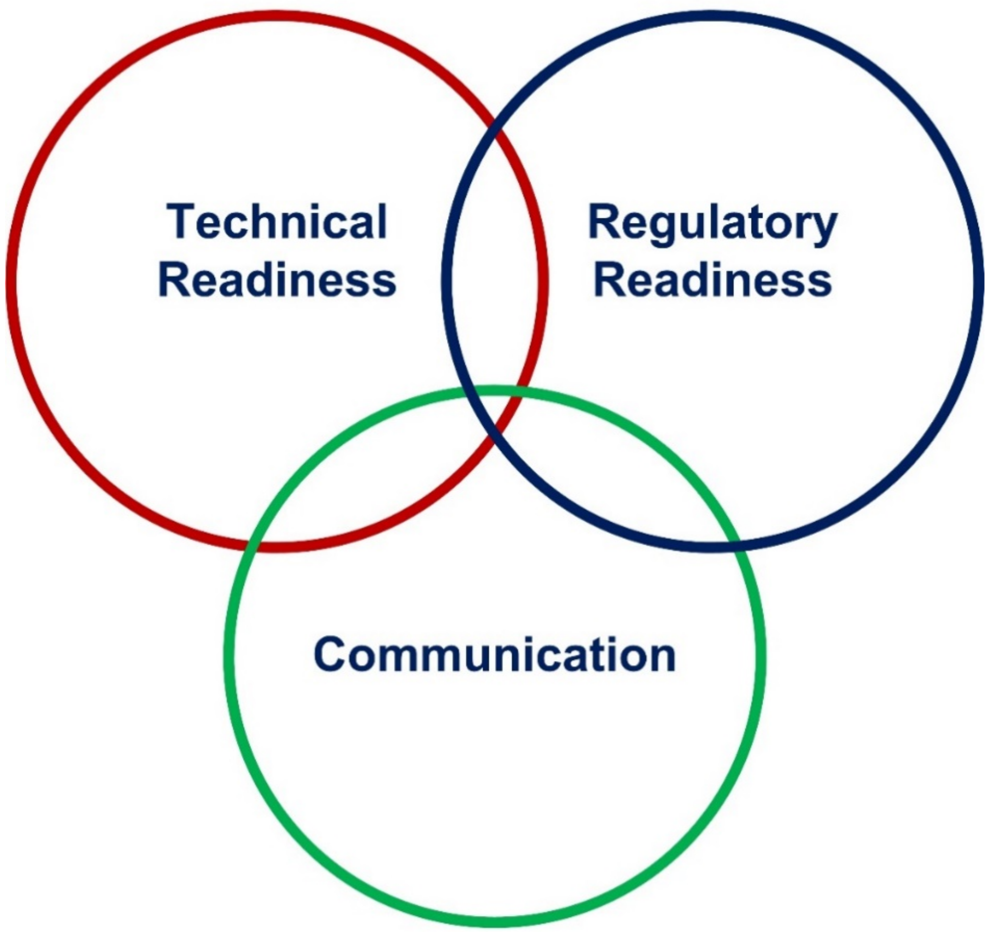
NRC Non-Light Water Reactor (Non-LWR) Vision and Strategy, Volume 4 – *Licensing and Siting Dose Assessment Codes*



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EXECUTIVE SUMMARY

This report describes the vision and strategy to achieve readiness for non-light water reactor (non-LWR) radiation protection and dose assessment codes. It provides an overview of the technical issues related to the different non-LWR design technologies that warrant code development, modifications, and/or literature reviews. These codes provide radiation dose assessments capabilities that encompass nuclear power plant (NPP) licensing (e.g., reactor siting, design-basis accidents and normal effluent releases). The codes also analyze dose assessments for emergency response and severe accidents; atmospheric transport and dispersion (ATD); and site decommissioning regulatory actions.

This report describes the computer codes and how they would be applied and consolidated for the non-LWR design types. It also summarizes the tasks to bring up to date the capability to model and simulate those designs to support the regulatory offices potential review needs. The report is generally oriented toward generic activities that benefit all non-LWRs; however, it does highlight radiation protection issues for specific designs. Moreover, the report suggests ways of leveraging resources with other code updates as described in previous vision and strategy volumes.

The codes have numerous current and legacy issues that call for code consolidation and modernization. The more consolidated and modernized codes will be modular and will have increased ability and flexibility to access designs, fuel types, and non-LWR reactor data as well as to address technical topics and issues related to radiation protection and dose assessments. These technical topics include (1) source term determination accounting for fuel form, geometry, and other relevant characteristics; (2) near-field ATD modeling; (3) selection of dose coefficients[1]; and (4) environmental exposure pathways including tritium and carbon-14 modeling.

This report represents the current and best knowledge of the radiation protection and dose assessment needs for the development of codes for application to advanced non-LWRs. In addition, the report provides tasks that describe what work is proposed to be done to enhance review capabilities for non-LWR licensing. Section 1 introduces the regulatory requirements that may be reviewed using radiation protection and dose assessment codes. Section 2 describes each code and gives examples of their use in various regulatory applications. Section 3 discusses tasks related to code consolidation, non-LWR design technical issues in the codes, and opportunities for leveraging code resources and research with other code programs (i.e., severe accident and neutronics computer codes). Section 4 discusses code readiness, impacts on staff, and regulatory independence, and Section 5 summarizes conclusions. As a living document, this plan will be updated as experience is gained and new information about specific non-LWR design needs are identified.

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[1] "Dose Coefficients" were formerly called "Dose Conversion Factors" in code documentation and literature. In this report, Dose Coefficients will be used to describe both terms.

ABBREVIATIONS

ALARA	as low as is reasonably achievable
ANL	Argonne National Laboratory
ANS	American Nuclear Society
ANSI	American National Standards Institute
ARCON	Atmospheric Relative Concentrations in Building Wakes computer code
ATD	atmospheric transport and dispersion
BDBA	beyond design-basis accident
BWR	boiling-water reactor
CFR	U.S. Code of Federal Regulations
CHEM	computer code of toxic chemicals in control room
Ci	Curies
CR	control room
D/Q	relative deposition factors
DandD	Decontamination and Decommissioning computer code
DBA	design-basis accident
DCFPAK	Dose Coefficient File Package
DEGADIS	EPA dense gas dispersion computer code
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EAB	exclusion area boundary
EIS	environmental impact statements
EPA	U.S. Environmental Protection Agency
EPZ	emergency planning zone
EXTRAN	external transport computer code
FGR	Federal Guidance Report
FHR	fluoride salt-cooled high temperature reactor
GALE	gaseous and liquid effluent computer code
GASPAR	dose analyses computer code for NPP radioactive effluents to the atmosphere
GUI	graphical user interface
HABIT	control room habitability computer code
HTGR	high temperature gas-cooled reactor
ICRP	International Commission on Radiological Protection
LADTAP	dose analyses computer code for NPP radioactive effluents to surface waters
LMR	liquid metal-cooled reactor
LOCA	loss-of-coolant accident
LPZ	low population zone
LWR	light water reactor
MACCS	MELCOR Accident Consequence Code System
MELCOR	Not an acronym
MSR	molten salt reactor
NCRP	National Council on Radiation Protection and Measurements
NEPA	National Environmental Policy Act

NRC	U.S. Nuclear Regulatory Commission
NRCDose	Not an acronym
non-LWR	non-light water reactor
NPP	nuclear power plant
PAG	protective action guide
PAVAN	ground-level χ/Q for accidental release computer code
PCMM	Predictive Capability Maturity Model
PWR	pressurized-water reactor
RADTRAD	Radionuclide Transport, Removal, and Dose Estimation computer code
RADTRAN	Radioactive Material Transport computer code
RAM	radioactive material
RASCAL	Radiological Assessment System for Consequence Analysis computer code
RESRAD	Residual Radioactivity computer code
RG	Regulatory Guide
SCALE	Standardized Computer Analyses for Licensing Evaluation computer code
SFR	sodium-cooled fast reactor
SLAB	DOE denser-than-air releases computer code
SMR	Small Modular Reactor
SNAP	Symbolic Nuclear Analysis Package
TADPLUME	RASCAL atmospheric transport and dispersion model using straight-line Gaussian models for wet and dry plume deposition
TADPUFF	RASCAL atmospheric transport and dispersion model using Lagrangian-trajectory Gaussian puff model for wet and dry plume deposition
TRISO	tri-structural isotropic fuel micro particles
XOQDOQ	computer code for atmospheric dispersion modeling for routine releases
χ/Q	relative air concentrations

1. INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) is preparing to review and regulate a new generation of non-light water reactors (non-LWRs). As part of that preparation, the NRC has developed a vision and strategy to assure their readiness to efficiently and effectively conduct the NRC mission for these technologies including fuel cycles and waste forms. In December 2016, the NRC published the vision and strategy document, “NRC Vision and Strategy: Safely Achieving Effective and Efficient Non-Light Water Reactor Mission Readiness,” in the *Federal Register* [1]. The vision and strategy document provides a connection to other NRC mission, vision, and strategic planning activities and describes the objectives, strategies, and contributing activities necessary to achieve non-LWR mission readiness.

This report provides an overview of technical topics associated with non-LWR design technologies that warrant code development, consolidation, and literature reviews supporting code development activities for a suite of radiation protection and dose assessment codes. These codes provide dose assessment and licensing support that encompasses nuclear power plant (NPP) licensing (e.g., reactor siting, design-basis accidents [DBAs], and normal effluent releases), emergency response and severe accidents, atmospheric transport and dispersion (ATD), and site decommissioning.

Non-LWR designs currently under consideration can be characterized into 10 generic design types [2] and 6 generic fuel designs [3]. For the purpose of this report, these general design and fuel types have been further categorized into four generic classes of non-LWRs to include:

1. Molten Salt Reactor (MSR).
2. High-Temperature Gas-Cooled Reactor (HTGR).
3. Liquid metal-cooled fast reactors (LMFRs).
4. Several stationary and transportable micro reactor designs.

Additional information about these reactors can be found in Section 3 of this report.

1.1 Regulatory Need for Radiation Protection and Dose Assessment Codes

The computer codes provide tools for the NRC staff to perform independent assessments and confirmatory calculations with respect to the regulations in various parts of Title 10 of the *U.S. Code of Federal Regulations* (10 CFR) and NRC regulatory guides (RGs). Figure 1-1 displays the regulatory requirements, four areas of licensing review, and the NRC-developed and maintained computer codes that support the NRC NPP licensing reviews and evaluations. The regulations in various parts of 10 CFR and RGs that apply to code design and development are discussed in the individual code descriptions in Section 2.

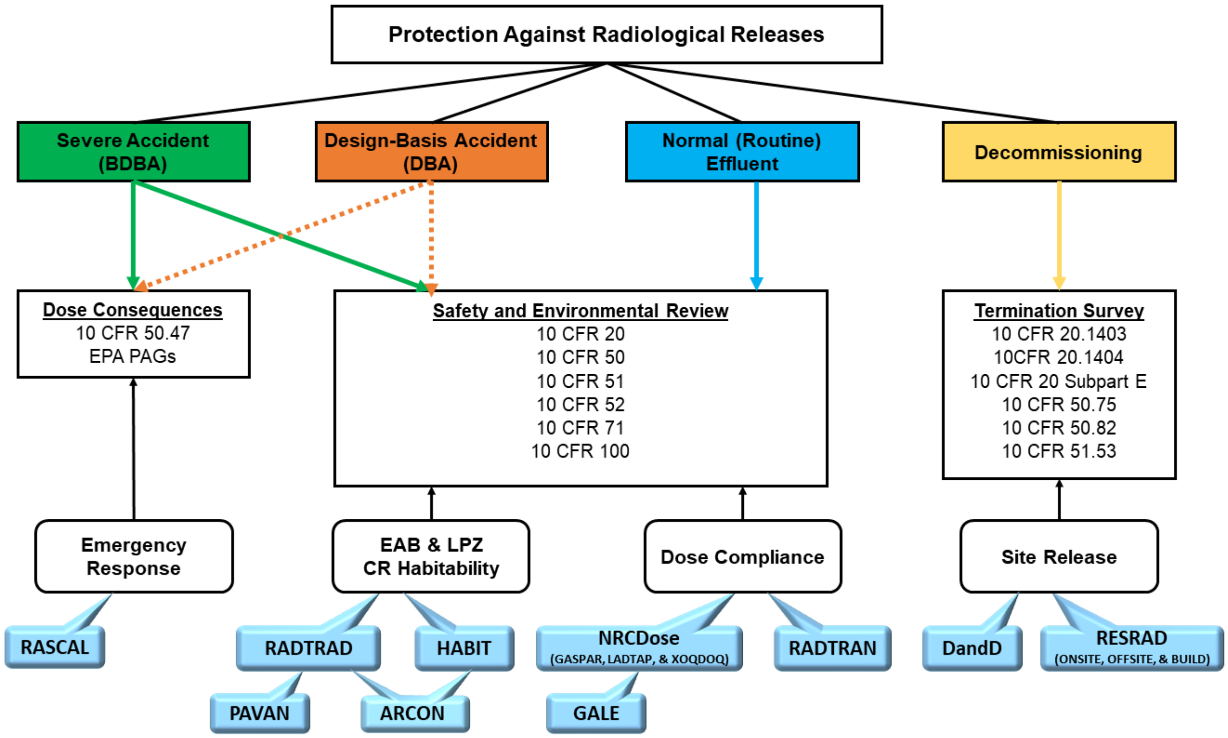


Figure 1-1. NPP Dose Assessment Code Applications and Regulations

1.2 Computer Codes

The specific NRC-developed and maintained computer codes in the above-mentioned areas include the following:

- Licensing Codes Used in Safety Reviews
  - Design Basis Accidents (DBA) – Radionuclide, Transport, Removal, and Dose Estimation (RADTRAD) code.
  - Control room (CR) habitability – Habitability (HABIT) code.
  - Atmospheric Relative Concentrations in Building Wakes in support of CR habitability – ARCON computer code.
  - Ground-level relative air concentrations (χ/Q) for accidental releases – PAVAN code.
- Siting Codes used in Environmental Reviews
  - Normal (routine) effluent source term – Gaseous and Liquid Effluent (GALE) code.
  - Normal (routine) effluent dose assessment and siting – NRCDose code.
    - Atmospheric χ/Q and relative deposition factors (D/Q) for normal (routine) or anticipated effluent releases – XOQDOQ code.

  - Radioactive material transport dose assessment and siting – Radioactive Material Transport (RADTRAN) code.

- Emergency Response Computer Code
  - Radiological Assessment System for Consequence Analysis (RASCAL) code.

- Decommissioning Codes Used in Termination Surveys
  - Decontamination and Decommissioning – DandD code.
  - Residual Radioactivity – RESRAD code.

- Research and Other Purposes
  - GENII – second generation environmental dosimetry computer code.
  - MACCS - severe accident consequence code as described in Volume 3.

Decommissioning codes used in license termination surveys (DandD and RESRAD) are not traditionally part of the licensing and siting process and are considered a lower priority for the purpose of this report. However, they are discussed in this volume to bring attention to the entire life cycle of non-LWRs, not just siting, licensing, and operation. Their need to be evaluated may become more apparent in the mid-term and long-term implementation action plan (IAP). In addition, the GENII code is normally used for research and other purposes but shares similar models and dose endpoints with siting, licensing, and other environmental codes. GENII, DandD, and RESRAD will be considered in this volume as part of the consolidation effort to update all codes for non-LWR readiness.

Other accompanying volumes on computer codes include plant systems analysis, Volume 1, [2]; fuel concepts, Volume 2, [3]; and severe accident progression, source term, and consequence analysis, Volume 3, [4]. Volume 4 computer codes are organized by siting, licensing, environmental, and decommissioning considerations, and most codes have similar endpoints (e.g., doses).

2. DESCRIPTION OF CODES AND THEIR USES

The computer codes discussed in this volume are designed and developed by the NRC and other agencies to support siting, licensing, emergency response and severe accidents dose assessments, atmospheric transport and dispersion (ATD), and decommissioning at conventional large light-water reactors (LWRs). Most computer codes in Volumes 1, 2, and 3 [2, 3, 4] emphasize engineering safety and accident analysis of nuclear power plants (NPPs). While knowledge of reactor plant systems and operations are important as described in these three volumes, the overall purpose of the computer codes described in this volume is to assess doses to human and non-human biota. As such, this section describes codes, regulations, guidance, inputs from other computer codes, and data sources that demonstrate protection of public health and the environment. Finally, this section gives examples of codes use by NRC staff and programs.

2.1 Description of Codes

2.1.1 Codes Used in Siting and Licensing

SNAP/RADTRAD

RADTRAD [5, 6] is a licensing confirmatory code used for various design-basis accident radiological consequences calculations including loss-of-coolant accident (LOCA) scenarios. The code is joined at the front end to a Symbolic Nuclear Analysis Package (SNAP) graphical user interface (GUI) and is referred to as SNAP/RADTRAD in this report. SNAP/RADTRAD is used by the NRC staff and NPP licensing organizations to calculate doses to demonstrate compliance with the nuclear plant siting criteria [7] at the Exclusion Area Boundary (EAB) and the Low Population Zone (LPZ). It is also used to calculate occupational radiation doses within the control room and/or other emergency onsite facilities [8, 9].

The SNAP/RADTRAD code provides options for the user to select from various DBA fixed parameters for LWRs including: (1) pressurized-water reactor (PWR) and boiling-water reactor (BWR) core inventories; (2) LOCA source term release fractions from NUREG-1465 [10], TID-14844 [11] or the alternative source term RG 1.183 [12]; and (3) dose coefficients [13, 14]. The code also provides options and features such as (1) reactor coolant system activity calculator that includes iodine spiking using plant inputs and (2) source term scenario flexibilities that allow the user to model radionuclide release fractions and timing for other than LOCA DBA using plant inputs (i.e., alternate source term scenarios [12] – fuel handling accident, BWR control rod drop and main steam line break accidents, and PWR steam generator tube rupture, rod ejection, and locked rotor accidents). The code is also flexible because it allows users to select "user-defined" core inventories for release, release fractions, and dose coefficients. SNAP/RADTRAD has an active user base with over 100 users and is currently being maintained by NRC contractors. Additional efforts are underway to explore the SNAP framework usefulness for other radiation and dose assessment codes and is discussed in Section 3.

HABIT

HABIT [15, 16] is a licensing confirmatory code used to examine control room habitability following a postulated release of toxic chemicals based on regulations [17] and RG 1.78 [18]. It does not evaluate radiological dose. The code consists of four Fortran codes connected through a common GUI to include: (1) the external transport (EXTRAN) computer code, (2) the CR chemical (CHEM) computer code, (3) the U.S. Environmental Protection Agency's (EPA's) Dense Gas Dispersion (DEGADIS) code [19], and (4) the U.S. Department of Energy's (DOE's) denser-than-air releases (SLAB) [20] computer code. The EXTRAN code includes a Gaussian puff dispersion ATD model to disperse toxic substances. The CHEM code models the dilution of the chemical concentrations estimated by the EXTRAN code based on air flows into the control room and determines the chemical exposure to personnel. In addition, the code evaluates the toxic chemical releases to determine the importance of denser-than-air effects [21, 22]. HABIT has an active user base with over 20 users and is currently being maintained by NRC contractors.

GALE

GALE [23, 24] is a siting and licensing confirmatory code used to estimate annual routine releases (activity per year) in radioactive gaseous and liquid effluents from PWRs and BWRs based on several regulations [25, 26] and RG 1.112 [27]. The code consists of four separate Fortran code modules: the PWR Gaseous and Liquid Effluent (PWRGE and PWRLE) modules and the BWR Gaseous and Liquid Effluent (BWRGE and BWRLE) modules, controlled by a single GUI. The reactor coolant normal source term options, as described in ANSI/ANS 18.1 (i.e., 1984, 1999, or 2016) [28, 29, 30] and which are included in GALE, are based on actual NPP operating experience. GALE is not currently being developed, and its user base is small because it is used mostly for siting of PWR and BWR LWRs.

NRCDose

NRCDose [31] is a siting and licensing confirmatory code used to estimate offsite doses from liquid and gases radioactive releases from normal NPP operations. The code is a software suite of three codes: LADTAP II, GASPAR II, and XOQDOQ. The three codes implement the NRC's as low as is reasonably achievable (ALARA) requirements for radioactive effluents from NPPs from Appendix I of 10 CFR Part 50. NRCDose incorporates the dose coefficients and dosimetric principles for workers and the public [32, 33].

LADTAP II [34] implements the liquid pathway models in RG 1.109 [35] and RG 1.113 [36] and estimates doses to individuals, population groups, and biota from ingestion of aquatic foods, water, and terrestrial irrigated foods and external exposure from boating, swimming, and shoreline recreational activities. GASPAR II [37] implements the atmospheric pathway models in RG 1.109 [35] and RG 1.111 [38] and estimates doses to individuals and population groups and biota from inhalation of contaminated air, direct exposure from ground, and consumption of food. The calculated doses of LAPTAP II and GASPAR II provide information for National Environmental Policy Act (NEPA) evaluations. Use of GASPAR II requires atmospheric dispersion/deposition inputs from XOQDOQ.

XOQDOQ [39] implements atmospheric pathway modeling in RG 1.109 [35] and RG 1.111 [38] and is used by the NRC meteorology staff in their independent meteorological evaluation of routine or anticipated intermittent releases from NPPs. XOQDOQ calculates the annual effluent χ/Q and annual average relative deposition factors (D/Q) at locations specified by the user and at various standard radial distances and segments for downwind sectors out to 80 km. The model is based on a straight-line Gaussian model and the code accounts for variation in the location of release points, additional plume dispersion due to building wakes, plume depletion via dry deposition and radioactive decay, and adjustments to consider non-straight trajectories.

NRCDose, which is currently being maintained by NRC contractors, has an active user base that includes NRC staff, licensees, and international organizations.

RADTRAN

RADTRAN [40] is a siting code used to estimate doses from routine and accident scenarios of transportation of radioactive material (RAM) including spent nuclear fuel [41]. The code estimates incident-free population dose, accident dose, and risk and non-radiological traffic mortality from road, rail, air, and water. RADTRAN also has a dispersion, ingestion, and economic model. The code is used in assessments for environmental impact statements (EISs) [42] pursuant to the NEPA requirements and NRC and U.S. Department of Transportation (DOT) regulations [43, 44, 45, 46]. These regulations establish maximum permissible package dose rates, maximum permissible dose rates to vehicle crew members, and other features of RAM transportation. RADTRAN has an active user base that includes NRC staff and licensees, DOE and DOE contractors, DOT contractors, and international organizations. It is currently being maintained by NRC contractors.

ARCON

ARCON [47] is a licensing confirmatory code used to calculate short-term (accident) χ/Q in support of control room habitability assessments as described in RG 1.194 [48]. The code uses a straight-line Gaussian ATD model that assumes a constant release rate. This assumption is made to permit evaluation of the potential effects of accidental releases without having to specify a complete release sequence. It uses hourly meteorological data and the atmosphere's influence (i.e., dilution and dispersion) near buildings and low-wind-speed conditions to calculate the χ/Q at CR air intakes. ARCON implements improved building wake and low-wind-speed dispersion algorithms; assessment of ground level, building vent, elevated, and diffuse source release modes; use of hour-by-hour meteorological observations; sector averaging; and directional dependence of dispersion conditions. The ARCON code is currently under maintenance, and its user base is small because it is used mostly for NPP LWR siting and Small Modular Reactor (SMR) licensing.

PAVAN

PAVAN [49] is a siting and license confirmatory code used to estimate relative ground-level short term χ/Q resulting from releases from design-basis accidents, usually at the EAB and outer boundary of the LPZ. PAVAN was developed because regulations require that meteorological conditions at the NPP site and surrounding area should be considered when determining the acceptability of a site. NRC guidance [50, 51] provides the methodology and technical basis for estimating ground-level short-term χ/Q due to plume meandering during the occurrence of stable atmospheric conditions and the recognition that atmospheric dispersion conditions are directionally dependent.

PAVAN uses joint frequency distributions of wind direction, wind speed, and atmospheric stability class to estimate χ/Q values for specific averaging time periods at specified distances. The model is based on a straight-line Gaussian ATD model that assumes the release rate is constant for the entire period of the release. PAVAN is not actively developed.

2.1.2 Code used in Emergency Response

RASCAL

RASCAL [52, 53] is an emergency response code used to perform independent dose and consequence projections during radiological incidents and emergencies, including severe accidents. It was designed to provide scientifically defensible dose projections within 15 minutes of the occurrence of the event to support protective action decisions. RASCAL models LOCAs, long-term station blackouts, steam generator tube ruptures, and spent fuel pool and transportation accidents. The methods used in the RASCAL source term are from numerous sources [54, 55, 56, 57], and user-defined releases from the plant can also be used as inputs. It has two ATD models—one called TADPLUME, which is used near the release point, and the other called TADPUFF, which is used at longer distances, for which meteorological conditions may be significant.

The dosimetry calculations performed by the RASCAL code employ dose coefficients [12,13, 58], and the code is written to provide dose results to compare to the EPA's Protective Action Guides (PAGs) [59]. RASCAL is actively maintained and has over 500 users including the NRC staff, State Emergency Response Centers, other Federal agencies, and the international community.

2.1.3 Codes used in Decommissioning

By regulations, NPP licensees are required to include a license termination plan in writing to the NRC before performing any decommissioning activity [60, 61]. The terminal radiation survey and associated documentation demonstrate that the facility and site are suitable for release in accordance with the criteria and guidance for decommissioning [62, 63, 64, 65, 66].

DandD

DandD [67] is used to support decommissioning by performing estimates of the annual dose from residual radioactivity remaining in soils and on building surfaces at the time of license termination. It is used to assess compliance with the dose criteria of 10 CFR Part 20, Subpart E. Specifically, DandD embodies the NRC's guidance on screening dose assessments to allow licensees to perform simple estimates of the annual dose from residual radioactivity in soils and on building surfaces. DandD is actively used by simple decommissioning sites, but there is no active development of the DandD computer code.

RESRAD

The RESRAD family of codes consists of a set of individual computer codes that evaluate the radiological impacts of residual radioactivity at facilities and sites. Two of the RESRAD codes, RESRAD-ONSITE [68] and RESRAD-BUILD [69], are commonly used by the NRC's decommissioning licensees. These codes have been approved by the NRC for use by licensees to demonstrate compliance with radiological criteria for license termination found in 10 CFR Part 20, Subpart E. RESRAD-OFFSITE [70] can also be used to evaluate the radiological impacts to offsite receptors, although data requirements for this code are significantly higher and may be cost prohibitive for simpler sites. RESRAD-OFFSITE is not commonly used by the NRC's decommissioning licensees.

Both RESRAD-ONSITE and RESRAD-OFFSITE are designed for estimating radiation doses and cancer risks to an individual from radioactively contaminated in soils. Both codes include nine exposure pathways (e.g., air, water, food, inhalation, ingestion) any of which can be selected or suppressed to reflect the land use and receptor scenario under consideration. In addition, RESRAD-OFFSITE employs a more complex Gaussian plume ATD model to calculate concentrations at downwind locations compared to the simpler model used in RESRAD-ONSITE to calculate air concentrations to an onsite receptor. Both codes include age-specific dose coefficients as well as morbidity or mortality slope factors in its database.

RESRAD-BUILD is designed for analyzing radiation exposures resulting from contaminated buildings, equipment, or furniture as well as the radiation exposure results from remediating the contamination. Exposure pathways include direct external radiation, inhalation of airborne contaminated dust particles, inhalation of radon, and incidental ingestion of contaminated dust particles.

The RESRAD family of codes has a long, active development history and over 400 users including DOE, the NRC, the nuclear industry, academia, and domestic and international research organizations. It is similar to MACCS (Volume 3) [4] because it is a probabilistic consequence code, but it was developed for decommissioning purposes, not for probabilistic risk assessment (PRA) Level III analyses.

2.1.4 Codes Used for Research and Other Purposes

GENII

The GENII [71] computer code is used for probabilistic consequence analysis for research and other purposes at the NRC. GENII models atmospheric releases of radioactive materials into the environment and the subsequent consequences of such releases. GENII uses probabilistic modeling of most technical elements of the PRA methods including radionuclide release, atmospheric transport and dispersion, meteorology, site data, dosimetry, health effects, and uncertainty. The GENII code has a long, active development history and a broad user base including the NRC, DOE, the EPA, the nuclear industry, academia, and domestic and international research organizations. The code’s applications are numerous and include environmental analysis of severe accident mitigation alternatives and design alternatives, PRA-type studies, consequence analyses, and other risk-informed activities. GENII can also be used for calculations of dose exceedance at distance to inform emergency planning and other types of decisions. Finally, the GENII code has the ability to model lakes and rivers.

GENII is similar to MACCS [4], but it was mostly developed for DOE and EPA needs and is mostly used for compliance analyses (e.g., DOE Hanford Site annual reports); environmental impact statements (e.g., Yucca Mountain pre-closure assessments); and research evaluations of novel exposure scenarios. The GENII code is used infrequently by the NRC staff but was used after Fukushima to assess severe accident consequences and can be used as a confirmatory code (i.e., SHINE Medical Technologies application).

Several other major computer code systems and data sources that provide inputs used by the NPP siting and licensing codes are described above. These computer codes include:

- The Standardized Computer Analyses for Licensing Evaluation (SCALE) code system and MELCOR are used in development of core radionuclide inventory and severe reactor accident source terms as described in Volume 3 [2] and

- The Dose Coefficient File Package (DCFPAK) that includes nuclear decay data and dose and risk coefficients for exposure to radionuclides.

Table 2-1 summarizes the siting and licensing codes described in this volume including the functions, descriptions, and major uses and endpoints.

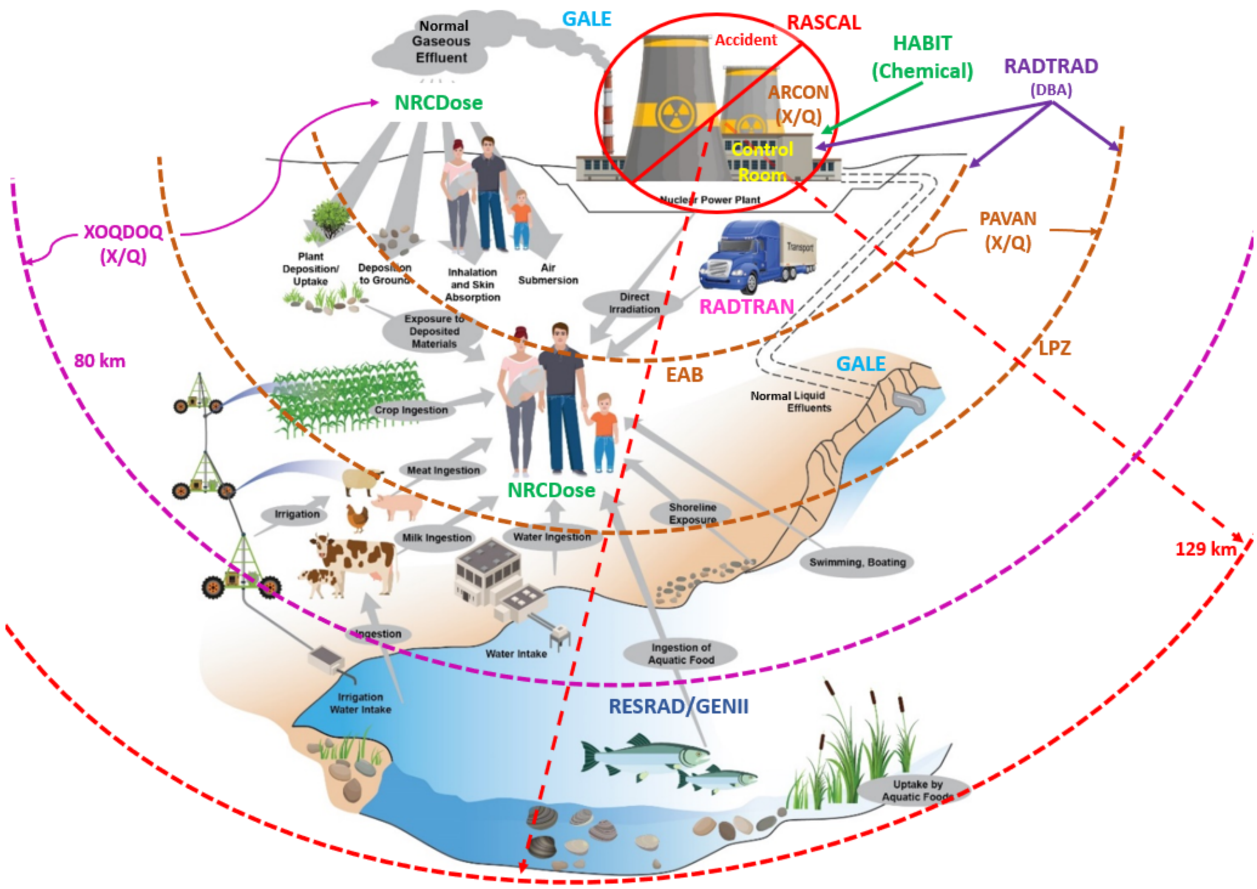
Table 2-1. NPP Dose Assessment Codes.

Regulatory Function	Code	Major Use	Major Dose Endpoints
Siting and Licensing Codes	SNAP/RADTRAD	DBA	Doses at the CR, onsite Technical Support Center, EAB and LPZ
	HABIT	Chemical Accidents	Chemical Exposure at CR
	GALE	Normal Effluents/Operation	Activity/Year
	NRCDose[1]	Normal Effluents/Operation	Doses to Population
	RADTRAN	Transportation	Doses to Population
	ARCON	DBA (ATD)	Short-term χ/Q at CR, site boundary in SMRs
	PAVAN	DBA (ATD)	Short-term χ/Q at EAB and LPZ
	XOQDOQ	Normal (ATD)	Annual effluent χ/Q (Far-Field 80 km), Annual-average D/Q
Incident Response Operations	RASCAL	Emergency Response	Dose Consequences to compare to EPA PAGs
Decommissioning	DandD	Screening Tool	Dose to Resident Farmer
	RESRAD	Probabilistic Doses	Doses to resident farmers, etc.
Other	GENII	Various	Various

Note 1 The NRCDose code includes the XOQDOQ Fortran code.

2.2 Overview of Code Usage

Most computer codes in this volume require a general knowledge of plant systems and components and accidents (design basis and severe) but are geared toward radiological health impacts on humans and non-human biota. In addition, most computer codes described in this volume were developed and are used independently of each other. For example, siting and licensing codes were developed independent of emergency response codes, and decommissioning codes have been developed with no direct relationship to the NPP siting process. While this is normal and necessary, it produces codes with overlapping models and functions. Figure 2-1 depicts the source term and dose pathways along with the codes that are used to perform different analyses. The discussions below explain how some codes are similar and give examples of how they are used by the NRC staff.



Note: Image adapted from: Soldat, J.K., N.M. Robinson, and D.A. Baker. 1974. "Models and Computer Codes for Evaluating Environmental Radiation Doses." BNWL-1754, Pacific Northwest Laboratories, Richland, Washington. ADAMS Accession No. ML12223A187.

Figure 2-1. Conceptual Model for Source Term to Dose Pathway

As stated above, codes such as GALE, SNAP/RADTRAD, and RASCAL require knowledge of radionuclide fuel inventory, reactor coolant inventory, plant design, and operations. These data are used to generate a source term that, for the purpose of this volume, is defined as radioactivity to the environment. GALE generates a normal source term reactor coolant activity and normal operational effluent data; SNAP/RADTRAD and RASCAL assume the radiological release to the containment and other user inputs (e.g., in-containment deposition rate, containment leak rate) to calculate a radiological release to the environment. Other codes, such as RADTRAN and RESRAD, require the analyst to input source terms from other sources, usually data from radiological surveys.

Once the source term is known, most codes use ATD models to carry the radioactivity to different receptors. The atmospheric codes ARCON and PAVAN are used to develop χ/Q values at different locations for use in other codes such as SNAP/RADTRAD. In addition, other codes have the ATD modeling codes embedded in them, such as RASCAL, and the NRCDose code has the XOQDOQ ATD code embedded in it. As noted earlier, the XOQDOQ code can be used either independently or in conjunction with the NRCDose code to develop χ/Q values out to 80 km. Once the radioactivity reaches the environment, environmental pathway models in codes such as NRCDose (GASPAR II and LADTAP II), RESRAD, and GENII model the dose to human and non-human biota. These codes have numerous pathway models such as direct external radiation, inhalation of airborne radionuclides, and ingestion of soil, water, and foods.

Once inhaled or ingested, dosimetry models are employed in most of the codes. These models include radiation and tissue weighting factors, metabolic and biokinetic information that produces a radiation dose based on the intended use of the code. For example, RASCAL calculates a thyroid dose because that organ is more sensitive during emergencies, and the EPA PAG Manual includes a child thyroid dose value as an early phase PAG for supplementary administration of potassium iodide [KI]. NRCDose calculates activity over an entire year to the population because it is a siting and licensing code used for normal effluent emissions, and RESRAD calculates dose from soil resuspension because it is used in decommissioning.

2.2.1 Use of RASCAL by the NRC

During NPP exercises and the unlikely event of an incident, the RASCAL code is used in the NRC Headquarters Operation Center and the Regional Incident Response Centers to evaluate licensee's protective actions recommendations with scientifically defensible dose projections within 15 minutes of the occurrence of the release event. This is to ensure that State and local officials have the data needed to make protection action decisions (e.g., shelter or evacuate) based upon the observed and forecasted meteorological conditions. In the event of an exercise or actual NPP accident with an anticipated release, the dose analyst inputs real time data such as the reactor shutdown time, core uncovered/recovery time, and release pathways in the RASCAL code. These real-time data are coupled with hard-wired data (i.e., radioactivity inventories, release fraction, and timing sequences) to generate a time-dependent inventory available for release into the environment. Based on real time accident progression data, the RASCAL analyst chooses options that best characterizes the release pathway of the time-dependent inventory available for release to the environment. Figure 2-2 provides examples of the RASCAL GUI screens available to make quick source term selections based upon plant conditions. In addition, Figure 2-3 provides an example of RASCAL GUI menu options that show the environmental release pathway options available to the analyst.

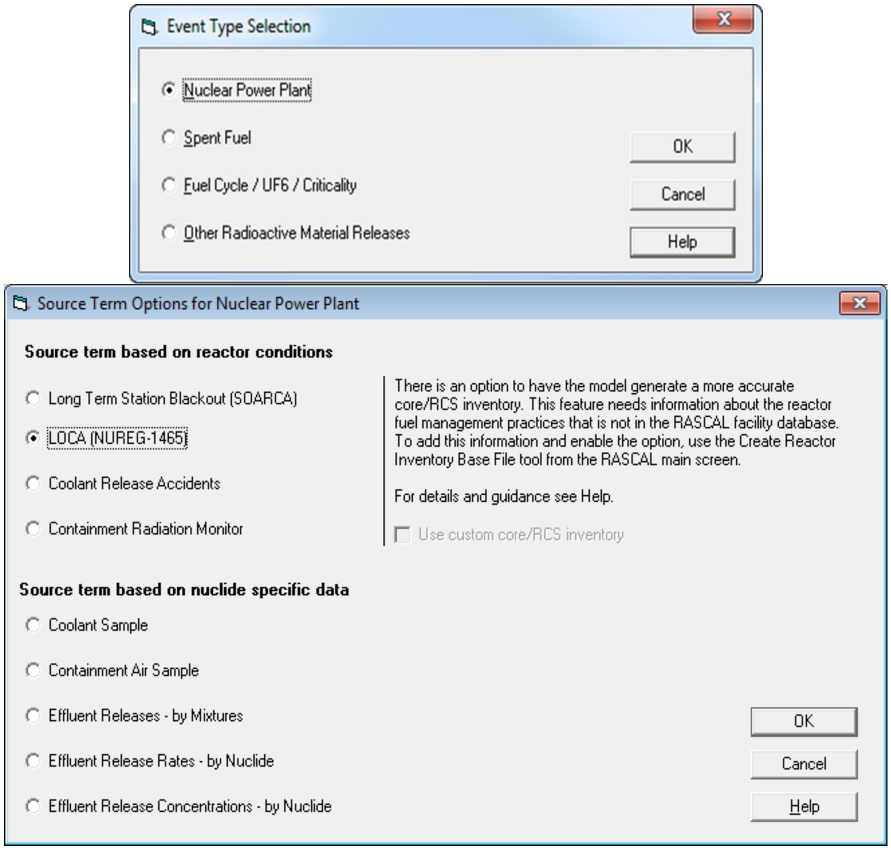


Figure 2-2. RASCAL GUI Source Term Options

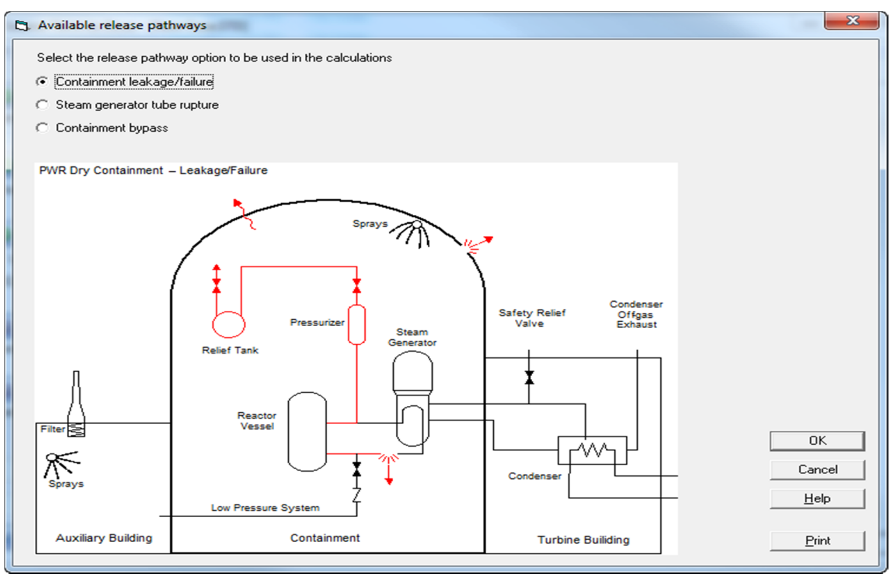


Figure 2-3. RASCAL GUI Release Pathway Options

After codes such as RASCAL calculate a source term and release rates to the environment, the ATD models along with the meteorological data and the dosimetric models are used to perform dose and consequence calculations at various distances. Figure 2-4 shows typical RASCAL output products that provide both tabular and graphical displays. State and local officials can use this data to make protective action decisions (e.g., shelter in place, evacuate, and administer potassium iodide [KI]).

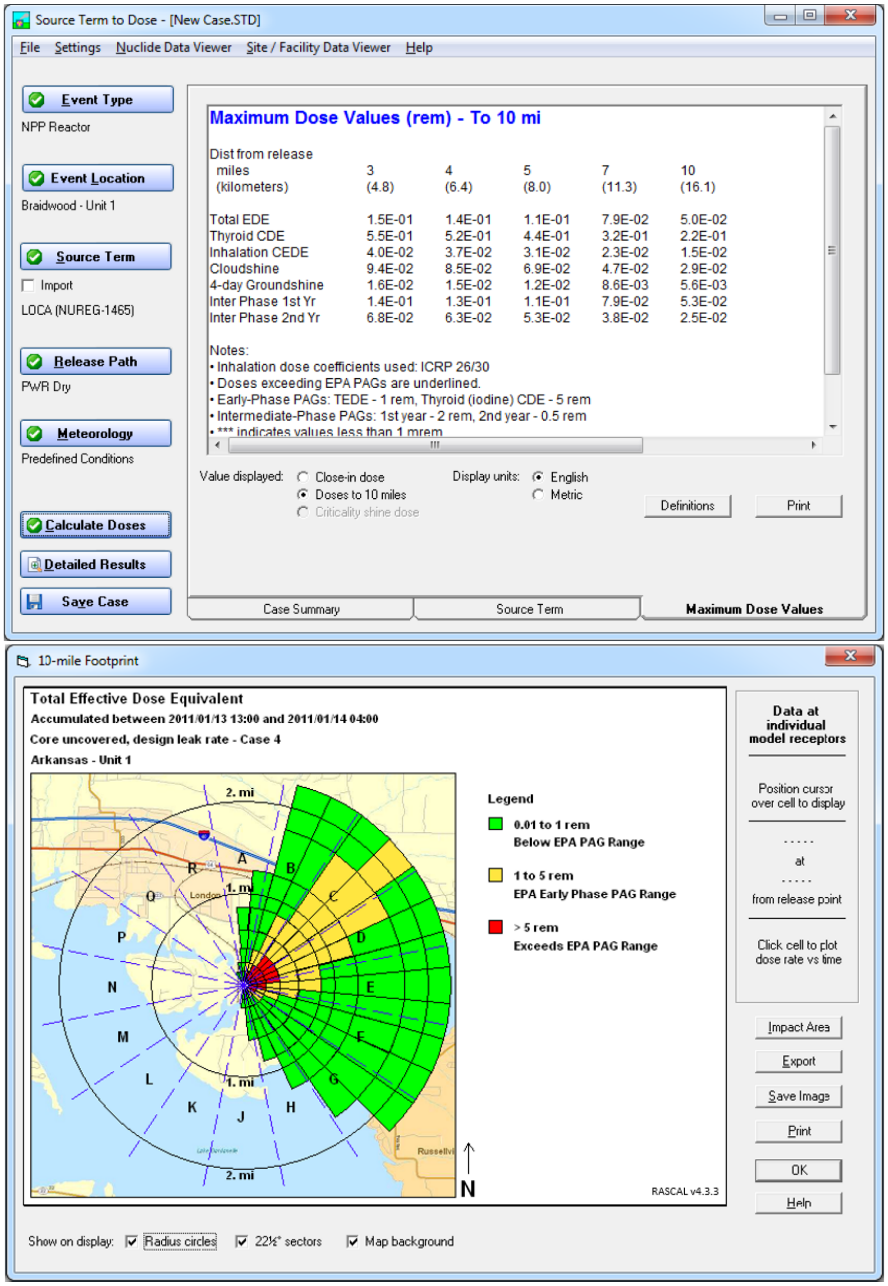


Figure 2-4. RASCAL Outputs

The RASCAL code is designed for rapid response decision-making during radiological incidents and emergencies, while the MACCS [72] code is designed for detailed emergency planning and research. As such, the required code inputs, outputs and user expectations for the RASCAL and MACCS codes are very different for their respective user communities. The MACCS code requires many more inputs and data points and can require several hours to days to setup and run calculations. For example, MACCS is often run with on the order of 1,000 weather trials and then reports average consequence measures over the large number of weather simulations. Therefore, it is aptly suited for accident consequence studies including emergency planning and post-accident/incident forensic analysis that do not require rapid dose projections for protective action decisions. As stated above, the RASCAL dose analyst is required to input severe accident plant conditions, analyze weather data, and select appropriate dosimetric models in a matter of minutes in high-stress environments. In addition, during NPP incidents, RASCAL dose analysts must be able to quickly run several "what if" scenarios during the event as plant conditions become better understood during the incident. RASCAL uses real-time observation and forecast meteorological data from the U.S. National Weather Services that can be downloaded by the RASCAL dose analyst in under 5 minutes depending upon the number of meteorology stations the user selects.

While the end user needs are different for each code, the RASCAL and MACCS codes do have many similarities in their underlying calculational methods and models. For example, both code use Gaussian plume models for atmospheric transport and similar vintages of dose coefficients. As such, the RASCAL and MACCS code resources are being leverage in these areas as discussed in Section 3. This allows the somewhat limited code development resources for code development to be used more effectively while ensuring the needs of their respective user communities are met.

2.2.2 Use of Other Codes by NRC Staff and Stakeholders

RADTRAN is used to evaluate transportation accident consequences in an EIS to address NEPA requirements and in spent fuel transportation risk assessment documents. RESRAD is used in the decommissioning process to show compliance with the license termination rule. ARCON and PAVAN are used for both siting and licensing reviews, depending on the application and submittal. They are used by NRC meteorology staff and NPP licensees to calculate χ/Q values for the near field (~100's m) and mid-field (~10 km) for the control room (CR), EAB and LPZ for use in DBA calculations in SNAP/RADTRAD. XOQDOQ calculates the annual effluent χ/Q in the far-field (80 km) and is used by staff and NPP licensees to determine the routine release doses to offsite locations as part of their Offsite Dose Calculation Manual assessments. In addition, many existing NPP licensees use ARCON and PAVAN for updating dispersion analysis and because these codes are not LWR-specific, they are also being used by non-LWR applicants.

In addition to their primary use, some codes were developed for secondary purposes. For example, RASCAL can also analyze transportation accidents, similar to RADTRAN; NRCDose can calculate doses to non-human biota, similar to GENII; and most codes have ATD models based on ARCON, PAVAN, and XOQDOQ. These examples are not all inclusive but show the overlapping nature of many of these codes. For this reason, code consolidation should be highly considered and supported and will be discussed in Section 3 of this document.

3. CODE DEVELOPMENT PLANS FOR NON-LWRS

Although independently developed, most of the NPP dose assessment codes have three major components: (1) source term input, in-plant transport, and release to the environment; (2) ATD model and environmental pathway models; and (3) a dose consequence component. These codes were integrated to address similar issues across NRC program offices and a wide range of stakeholders (e.g., other Federal agencies and Agreement States) and most licensee categories (e.g., NPP, non-NPP, and decommissioning). This section will describe how the independently developed codes can be consolidated to accept non-LWR technologies.

Many different non-LWR technologies under design considerations are being developed by potential commercial applicants. Descriptions of 10 major plant design types and 6 fuel types are briefly described in Volumes 1 and 2, respectively. Brief descriptions of the four major design types are provided below, and some of the unique non-LWR safety issues are described in the subsection. Non-LWR dependent safety concerns are also described in the sections below.

- Molten salt reactors (MSRs) come in several varieties. Many designs use molten fluoride salt, while others use chloride salts as the coolant. Some designs have stationary fuel rods or plates, while others have moving fuel pebbles or fissile material dissolved within the flowing reactor coolant. In addition, some MSRs use a fast neutron spectrum, while others use a thermal neutron spectrum. Fluoride salt-cooled high temperature reactors (FHRs) refers to a hybrid design that uses pebble fuel elements (like pebble bed high-temperature gas-cooled reactors [HTGRs]) and a fluoride salt coolant (like salt-cooled MSRs). Some fixed-fuel FHR designs (like prismatic HTGRs) have been proposed, but none are currently under commercial consideration. MSR designs are being proposed by Kairos, Terrestrial Energy, TerraPower, and others.

- High-temperature gas-cooled reactors (HTGRs) refer to graphite-moderated, helium-cooled systems using tri-structural isotropic (TRISO) fuel micro particles. The TRISO particles are packed into a graphite matrix to form either spherical or cylindrical fuel elements. The pebble bed version of the HTGR uses spherical billiard ball-sized fuel elements that flow continuously through the reactor. The prismatic version of the HTGR uses the cylindrical fuel compacts in hexagonal blocks in a fixed geometry. HTGRs may be used for electricity production and/or process heat applications. HTGR designs are being proposed by X-Energy, General Atomics, Framatome, and others.

- Liquid metal-cooled fast reactors (LMFRs) include sodium-cooled reactors and lead-cooled reactors. LMFRs are classified based on the liquid metal coolant used such as sodium, lead, and lead bismuth eutectic alloy. Sodium fast reactors generally refer to fast neutron spectrum systems that have metal alloy fuel in a densely packed core within a liquid sodium coolant pool. Sodium-cooled fast reactors are being proposed by GE-Hitachi, TerraPower, and others. Lead- and lead bismuth-cooled fast reactors are being proposed by Westinghouse, Columbia Basin Consulting Group, and others.

- In addition, several stationary and transportable micro reactor designs are being proposed. Heat pipe reactors have been proposed for low-power level applications in remote areas. Heat pipe reactors are relatively small reactors in which the sodium or potassium coolant is contained within heat pipes and is not pumped through a primary system. Westinghouse, Oklo, and others are proposing micro reactor designs.

As discussed in the Section 2, some of the NPP siting and licensing codes are actively developed and maintained by staff and/or contractors, while others are not as actively maintained. Some codes may not be updated until an immediate programmatic need exists (e.g., a licensing action) or until codes need to conform to an operating system change (e.g., upgrading to Microsoft Windows 10). Most of these codes are rigid in their application and were developed under the constraints of older limited computing power and operating systems that resulted in many parameters being hard-wired into the code with limited user options to change these parameters. In addition, the degree of implementation of software quality assurance among the NPP siting and licensing codes tends to differ, based on the needs of stakeholders. Over the years, these practices have resulted in codes that may not be completely compatible or consistent even though they calculate very similar endpoints (e.g., doses).

For a few codes (e.g., SNAP/RADTRAD), different characteristics of non-LWRs technologies can be easily and reasonably addressed by modifying selected input parameters, such as the core inventory file and source term release fractions and timing parameters. However, to address the non-LWR technologies for the variety of regulatory actions (e.g., siting and licensing, emergency response, NEPA analysis) these codes are used for, consolidating codes with redundant models is a more efficient use of resources.

This section describes the specific numbered tasks that address some of the existing non-LWR model challenges to be evaluated for the existing codes including how they can be leveraged with tasks described in other volumes.

3.1 Code Consolidation and Modernization (Task 1)

The first task is to establish a code consolidation framework including the ability to perform analyses for all non-LWR designs and fuel types. Given the large number of non-LWR technologies being conceived and developed, it will be resource intensive to modify each of the siting, licensing, and emergency response codes for each design type. Therefore, the staff is proposing to consolidate and integrate them into a code that is modular, flexible, efficient, and user-friendly. Moreover, code consolidation is necessary to optimize the use of resources and because the codes have numerous current and legacy issues that limit their ability to assess non-LWR designs.

These issues include the following:

- Inefficiencies of having and maintaining multiple codes with the same models.
- Functional redundancy between codes.
- Hard-wired outdated models within the codes.
- Rigid and outdated data handling and transfer methods.
- Lack of standardized code writing.
- A history of changing ownership and associated loss of code knowledge.
- Inconsistent maintenance.

- Lack of standardized quality assurance.

As stated above, dose assessment for NRC licensing has historically consisted of determining the source term, dispersing the source term into air, and determining environmental accumulation and consequences to humans. Therefore, modules within the consolidated code will be grouped or characterized within this general dose assessment approach. In addition, modules will be further broken down into scientific disciplines to account for the unique differences of these fields. The proposed consolidated code would have several modules or components each of which will contain like phenomenological models from the existing LWR codes. The eight modules of the consolidated code include:

- Source term (i.e., core inventories and release fractions and timing sequences).
- ATD model including near- and far-field models.
- Aquatic pathways (ocean/river/lake dispersion).
- Environmental accumulation.
- Human biota consequences.
- Non-human biota consequences.
- Dose coefficients and health risk factors.
- An integrated dose GUI.

Figure 3-1 is a conceptual diagram of the proposed consolidated code paradigm showing how the physics models from the existing siting and licensing codes could be integrated into the new consolidate code. Descriptions of each eight conceptual modules and how they are related to codes, including non-LWR capabilities, are discussed in the task below.

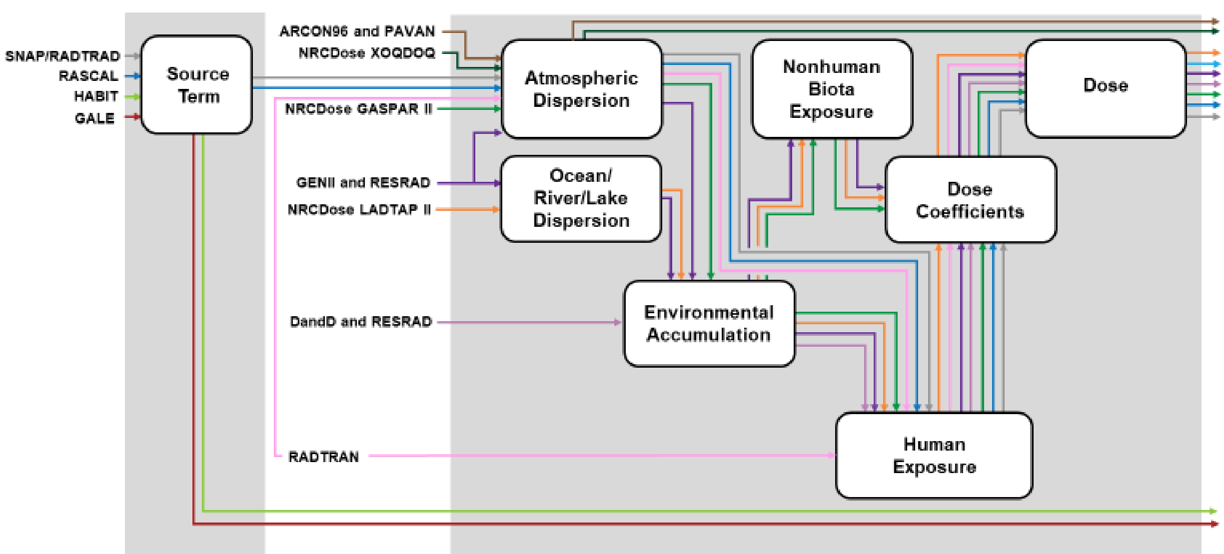


Figure 3-1. Conceptual Model for the New Consolidated Code Paradigm

The code consolidation will involve the development of modules over time based on several factors. A significant factor is the ability to fund code consolidation efforts as limited advanced reactor resources are available. Other factors are the type and timing of the submittals of non-LWR applications. Some design types have a very low probability of releases to the environment. As such, some of the functionality of the codes in this volume may not be needed to assess dose consequences; therefore, module development and code consolidation for these designs are not a high priority. For example, Oklo submitted a combined license application in March 2020, and their Final Analysis Safety Report states that the design has inherent and passive safety features that result in a small inventory of radionuclides and release to the environment. Therefore, although the application is currently being reviewed by NRC staff, some of the codes may not be needed for confirmatory dose assessment purposes. Another factor that needs to be considered is the GUI needs of the dose assessment analyst. For example, NRC staff who use RASCAL in the emergency response center will need a more simplified user interface than staff conducting confirmatory analysis, and staff in decommissioning will not need to know much about how the NPP source is generated, only the amount of residual radioactivity after the plant has ceased operations.

Considering the factors discussed above, the modules will be developed in phases. Phase one will consist of developing the framework for code consolidation and gathering information about source terms for reactor designs that are more advanced (e.g., FHRs, SFRs, and HGTRs). Phase one may also include inserting source terms for non-LWR designs currently being submitted to the NRC if the need exists. This phase may also consist of consolidating existing ATD, dose coefficient, and environmental accumulation models used to complete the dose assessment process. Future phases will focus on additional task needs as described below and will include consideration of the timing of non-LWR submittals and lessons learned from the first phase. As such, it is envisioned that these tasks will be completed throughout the near-term and mid-term of the Implementation Action Plan Strategies [1]. Figure 3-2 is an example of the conceptual model for a consolidated code showing the normal operations and decommissioning modules and engines behind the non-LWR GUI.

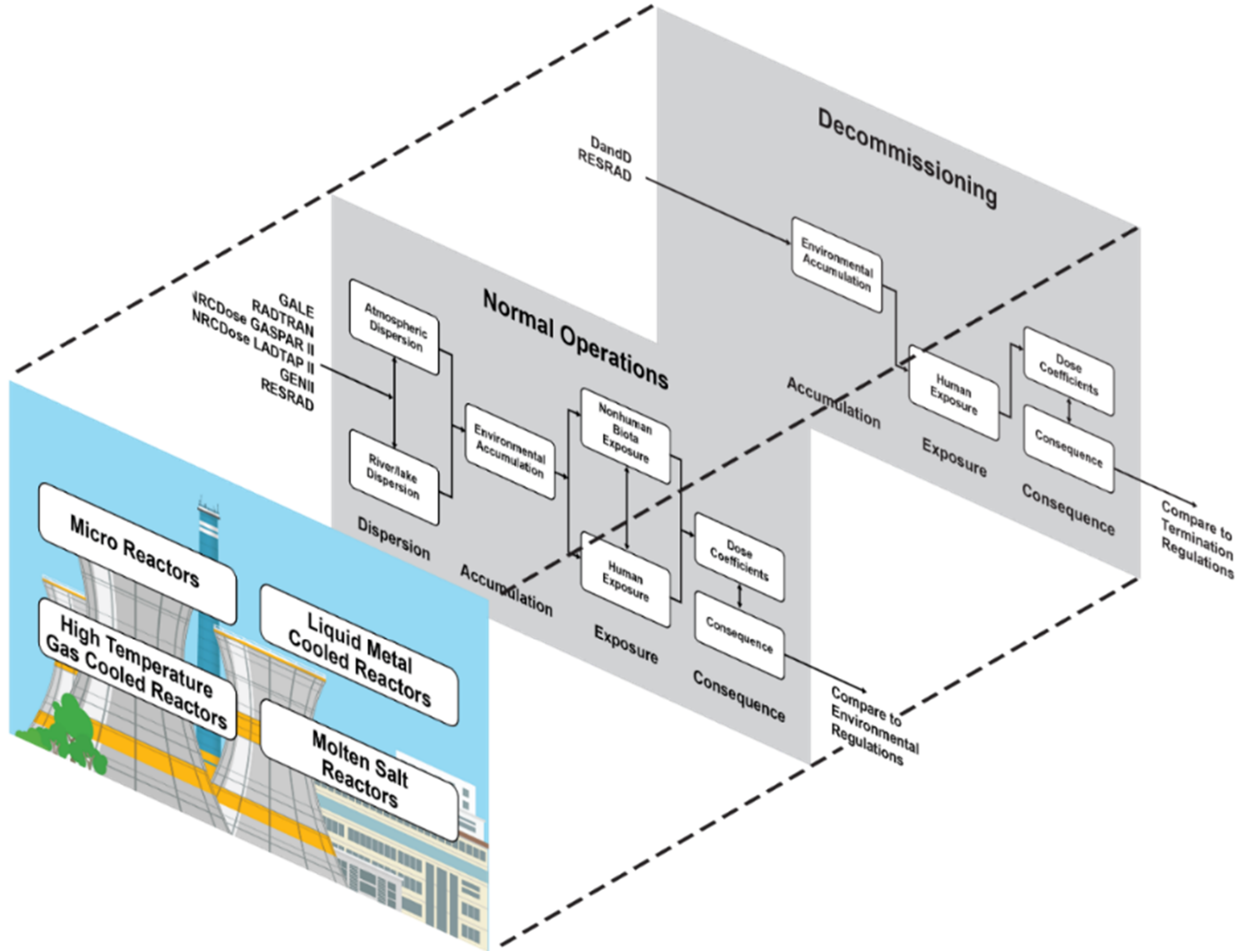


Figure 3-2. Conceptual Model of non-LWR Graphical Use Interface

While these factors and a phased approach for code consolidation represent a new paradigm for codes in this volume, the practice of consolidation codes in modular forms is not entirely new. As discussed in Section 2, efforts are underway to explore the SNAP/RADTRAD framework usefulness in other codes because the code has been designed to be flexible. Its input decks can generally be made plant-specific, site-specific, and accident-specific by modifying a subset of the input parameters and the handful of input files. The code development history to modernize SNAP/RADTRAD will be leveraged in developing the consolidated code.

Table 3-1 summarizes the proposed consolidation tasks for the siting and licensing code modules with a brief description of the task, the codes affected, and a list of possible resources to be leveraged to prepare those modules to perform dose assessments for the various non-LWR technologies. Details about each of the tasks represented in Table 3-1 are provided in the following sections.

Table 3-1. Summary of Pathway Modules, Codes Affected and, Resources Leveraged

<table>
<tr><th>Task</th><th>Code Module</th><th colspan="2">Brief Description of TASK</th><th>Resources Leveraged</th></tr>
<tr><td>1</td><td colspan="4">Developed Consolidated Framework for non-LWR technology dose assessment paradigm</td></tr>
<tr><td rowspan="3">2</td><td rowspan="3">Source Term Modules</td><td>RASCAL
SNAP/RADTRAD</td><td>Bring in radionuclide inventories, release fractions and timing sequences for DBA and BDBA.</td><td rowspan="3">SCALE

MELCOR

Non-LWR RCS experience</td></tr>
<tr><td>RADTRAN</td><td>Add transportation source terms.</td></tr>
<tr><td>GALE</td><td>Normal Effluent (RCS) Source Term: add operational data as it becomes with special consideration for MSR source term</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">ATD Modules</td><td>ARCON
PAVAN</td><td>Improve near field models</td><td rowspan="2">MACCS</td></tr>
<tr><td>HABIT</td><td>Explore changes to industrial plants proximity non-LWRs</td></tr>
<tr><td rowspan="2">4</td><td rowspan="2">Dose Coefficients Modules</td><td rowspan="2">NRCDose
RASCAL
RADTRAN
SNAP/RADTRAD
GENII
RESRAD</td><td>Aerosol particle size relationship to dose coefficients</td><td rowspan="2">DCFPAK

MACCS</td></tr>
<tr><td>H-3 and C-14 relationship to dose coefficients</td></tr>
<tr><td>5</td><td>Aquatic Pathway, Environmental Accumulation, and Human/Non-Human Biota Consequence Modules</td><td>NRCDose
RADTRAN
GENII
RESRAD</td><td>H-3 and C-14 relationship to environmental pathways</td><td>Non-LWR technology experience</td></tr>
</table>

3.2 Source Term (Task 2)

The second task is to identify source terms inputs (i.e., radionuclide fuel inventories, reactor coolant inventories, plant design and operational data) for each of the non-LWR designs. Once a code consolidation framework has been developed, the source term information would be included as one of the modules in the consolidated code. The source terms are one of the higher priority modules because it is the first data needed in the dose assessment process and will be completed in phase one.

For normal operations, the radionuclides of interest in the source term include fission products, capture products, and activation products produced during normal operation in the reactor coolant system. These source terms are deeply embedded in the NRC's regulatory policy and practices and are incorporated in several of the existing computer codes. For accident conditions, a regulatory source term is a description of the time-dependent release of radionuclides to the containment and the behavior of these radionuclides in the containment. For non-LWR designs, some of which do not include pressure retaining containment like LWRs, the source term information may be provided as assumptions on magnitude and mix of radionuclides and timing of their release to the environment or may also model transport and removal within the facility before release to the environment. Depending upon the computer code's application, these source terms may be used for normal (routine) effluent releases and transportation events, accident conditions, both severe accidents (beyond design-basis accidents [BDBAs]), and DBAs.

Specifically, information on the source terms for the various non-LWR technologies is needed as inputs for the source term module of the consolidated code consistent with the type of source term information available in current versions of GALE, SNAP/RADTRAD, and RASCAL. The primary source of source term information will be from the SCALE code or from the MELCOR code as described in Volume 3. Source term information needs specific to codes in this volume are described below.

3.2.1 Normal Operations (Routine) Source Term Development

Currently, the GALE code uses reactor coolant source terms from ANSI/ANS 18.1 (i.e., 1984, 1999, or 2016) and is based on the operating experience of LWRs. It is anticipated that the ongoing development work for SCALE version 6.3, which will include enhancements and analysis capabilities for non-LWRs including MSRs, HTGRs, FHRs, and SFRs, may be used for the reactor coolant normal source term for the consolidated siting and licensing code. However, for non-LWRs, the reactor coolant normal source terms may be difficult to predict for technologies with limited or no operating experience, so bounding source terms may need to be used.

In addition, in GALE, most of the parameters including the reactor coolant source term are fixed, and the user will have limited flexibility to change the source term parameters for the different types of non-LWRs reactor coolants. The source term module being developed for the consolidated code will need to allow for both LWR and non-LWR reactor coolant source term inputs and designs. It is envisioned that this module will have the options that allow the analyst to select the non-LWR source term and designs of the license application being submitted.

Special Considerations for MSR Source Terms

Some non-LWR MSR technologies are being designed with the possibility of accommodating continuous fission product removal using physical and chemical processes. Depending on the specific MSR design, the fuel salts can be processed in an online mode or in batches to retrieve fission products and actinides, and the latter can subsequently be reintroduced into the power production cycle of the reactor. These proposed MSR design source terms have the potential to significantly change the safety and safeguards posture and economics of nuclear energy production by processing fuel online, removing waste products, and adding fresh fuel without lengthy refueling outages. These MSR reprocessing processes may also significantly contribute to the potential chemical hazards faced by CR operators including the more significant production of tritium. These factors will need to be considered when developing a consolidated code.

3.2.2 RASCAL Core Inventories

The RASCAL inventories are based on calculations made using the SCALE computational sequences that involve depletion calculations with functional modules such as Oak Ridge Isotope Generation (ORIGEN-S) computer code to compute time-dependent concentrations of many radionuclides. Because the RASCAL code is used during emergency response events, default core inventories on a per thermal megawatt basis for LWRs are hard-wired into the code with pre-loaded plant power for each NPP to ensure faster run times although experienced users can modify the reactor core inventory by changing a few input parameters (e.g., the rated reactor power and the burnup). It is envisioned that this source term module related to RASCAL will not change for non-LWRs but will be modified to accept non-LWR core inventories.

The severe accident source term fission product release fractions and timing sequences in RASCAL are designed as fixed parameters in the code and are not based on non-LWR technologies. The consolidated code would be designed to include these parameters but have flexibility to choose between non-LWR severe accident source terms. However, most non-LWR severe accident source terms are not known at this time. Considering the state of design development and licensing plans as understood by the NRC, non-LWR plants are not expected to be operational within 5 years at the earliest so the need for an incident response tool for an operating non-LWR facility is not urgent. For these reasons, consolidation of RASCAL with the other codes is a low priority.

3.2.3 SNAP/RADTRAD Core Inventories

For siting and dose assessment analyses, the SNAP/RADTRAD code contains two default core inventory libraries. These libraries can be edited and adjusted by the user by using the customer editing features of the code to duplicate and append/amend the core inventories in each file. This flexibility in the current SNAP/RADTRAD code will allow for easy adaptation of core inventories associated with the various non-LWR technologies. Therefore, the source term module related to the SNAP/RADTRAD core inventory is now ready to support licensing for non-LWRs.

In addition to obtaining the core inventory, SNAP/RADTRAD pulls in source term information from several sources to obtain the accident source term. However, the NRC staff has determined the need to consider other accident sequences of lesser consequence but higher probability of occurrence in the context of the frequency-consequence approach described in RG 1.233 [73] and Nuclear Energy Institute (NEI) Report 18-04 [74]. This regulatory approach to accident source term development and analysis may need to be applied to all the non-LWR technologies.

3.2.4 Transportation Source Term

To evaluate doses from transportation accidents, the assessment methodology in the RADTRAN computer code is based on current LWR spent fuel designs and transportation casks configuration. For most non-LWRs, the spent fuel transportation options vary significantly and are not well developed at this point in time. The range of fuel types spans from salt to more conventional TRISO ceramic pebbles and metallic fuel options adopted for various non-LWRs. In addition, some non-LWR designs adopt a “battery” type approach where it is likely that the entire core containing the spent fuel will be transported as a single shipment unlike the transportation configuration for LWRs where a group of assemblies is transported in a single cask. Also, cask designs for non-LWR shipments containing spent fuel are largely in early development stages. Therefore, the transportation source term module will need to take these issues into consideration.

Finally, the MACCS non-LWR code development work includes a screening analysis to identify which subset of radionuclides to include in accident consequence calculations for each reactor type given the different mix of radionuclides that may be released in accidents from those reactors. This work could be leveraged for source term development work for RADTRAN and the consolidated code.

3.3 ATD Module (Task 3)

The third task will also be completed in phases. The first phase will consist of consolidating the ATD models of the individual ATD codes (e.g., ARCON, PAVAN) into a single module and incorporating existing ATD models from other related codes (e.g., NRCDose — XOQDOQ). The second phase will be to evaluate the applicability of the near-field and depositions atmospheric models for non-LWR technologies including the stationary and transportable micro-reactor designs. These phases would leverage the experience of the NRC’s meteorology staff to ensure the ATD modules have the flexibility to address different non-LWR applications and submittals for siting and licensing. This task would also leverage the MACCS near field modelling efforts for non-LWRs as discussed in Volume 3.

3.3.1 Near-Field ATD Modeling

Several of the NPP siting and licensing codes employ Gaussian ATD models [75, 76] to account for enhanced dispersion near a building at low and high wind speeds. However, the Gaussian ATD models neither provide for, nor evaluate, the differing levels of complexity of calculating air concentrations and deposition in the near-field close to buildings and structures. For non-LWR applicants, it is anticipated that EABs, LPZs, and emergency planning zones (EPZs) will be much smaller than those areas associated with large LWRs. This is based upon the non-LWR developer’s claims of improved safety characteristics relative to large LWRs (i.e., smaller, slower, less energetic, and less likely accidents). Specifically, some of these non-LWR applicants have proposed EABs, LPZs, and EPZs that coincide with the plant’s site boundary, which could be on the order of several hundred feet from the plant. Therefore, the near-field ATD modeling becomes a critical factor in dose assessment calculations for siting, licensing, and emergency response of non-LWRs.

RASCAL and ARCON Near-Field ATD Modeling

This sub-task would evaluate the RASCAL and ARCON code’s ATD models applicability for each of the non-LWR technologies, considering the greater emphasis being placed upon the near-fields, smaller EABs, LPZs, and EPZs. The RASCAL near-field ATD models would probably stay the same or leverage the changes in the ARCON model. However, the change would be to re-code the RASCAL model in the applicable non-LWR framework design in a fast and efficient manner that would allow real time and forecast data to be used. In addition, the staff plans to leverage the improved MACCS near-field ATD capability to better treat building wake effects in the near-field given the need for probabilistic dose calculations closer to non-LWRs. This task would include guidance from the NRC's meteorology experts to ensure the module for the consolidated code has the flexibility and right level of detail to address the different atmospheric assessments in siting and licensing.

HABIT Near-Field ATD Modeling

Many of the non-LWRs developers emphasize the "inherently safe" aspects of these technologies based upon their claims of improved safety characteristics relative to large LWRs as noted above. This has led to the non-LWR developers stating that these plants could be sited relatively close to industrial and residential areas. Because of the potential for non-LWR NPP collocation with industrial processing plants, a greater likelihood exists that larger chemical inventories (non-radiological) would be present near the plant and that releases of these chemicals to the environment after an accident could affect CR habitability.

Analyses using the HABIT code demonstrate that the CR of the LWR NPPs are appropriately protected from hazardous chemicals that may be discharged because of equipment failures, human errors, or events and conditions beyond the control of the NPP. The current version of the HABIT code includes a Gaussian puff dispersion ATD model (EXTRAN) to disperse the toxic substances and denser-than-air ATD models (i.e., DEGADIS and SLAB). Additionally, the HABIT code contains a chemical data file that contains information about the physical characteristics of 21 chemicals. Based on the higher potential for non-LWR collocation with industrial processing plants, this data file should be reviewed to include additional chemicals based on each of the non-LWR technologies. Finally, a review should be conducted of the Gaussian (EXTRAN) and denser-than-air (DEGADIS and SLAB) ATD models in the HABIT code to assure their applicability to all the non-LWR technologies.

3.3.2 Leveraging Activities from other Vision and Strategy Volumes

The staff plans to leverage ATD models being developed for the MACCS code that are described in Volume 3 . More specifically, the plan includes an evaluation of the extent to which radionuclides are released from different non-LWR technologies, transformed in the atmosphere, and deposited thus producing doses to humans, the environment, and biota. This task does not involve experimental research; rather, it just seeks to evaluate the applicability of the existing deposition (wet and dry) models. An exception could be HTGRs, which use graphite as a structural material and as the neutron moderator. Air ingress accidents for HTGRs expose graphite to an oxygen-containing environment and can produce severe oxidation at high temperatures. This oxidation can produce non-spherical aerosol particles with a shape factor significantly greater than unity. This phenomenon is of potential importance to dose assessment codes because it can affect dry deposition.

However, leveraging the MACCS ATD probabilistic risk assessment model within siting and licensing codes may not be a good use of resources. The MACCS code analyzes the magnitude of adverse consequences and the likelihood of occurrences of each consequence mostly in terms of severe accidents, but the siting and licensing codes confirm submittals that evaluate normal effluents and DBAs as well.

With regard to the HABIT near-field ATD modeling as described above, another task will be to leverage MACCS analyses that will help the staff understand whether non-LWRs themselves, or their potential collocation with industrial processing plants, create a greater likelihood of chemical releases to the environment.

3.4 Dose Coefficient Module (Task 4)

The fourth task involves: (1) developing dosimetry modules/engines that have the flexibility to use different dose models and dose coefficient values and (2) examining dose coefficient models with respect to aerosol particle size in addition to exploring the impact of tritium and carbon-14 biokinetics since these radionuclides may be in higher quantities in non-LWRs. The first task will be performed in phase one, and the staff proposes to consolidate the dose coefficients from multiple codes into a single module and give the user the flexibility to choose dose coefficients based on different regulations, guidance, and scenarios pertaining to individual non-LWR technology designs.

Current regulations such as 10 CFR Part 20 require that licenses use dose coefficient values from older dosimetry models and systems. These models incorporate outdated science but are still protective of public health and the environment. Typically for the LWR codes, the dose coefficients and dosimetry models are hard-wired into the code, and the user has few options to edit or change values. An important element of this task is to design this module and the GUI with an understanding of the different dose endpoints of siting, licensing, and emergency response for non-LWRs.

Some users prefer that dose coefficients be hard-wired, while others prefer the flexibility to choose the best coefficients for their scenario. Over the years, some code developers have hard-wired dose coefficients in response to stakeholders needs for simpler codes. For example, in the DandD code, dose coefficients are hard-wired into the code because it is a screening tool to see if further detailed analysis is warranted. The RASCAL code, on the other hand, has two hard-wired options for the selection of dose coefficients based upon the EPA PAGs. Moreover, in the early phases of a radiological event, the EPA suggests administration of potassium iodide (KI) when the projected dose to the child thyroid exceeds 5 rem. Therefore, the RASCAL dose analyst has the ability to select child dose coefficients to evaluate child thyroid doses.

Finally, this task would also leverage the MACCS non-LWR dose coefficients code development work and the DCFPAK code that has numerous dose coefficient libraries that will be inserted in the consolidated code.

3.4.1 SNAP/RADTRAD and RESRAD Dose Coefficients

As discussed in Section 2, the SNAP/RADTRAD computer code has undergone modernization and contains two options for the selection of dose coefficients: (1) hard-wired dose coefficients in accordance with Federal Guidance Reports (FGR) 11 and FGR 12 or (2) user-defined dose coefficients. Therefore, as currently configured, the SNAP/RADTRAD code provides the user with some flexibility regarding the selection of dose coefficients for use with non-LWR technologies. Future updates to the dose coefficient module for the consolidated code could incorporate the option for users to choose state-of-the-art dose coefficients and dosimetry models (e.g., International Commission on Radiological Protection (ICRP) Report 103 [77]).

In the RESRAD family of codes, the dose coefficient libraries are accessed by the user through a stand-alone utility program called RESRAD Dose Conversion Factors Editor. This editor is flexible to choose between internal (FGR 11) , external (FGR 12), age-dependent (FGR 13), and user-defined libraries. This may be the preferred method of accessing dose coefficient values.

3.4.2 Aerosol Particle Size Effects on Dose Coefficients

A common theme among codes is the applicability of dose coefficient options to aerosol particle size of the radionuclide. Typical dose coefficients assume particle diameters of 1 to 10 microns; however, non-LWR technologies could release particles closer to the nanometer range. This could directly impact the calculated dose.

3.4.3 Tritium and Carbon Dose Coefficients

The dose coefficients might also need to be modified to account for the various forms of volatile carbon (i.e., carbon monoxide [CO], carbon dioxide [CO_2], and other organic molecules) that interact with the human body via inhalation and ingestion. The carbon-14 dosimetry models used in several computer codes (including RASCAL, SNAP/RADTRAD, and NRCDose) will be reviewed and updated to assure that the doses associated with the carbon-14 releases are correctly calculated for non-LWR technologies.

The dose coefficients might also need to be modified to account for the unique ways that tritiated water interacts with the human body via inhalation, ingestion, and skin absorption [78]. The tritium dosimetry models used in several of the computer codes (including RASCAL, SNAP/RADTRAD, and NRCDose) will be reviewed and updated to assure that the doses associated with tritium releases are correctly calculated for non-LWR technologies (HTGRs and MSRs), particularly in light of the recent National Council on Radiation Protection and Measurements Report No. 181 (NCRP 181) [79].

3.5 Aquatic Pathway (River/Lake/Ocean Dispersion), Environmental Accumulation, and Human and Non-Human Biota Consequence Modules (Task 5)

Task 5 consists of further developing the aquatic pathways (river/lake/ocean dispersion), environmental accumulation, and human/non-human biota consequence modules. These tasks are in future phases because they are less dependent on non-LWR design and fuel types. As stated above, the first task and phases will bring in existing models to consolidate the codes and complete the dose assessment process. This task also will explore the feasibility of radionuclide particle size behavior in the environment for some non-LWR designs and will explore tritium and carbon-14 modeling in the environment.

In addition, the latter phases would bring in the additional models for the decommissioning codes that have more detailed environmental models. This task would leverage the experienced of the NRC decommissioning staff because the modules need hard-wired parameters and the flexibility to choose environmental accumulation models based on the applicable regulations and guidance for those scenarios. This task will also leverage work planned for the MACCS code to examine deposition models.

3.5.1 NRCDose (GASPAR II and LADTAP II) Environmental Pathways

As mentioned in Section 2, the NRCDose computer code calculates the environmental dose impacts of liquid and gaseous radiological effluent pathways using the LADTAP II and GASPAR II Fortran computer codes. The calculated doses provide information for NEPA evaluations and for determining compliance with the ALARA philosophy of Appendix I of 10 CFR Part 50.

GASPAR II and LADTAP II Environmental and Biota Dose Calculations

The GASPAR II and LADTAP II codes implement the gaseous and liquid exposure pathways, respectively. They model and estimate the radiation doses to individuals, population groups, and biota. The tritium and carbon-14 food pathway models in these codes will be evaluated due to the availability of it from some non-LWR designs and because they are very mobile and can enter biological systems part of water and organic molecules.

GASPAR II and LADTAP II also produces a special "cost-benefit" table representing the sum of ALARA population doses at all locations for compliance with regulations. Finally, they included biota dose parameters and models to estimate non-human biota doses from liquid and gaseous effluent releases.

3.5.2 Tritium Modeling Considerations

Tritium is a radioactive isotope of hydrogen that is formed in nuclear reactors by neutron absorption and ternary fission events. Tritium is particularly important because it can be produced in large quantities during normal operation and because it diffuses rapidly through metals at elevated temperatures. The pathways for advanced non-LWRs, such as HTGRs and MSRs, for tritium are largely dependent on the design specifics and presence or absence of hydrogenous environments. While HTGRs produce more tritium than LWRs, MSRs produce significantly more as described in Idaho National Laboratory Report INL/EXT-12-26758 [80]. Lithium-containing MSRs primarily produce tritium from neutron absorption reactions of lithium-6 and lithium-7. While tritium can be released to the environment in different forms, it is commonly treated as tritiated water.

The behavior of tritium in exposure pathways could be handled in a more refined manner because the behavior of this environmentally mobile radionuclide mimics that of stable hydrogen in biological processes. The concentrations of tritium in environmental media (soil, plants, and animal products) are assumed to have the same specific activity (curies of radionuclide per kilogram of soluble element) as the contaminating medium (air or water). The fractional content of hydrogen in a plant is then used to compute the concentration of tritium in the food product under consideration. The hydrogen content in both the water and the non-water (dry) portion of the food product is used when calculating the tritium concentration.

3.5.3 Carbon-14 Modeling Considerations

Carbon-14 is another radionuclide that warrants special attention. Carbon-14 is formed in all nuclear reactors due to absorption of neutrons by carbon, nitrogen, or oxygen. These may be present as components of the fuel, moderator, or structural hardware, or they may be present as impurities. Releases of carbon-14 are currently one of the leading sources of offsite dose to the public from routine operations (LWRs).

Carbon is also one of the building blocks of plant and animal life but, unlike tritium (and hydrogen), it tends to be more fixed in plant materials via photosynthesis from air. A variant of the specific activity model is also appropriate for radiocarbon nuclides in the atmosphere. However, it is difficult to estimate the transfer of radioactive carbon-14 from irrigation water or soil to plants. The approach used by RESRAD is to assume that carbon deposited in the soil slowly converts to CO_2 and to then estimate the amount of carbon-14 in the CO_2 concentration in the air near crops. Carbon volatilization by microbial action in the soil, measured by the emission rate (the “evasion rate” in RESRAD), is the dominant mechanism for removing carbon-14 from the soil. In comparison, losses due to leaching, radioactive decay, and soil erosion are slight.

4. Other Non-LWR Considerations

4.1 Characterization of Code Readiness

To characterize the state of readiness for the NRC's tools for advanced non-LWRs, a method known as the Predictive Capability Maturity Model (PCMM) was employed for Volumes 1, 2, and 3 computer codes. The PCMM [81] was developed by Sandia National Laboratory and has been used in some of the DOE code development activities. The PCMM examines a complex analysis tool in terms of six fundamental modeling and simulation elements: (1) representation and geometric fidelity, (2) physics and material model fidelity, (3) code verification, (4) solution verification, (5) model validation, and (6) uncertainty quantification and sensitivity analysis. In addition, each of these six modeling and simulation elements were rated by NRC staff on a "maturity level" ranging from 0 to 3. A maturity level of 0 implied a low state of readiness while a level of 3 indicates a highly advanced capability.

The staff has not used the PCMM process nor performed maturity assessments for the codes referenced in this volume primarily because code development in the context of non-LWR siting, licensing, and emergency response is not far enough along.

4.2 Impacts on Staff

A substantial number of companies have varying plans and experience developing non-LWR designs, some of which are more mature than others. To date, limited resources have been designated for code development activities in this area related to radiation protection and dose assessment. Moreover, codes in this volume have similar models but are for very different regulatory functions (e.g., siting and licensing, emergency response, decommissioning). In addition, the complexity of the consolidated code suite must be considered because this is a large paradigm shift on how codes are currently being independently developed albeit input parameters, assumptions, and models will be the same.

For this reason, the newer consolidated code will need to be developed in phases to accommodate non-LWR readiness while the conventional codes are still being used for LWRs. An important part of the process of developing and using a consolidated code for the purposes mentioned herein will be providing staff with training opportunities to gain experience across the entire regulatory framework. Mastering this new complexity is recommended and possibly essential because the added flexibility afforded by the consolidated code approach will reduce the total "life-cycle cost" associated with code development and maintenance of all of the individual codes. Total "life-cycle costs" are those costs for code development, verification and validation, code maintenance, and staff training.

Another consideration is that some of the potential applicants have indicated that they will be using consolidated computer codes that model source term to dose and thus the staff may eventually need to develop a "cradle to grave" understanding of this approach to perform a sufficient confirmatory analysis. Nevertheless, NRC staff has extensive experience in use of Volume 4 codes and may use what flexibility is available in the current versions of the codes, or can use alternate methods (e.g., audit) to perform licensing evaluations for non-LWRs in the near term.

4.3 Regulatory Independence

A final consideration for code selection is that of independence, which is one of the NRC's Principles of Good Regulation. Confirmatory calculations made by the staff are intended to support the staff's technical licensing reviews. By independently modeling and simulating an applicant's design, the staff gains the expertise and knowledge to fully understand the design and, when necessary, request additional information from the applicant to justify the safety case.

Comparing NRC confirmatory calculations to those of an applicant may show different endpoints and allows the staff to question the reason for those differences and whether they are safety-significant.

The principal of independence does not preclude the NRC use of applicant codes for performing confirmatory analysis nor does it preclude the NRC and licensees from using the same code. In fact, the licensees and the NRC use the same codes for many of the analyses described in this volume. Independence can be maintained by performing additional sensitivity and uncertainty studies to explore the margin to safety limits or to search for cliff-edge effects that can significantly impact the behavior of the fuel type in question.

Regardless of the choice of codes used in performing confirmatory analyses, the NRC staff who perform the analyses must have a clear understanding of the assumptions and limitations of the analytical tools that it uses. Maintaining the NRC's independent licensing evaluations is critical for effective NRC licensing and is an important aspect of upholding public confidence in the process.

5. CONCLUDING REMARKS

This report describes the vision and strategy to achieve readiness for non-LWR siting and licensing for radiation protection and dose assessment codes. It provides an overview of the technical issues related to the different non-LWR design technologies that warrant code development, modifications, and/or literature reviews. The report describes the computer codes and how they would be applied and consolidated for the non-LWR design types. It also summarizes the tasks to bring up to date the capability to model and simulate non-LWR designs to support potential review needs by the regulatory offices. Moreover, the report suggests ways of leveraging resources with other code updates as described in previous vision and strategy volumes.

As discussed in previous sections, these codes have numerous current and legacy issues that call for code consolidation and modernization. The more consolidated and modernized code(s) will be modular and have increased ability and flexibility to assess designs, fuel types, and non-LWR reactor data. In addition, technical topics related to radiation protection and dose assessments issues were addressed. Technical topics include (1) source term input, (2) near-field ATD modeling, (3) selection of dose coefficients, and (4) aquatic pathway (river/lake/ocean dispersion), environmental accumulation, and human/non-human biota consequences that include tritium and carbon-14 modeling.

This plan identifies many, but not all, of the “gaps” in code development and assessment for non-LWRs designs, and the staff is currently prioritizing these designs to input into the consolidate code. The staff is also monitoring submittals to ensure we have the necessary confirmatory tools. Therefore, this report represents the current and best knowledge of technical needs for development of the siting and licensing codes necessary for non-LWR radiation protection and dose assessment analysis.

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