U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

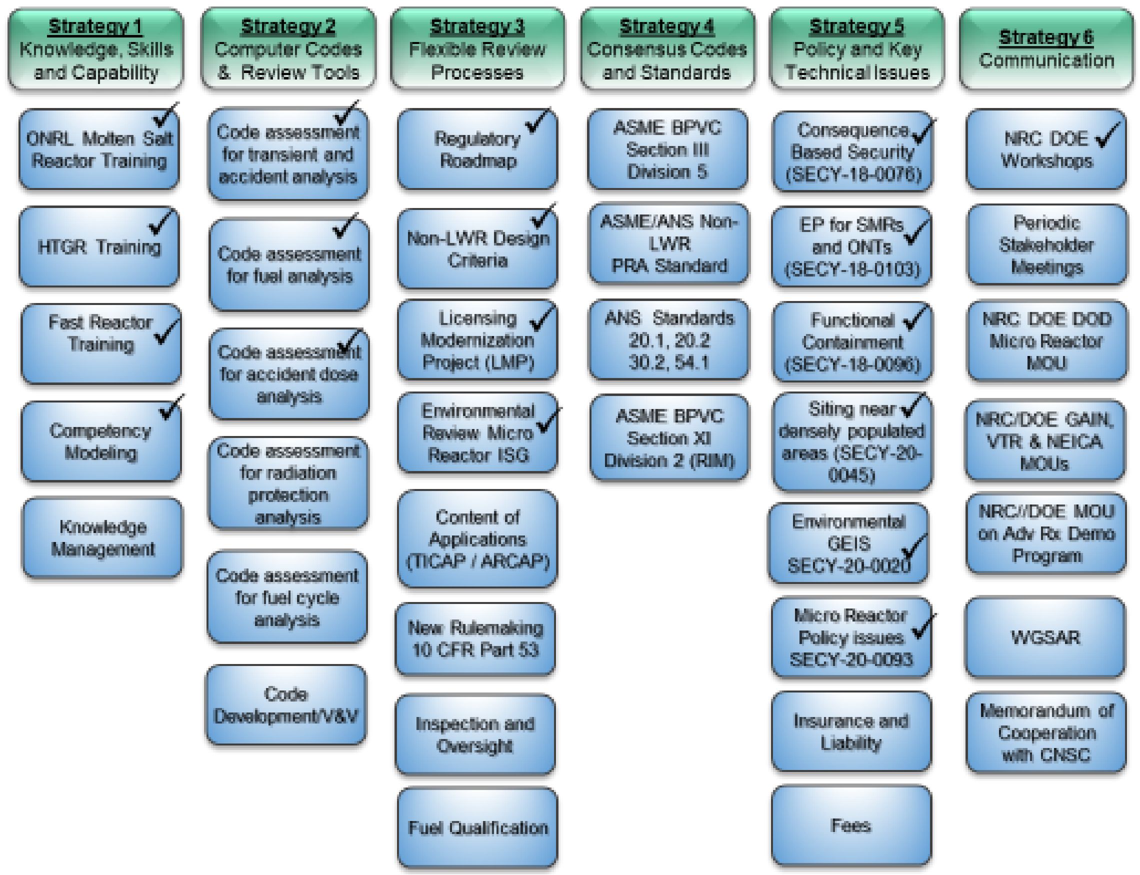
MACCS Development for Non-Light Water Reactors

Keith L. Compton (USNRC)
Daniel J. Clayton (SNL)
Kyle A. Clavier (SNL)

2022 European MELCOR and MACCS User Group
27 April 2022

NRC Advanced Reactor Readiness

- NRC Vision and Strategy (2016)
- Implementation Action Plans (2017)
- Computer Code Development Plans for Severe Accident Progression, Source Term, and Consequence Analysis (2020)



Code Development Plan for Consequence Analysis

- What is the plan?
  - Potential technical issues identified in “Computer Code Development Plans for Severe Accident Progression, Source Term, and Consequence Analysis (2020)”
- What have we accomplished?
- What do we have remaining?

MACCS Technical Issues for Non-Light Water Reactors

- Near-Field Atmospheric Transport and Dispersion

  Based on the potential for non-LWRs to be located on sites with shorter site boundary distances than traditional LWR sites, improve MACCS near-field atmospheric transport and dispersion capability

- Radionuclide Screening

  Perform a screening analysis to identify which subset of radionuclides to include in MACCS calculations for each non-LWR type given the different mix of radionuclides that may be released in accidents from each type

- Impacts on Decontamination

  Based on the potential for non-LWRs to be sited in areas with different land use patterns than traditional LWR sites, develop updated decontamination cost models

MACCS Technical Issues for non-Light Water Reactors (Continued)

- Chemical Form, Particle Size, and Shape Factor of Radionuclides and Impact on Atmospheric Transport and Dosimetry

  Evaluate potential differences in radionuclide releases from non-LWRs relative to LWRs including different aerosol size distributions, shape factors, and chemical forms. Based on the evaluation, improve MACCS capabilities for atmospheric transport and dosimetry to appropriately capture these issues for probabilistic consequence analysis. If necessary, consider a state-of practice resistance model for dry deposition.

- Evolution of Radionuclide Properties in the Atmosphere

  Identify whether non-LWR accident releases may be more subject to evolution in the atmosphere relative to LWR releases based on differences in hygroscopic properties or potential for chemical reactions during transport.

- Tritium Modeling

  Develop MACCS model and/or dosimetry updates to better account for the unique behavior of tritium which is very mobile and can enter biological systems as part of water and organic molecules.

Code Development Plan for Consequence Analysis: Accomplishments

- MACCS nearfield code capability assessment
- MACCS nearfield code capability improvements
- Preliminary radionuclide screening for non-LWR technologies

Near-Field Atmospheric Transport and Dispersion

- Non-LWRs and small modular reactors may be located on smaller sites than traditional light-water reactors.
- MACCS2 code manual cautions against use of MACCS results at distances less than 500 meters
- Assessment of MACCS 4.0 near-field dispersion model (Clayton and Bixler 2020) concluded that:
  - MACCS 4.0 can be used in a conservative manner at distances significantly shorter than 500 m downwind from a containment or reactor building
  - However, the MACCS user needs to select the MACCS input parameters appropriately to generate results that are adequately conservative for a specific application

Near-Field Atmospheric Transport and Dispersion

- MACCS code improvements to add flexibility for modeling nearfield dispersion were added to MACCS 4.1 (Clayton 2021)
- Additional nearfield models added to MACCS 4.1 include the ability to:
  - Generate results comparable to those from ARCON96 when using the Ramsdell and Fosmire meander model
  - Generate results comparable to those from PAVAN when using the full US NRC Regulatory Guide 1.145 meander model
  - Maintain capability to bound AERMOD and QUIC results using recommended MACCS parameter choices
- Comparing the model results shows
  - When using the full US NRC Regulatory Guide 1.145 meander model, the X/Q values for the test cases are **higher** than for the other two models
  - The X/Q values for the test cases with MACCS Ramsdell and Fosmire plume meander model are **lower** than the other two models **except at distances of less than 200-300 m**
  - Beyond 1 km, the **three models converge** with differences on the order of 5-10% at a distance of 35 km.

Radionuclide Screening

- "*MACCS has been structured to permit any combination of radioactive nuclides to be included in the consequence analysis. This flexibility could permit consequence assessments for other parts of the nuclear fuel cycle or for other reactor types, such as breeder or fusion reactors, provided appropriate dosimetry and health effects models were available*." (Alpert et al. 1986)
- Currently recommended list of radionuclides for light-water reactor applications includes 71 radionuclides
  - This list includes the 60 nuclides identified in Alpert et al. (1986) along with 11 short-lived decay progeny that were implicitly included in the original MACCS dose coefficients
  - "*An examination of the 500 nuclides considered in ORIGEN indicated that 60 nuclides of 25 elements could be important for offsite consequence analyses of LWRs. This conclusion was based on the inventory, half-life, and potential biological hazard of the radionuclides of each element. The 60 nuclides are listed in Table 1. For some nuclides, short-lived daughters are included in the external dose factors of a parent nuclide [8]. These short-lived daughter nuclides are listed in Table 2*." (Alpert et al. 1986)
  - Inventories based on 3412 and 1518 MWt PWRs and a 3578 MWt BWR
- How well does this list of radionuclides translate to other reactor designs?

Radionuclide Screening (Preliminary Assessment)

- A preliminary assessment (Andrews et al. 2021) identified an additional 58 radionuclides that **may** need to be accounted for in the following non-LWR systems:
  - High-temperature gas reactors (HTGRs)
  - fluoride-salt-cooled high-temperature reactors (FHRs)
  - thermal-spectrum fluoride-based molten salt reactors (MSRs)
  - fast-spectrum chloride-based MSRs
  - liquid metal fast reactors with metallic fuel (LMRs)
- Assessment based on consideration of:
  - Composition of coolant and/or structural materials
  - Neutron spectrum
  - Fissile material

Code Development Plan for Consequence Analysis: In Progress

- Quantitative radionuclide screening
- Initial assessment of the effects of the radionuclide chemical and physical forms on dispersion and dosimetry modeling
- Focused review of methods for modeling the consequences of tritium releases under accident conditions

Radionuclide Screening

Quantitative Assessment

- Quantitative assessment in progress
- Methodology:
  - Obtain inventory computed using SCALE/ORIGEN
  - Eliminate radionuclides with short half-life (e.g., <1 hr), which are a small fraction (e.g., $<1x10^{-6}$) of total core activity, or for which dose coefficients are unavailable
  - Compute a radionuclide-specific unit dose factor using MACCS by modeling a unit (e.g., 1 Ci) release of each radionuclide and computing an early phase and a late phase all-pathways exposure
  - Weight the inventory by the MACCS unit dose factor to obtain a relative importance (implicitly assumes equal release fractions) relative to I-131 (for early phase exposures) and Cs-137 (for late phase exposures)
  - Identify nuclides greater than a fixed relative importance (e.g., >0.01 I-131 equivalent)

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Radionuclide Screening

Quantitative Assessment

- Approach being tested using INL HPR-A inventory available from https://code.ornl.gov/scale/analysis/non-lwr-models-vol3/-/tree/master/INL-A/full_core/depletion
- Potential technical issues:
  - Development of MACCS-formatted inventory from SCALE output files
  - Verification of activation product inventories from SCALE output files
  - Sensitivity of results to exposure period assumption and travel distance
  - Treatment of radionuclides with no tabulated dose coefficients in FGR13 dose coefficient file or no decay chain data in INDEXR.DAT file
  - Selection of inhalation clearance class and ingestion uptake fractions from FGR13 databases
  - Nuclide array limit (150) in current and previous versions of MACCS
  - Selection of screening thresholds

Radionuclide Screening

Quantitative Assessment

- Concluding observations:
  - Assessment is technology-specific because of differences in relative inventory or radionuclide chemical/physical form affecting dosimetry
  - Will require re-evaluation for different technologies and designs
  - May require re-evaluation depending upon outcome of task CA3 (effects of radionuclide chemical and physical form)
  - Only MACCS code limitation is the 150 radionuclide limit in current versions of MACCS
  - MelMACCS inventory files are flexible and can represent all radionuclides included in SCALE but:
    - Inventory files must be developed from SCALE outputs, and
    - Selection of additional radionuclides from inventory file requires modification to MelMACCS initialization files
- Initial report illustrating methodology using INL HPR-A inventory expected in FY22

Radionuclide Physical and Chemical Forms

- Issue: the physical and chemical form of released radionuclides affects both the atmospheric dispersion (e.g., deposition processes) and the dosimetry
- Work ongoing to assess potential limitations of existing MACCS code

Radionuclide Physical and Chemical Forms:

Examples of MACCS Code Assumptions

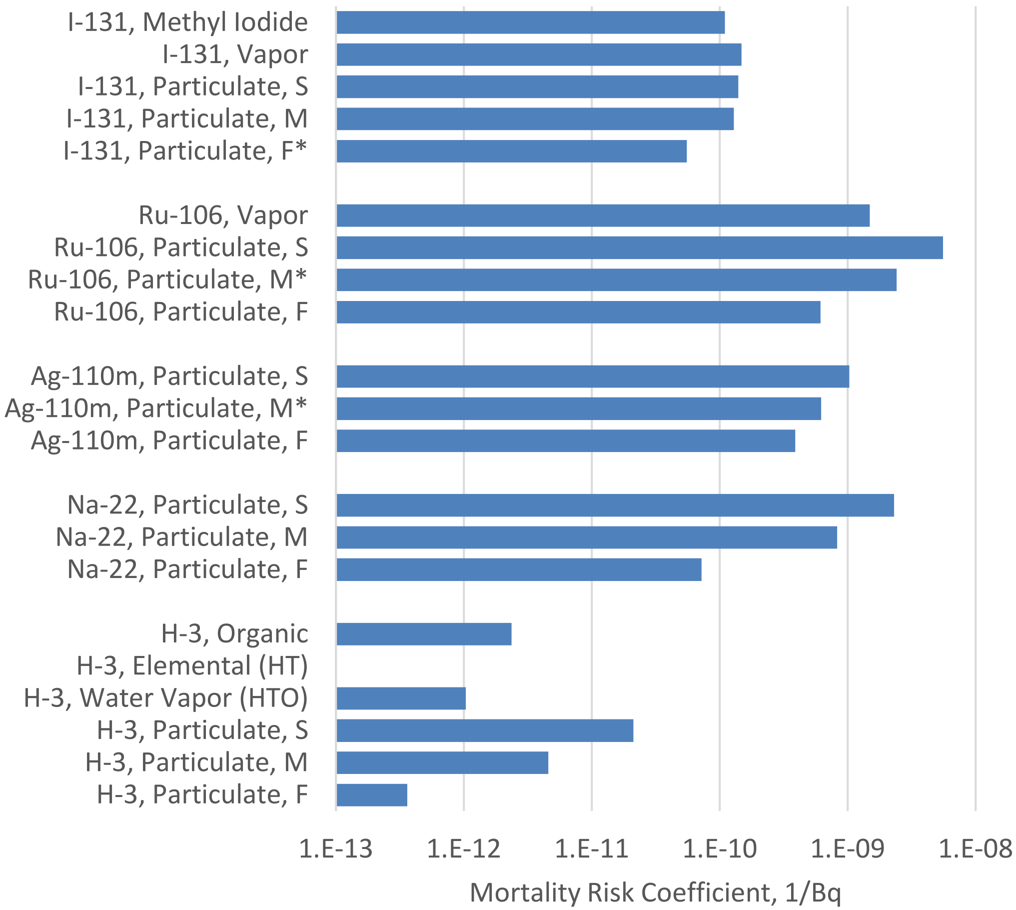
- Radionuclides may not be modeled with multiple chemical forms
  - Each element must be assigned to a specific MACCS chemical group
  - Dose coefficients are based on an assumed chemical form
- Radionuclides do not undergo physical or chemical transformations after release
- Dry deposition is currently modeled with a dry deposition velocity based on particle size, annual representative windspeed, and regional average surface roughness

Radionuclide Chemical and Physical Forms

Example: Dosimetry

- FGR13DCF dose coefficients are based on FGR13.
- The dosimetric effect of the chemical form is based on the rate of clearance from lungs to the blood as represented by a “clearance class”
- Dose coefficients in FGR13 DCF files (Haaker and Bixler 2019) are based on the clearance classes recommended in Runkle and Ostmeyer (1985), which in turn states that clearance classes are based on recommendations in ICRP-30 (ICRP 1979)

Variability in FGR-13 Inhalation Mortality Risk Coefficients for Selected Radionuclides



Radionuclide	Range (max/min)
I-131 (8.04d)	2.7
Ru-106 (368d)	9.1
Ag-110m (250d)	2.6
Na-22 (2.6yr)	32
H-3 (12.4yr)	200,000

Radionuclide Chemical and Physical Forms

Focused Review of Tritium Modeling

- Conducting literature review of existing tritium consequence models
- Proposed organization of report
  - Review of how tritium moves through environment
  - Brief model description of each of the identified models
  - Recommendations for MACCS

Summary

- Near-field capabilities have been evaluated and enhanced
- Radionuclide screening methodology has been established and is being exercised
- MACCS was designed from the outset with flexibilities to accommodate a wide range of potential facilities
- Investigations of MACCS capabilities to handle diverse chemical and physical forms, including radionuclides such as tritium, are underway

REFERENCES

- U.S. Nuclear Regulatory Commission (NRC), 2016. “NRC Non-Light Water Reactor (Non-LWR) Vision and Strategy, Volume 3: Computer Code Development Plans for Severe Accident Progression, Source Term, and Consequence Analysis, Revision 1” US Nuclear Regulatory Commission, Washington D.C., December 2016. ADAMS Accession Number ML16356A670
- U.S. Nuclear Regulatory Commission (NRC), 2017. “NRC Non-Light Water Reactor Mid-Term and Long-Term Implementation Action Plans”, US Nuclear Regulatory Commission, Washington D.C., July 2017. ADAMS Accession Number ML17164A173
- U.S. Nuclear Regulatory Commission (NRC), 2020. “NRC Non-Light Water Reactor (Non-LWR) Vision and Strategy, Volume 3: Computer Code Development Plans for Severe Accident Progression, Source Term, and Consequence Analysis, Revision 1” US Nuclear Regulatory Commission, Washington D.C., January 2020. ADAMS Accession Number ML20030A178
- U.S. Nuclear Regulatory Commission (NRC), 2021. “Advanced Reactor Program Status (SECY-21-0010)” US Nuclear Regulatory Commission, Washington D.C., February 2021. ADAMS Accession Number ML20345A239
- Clayton D.J and N.E. Bixler, 2020. “Assessment of the MACCS Code Applicability for Nearfield Consequence Analysis” SAND2020-2609, Sandia National Laboratories, Albuquerque, NM, February 2020. ADAMS Accession Number ML20059M032
- Clayton D.J, 2021. “Implementation of Additional Models into the MACCS Code for Nearfield Consequence Analysis” SAND2021-6924, Sandia National Laboratories, Albuquerque, NM, June 2021. ADAMS Accession Number ML21257A120
- Alpert, D. J. , D. I. Chanin, and L. T. Ritchie, 1986. “Relative Importance of Individual Elements to Reactor Accident Consequences Assuming Equal Release Fractions.” NUREG/CR-4467, SAND85-2575, Sandia National Laboratories, Albuquerque, NM, March 1986. https://www.osti.gov/servlets/purl/5854735.
- Andrews, N.C., M. Higgins, A. Taconi, and J. Leute, 2021. “Preliminary Radioisotope Screening for Off-Site Consequence Assessment of Advanced Non-LWR Systems” SAND2021-11703, Sandia National Laboratories, Albuquerque, NM, September 2021. ADAMS Accession Number ML21274A182
- Runkle, G.E. and Ostmeyer, R. M., 1985. An Assessment of Dosimetry Data for Accidental Radionuclide Releases from Nuclear Reactors (NUREG/CR-4185, SAND85-0283), Albuquerque, NM: Sandia National Laboratories. ADAMS Accession Number ML20132F001
- Haaker, R. F. and N. E. Bixler, 2019. “FGR 13 Dose Conversion Factor Files” (SAND2019-13422R). Albuquerque, NM: Sandia National Laboratories. https://www.osti.gov/servlets/purl/1573442.