SCALE/MELCOR Non-LWR Source Term Demonstration Project – Heat Pipe Reactor

June 2021
Outline

NRC strategy for non-LWR source term analysis
Project scope
Heat pipe reactor fission product inventory/decay heat methods and results
Heat pipe reactor plant model and source term analysis
Summary
Appendices
  • SCALE overview
  • MELCOR overview
Integrated Action Plan (IAP) for Advanced Reactors

Near-Term Implementation Action Plan

- Strategy 1: Knowledge, Skills, and Capacity
- Strategy 2: Analytical Tools
- Strategy 3: Flexible Review Process
- Strategy 4: Industry Codes and Standards
- Strategy 5: Technology Inclusive Issues
- Strategy 6: Communication
These Volumes outline the specific analytical tools to enable independent analysis of non-LWRs, “gaps” in code capabilities and data, V&V needs and code development tasks.
NRC strategy for non-LWR analysis (Volume 3)

Evaluation Model and Suite of Codes

Code strategy for source term
Role of NRC severe accident codes

**Safety Review (Regulations)**
- **Siting and Safety Analysis**\(^1,2\) - 10 CFR 100.21, 10 CFR 50.34, Part 52 (various)
- **Control Room Habitability**\(^3\) - 10 CFR 50, Appendix A, GDC-19
- **Technical Support Center Habitability**\(^4\) - 10 CFR 50, Appendix E, 10 CFR 50.47
- **Severe Accidents, FSAR Chapter 19**
- **Emergency Planning** - 10 CFR 50.160 (expected future use assuming this regulation is promulgated)
- **Emergency Response** - Nuclear/Radiological Incident Annex (NRIA) to the National Response Framework (NRF)

**Environmental Review (Regulations)**
- **Environmental Report** - 10 CFR 51.50
- **Draft EIS (general)** - 10 CFR 51.70
- **Draft EIS (CP, ESP, COL)** - 10 CFR 51.75
- **Severe Accident Mitigation Design Alternatives (SAMDA)** - 10 CFR 51.55

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### Dose Criteria Reference Values (10 CFR 50/52)

1. An individual located at any point on the boundary of the exclusion area for any 2-hour period following the onset of postulated fission product release, would not receive a radiation dose in excess of 0.25 Sv (25 rem) total effective dose equivalent (TEDE).
2. An individual located at any point on the outer boundary of the low population zone, who is exposed to the radioactive cloud resulting from the postulated fission product release (during the entire period of its passage), would not receive a radiation dose in excess of 0.25 Sv (25 rem) TEDE.
3. Adequate radiation protection is provided to permit access to and occupancy of the control room under accident conditions without personnel receiving radiation exposures in excess of 0.05 Sv (5 rem) TEDE.
4. Dose criteria not in regulation but found in NUREG-0737/NUREG-0696. GDCs are applicable to light-water reactors. Non-LWRs will have principal design criteria (PDCs) which may have a similar requirement.
Project Scope
Project objectives

Understand severe accident behavior
  • Provide insights for regulatory guidance

Facilitate dialogue on staff’s approach for source term

Demonstrate use of SCALE and MELCOR
  • Identify accident characteristics and uncertainties affecting source term
  • Develop publicly available input models for representative designs
Project scope

Full-plant models for three representative non-LWRs (FY21)
- Heat pipe reactor – INL Design A
- Pebble-bed gas-cooled reactor – PBMR-400
- Pebble-bed molten-salt-cooled – UC Berkeley Mark I

FY22
- Molten-salt-fueled reactor – MSRE
- Sodium-cooled fast reactor – TBD
Project approach

1. Develop SCALE model to provide MELCOR with decay heat, core radionuclide inventories, kinetics parameters, power distribution
2. Build MELCOR full-plant input model
3. Scenario selection
4. Perform simulations for the selected scenario and debug
   • Base case
   • Sensitivity cases
   • Uncertainty cases
Advanced Reactor Designs

**Liquid Metal Cooled Fast Reactors (LMFR)**
- TerraPower/GEH (Natrum)*
- GEH PRISM (VTR)
- Oklo
- Advanced Reactor Concepts
- Sodium-Cooled
- Westinghouse
- Columbia Basin
- Hydromine
- Lead-Cooled

**High-Temperature Gas-Cooled Reactors (HTGR)**
- X-energy*
- Framatome
- StarCore
- MIT

**Molten Salt Reactors (MSR)**
- Kairos*
- Kairos (Hermes|RTR)
- Liquid Salt Cooled

**Micro Reactors**
- Westinghouse (eVinci)
- BWX Technologies
- X-energy
- Radiant | RTR
- Transportable
- Ultra Safe | RTR
- Oklo

**TRISO Fuel**
- General Atomics (EM2)
- General Atomics

**LEGEND**
- ARDP Awardees
- Demo Reactors
- Risk Reduction
- In Licensing Review
- RTR
- Preapplication
- RTR
- Research/Test Reactor
- TerraPower
- Southern (TP MCFR) | RTR
- ACU | RTR *
- Elysium
- Thorcon
- Muons
- Flibe
- Alpha Tech
- Alpha Tech
Heat Pipe Reactor
Heat pipe for reactor use

Construction

• Metal pipe with wick along pipe inside surface
• Liquid coolant fills area between wick and pipe inside surface

Operation

• The core heats the liquid coolant which generates vapor
• The vapor flows to the other end of the heat pipe where it condenses, heating the secondary system fluid
• Coolant film return flow by capillary forces
Heat pipe wick being installed
First heat pipe reactor

KRUSTY experiment

• Kilowatt Reactor Using Stirling Technology
• Part of NASA’s Kilopower project
• 3 kW thermal power
• 8 heat pipes clamped to uranium cylinder
• Heat pipes transfer heat to Sterling engine
• Operated 28 hours (March 20-21, 2018)
• LANL video on Kilopower
Publicly available designs

LANL Megapower
- Megawatt-size heat pipe reactor
- Described in LA-UR-15-28840

INL Designs A and B
- Two alternatives to Megapower for improved performance and ease of construction
- Described in INL-EXT-17-43212, Rev 1
LANL Megapower versus INL Design A

LANL Megapower
• UO$_2$ High-Assay Low-Enriched Uranium (HALEU) fuel
• Fuel region contained between the top and bottom reflector assemblies
• Negative temperature coefficient from Doppler broadening and axial elongation
• Passive removal of decay heat

INL Design A
• To address potential issues with manufacturing and defense in depth
  ▪ No stainless-steel monolith (reduces thermal stress, intended to simplify construction)
  ▪ The fuel is encased in stainless steel cladding
  ▪ Heat pipes fabricated separately and inserted into central hole in fuel element
• Used for SCALE/MELCOR demonstration project
Reactor

- 5 MW thermal power
- 1134 fuel elements
  - $\text{UO}_2$ HALEU fuel (5.2 MT)
  - Annular fuel elements with stainless steel cladding on both sides
  - Outside of fuel element has hexagonal shape
  - HP at the center of each fuel element
- 1134 heat pipes
  - Potassium at 650 to 750 C
  - Vertical orientation for gravity-assisted performance
  - 1.8 cm outside diameter
- 2 emergency control rods of $\text{B}_4\text{C}$
- 12 alumina control drums with arcs of $\text{B}_4\text{C}$ for reactivity control
Reactor
• 3 neutron reflectors (top, side, bottom) around the core
  ▪ Top/bottom reflectors are stainless steel + beryllium oxide (BeO)
  ▪ Side reflector is alumina (Al₂O₃)
• Radiation shield surrounds the core
  ▪ 5.08 cm stainless steel core barrel
  ▪ 15.24 cm B₄C neutron shield

Secondary system
• Open-air Brayton cycle
  ▪ Operates at 1.1 MPa
  ▪ 1.47 MW electrical power output (29% efficiency)
Heat Pipe Reactor Fission
Product Inventory/Decay
Heat Methods and Results
• SCALE capabilities used
  • KENO or Shift 3D Monte Carlo transport
  • ENDF/B-VII.1 continuous energy physics
  • ORIGEN for depletion
  • Sequences
    ▪ CSAS for reactivity (e.g. rod worth)
    ▪ TRITON for reactor physics & depletion

• Relatively small amount of data except for nuclide inventory
  • new interface file developed for inventory using standard JSON format
  • easily read in python and post-processed into MELCOR or MACCS input
  • contains nuclear data such as decay Q-value for traceability when performing UQ studies
INL Design A Neutronics Summary

- 5 MWt rated power with 5-year operating lifetime
- UO₂ fuel with 19.75% ²³⁵U enrichment
- 4.57 MTU initial core loading
- 1.0951 MW/MTU specific power
- 2.0 GWD/MTU discharge burnup
- 1,134 heat pipe/fuel element units
- Discretized with 20 axial and 5 radial fuel zones
HPR-Related SCALE Updates

• New fast-spectrum nuclear data library
  • New 302-group structure was developed based on group structures optimized for fast systems (sodium-cooled fast reactors)
  • Enables fast depletion
    ▪ ~6.6 hours → ~1.12 hours using KENO

• Added 3D data visualization
  • Input geometry
  • Mesh data overlay (flux, fission source)

• Probability table update for unresolved resonance region for fast systems
  • ~400 pcm error for fast-reactor systems with Pu

• Shift integration
  • Full-core continuous-energy (CE) depletion is tractable for HPRs and TRITON-Shift scales to 10,000's of cores for faster turnaround (TRITON-KENO only scales to <100's of cores)

• Developed MADRE test suite for advanced reactors
  • Finds equivalent multigroup (MG) vs. CE performance
  • ENDF/B-VIII.0 ~400 pcm less than ENDF/B-VII.1
HPR-Related SCALE Updates

- Example of 3D beginning-of-life (BOL) flux map overlay

Front (X-Z)  Top (X-Y)  3D
Modeling Assumptions

- Full-core 3D Monte Carlo with continuous energy physics
- System state defined in INL report
  - Temperature
    - Fuel
      - iteration 1: uniform 1,000K
      - iteration 2: informed by MELCOR temperature profile
    - Working fluids 950K
    - Reflector 950K
  - Geometry
    - Annular fuel
    - Thermal expansion of
      - fuel stack (UO₂)
      - radial reflector (Alumina)
      - fuel cladding (stainless steel [SS])
Verification and Validation

• Verification
  • Compared to INL A reference design description
    ▪ Axial power shape
    ▪ Control drum worth
  • Multigroup (faster) vs. continuous energy physics (more accurate) comparison shows an average ~150 pcm higher reactivity
  • ENDF/B-VII.1 vs. ENDF/B-VII.1 comparison shows an average ~300 pcm lower

<table>
<thead>
<tr>
<th>Years</th>
<th>0.00</th>
<th>0.01</th>
<th>0.42</th>
<th>1.25</th>
<th>1.67</th>
<th>2.08</th>
<th>2.50</th>
<th>2.92</th>
<th>3.33</th>
<th>3.75</th>
<th>4.17</th>
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<th>5.00</th>
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<tbody>
<tr>
<td>MG-CE Diff (pcm)</td>
<td>141</td>
<td>60</td>
<td>62</td>
<td>260</td>
<td>122</td>
<td>145</td>
<td>104</td>
<td>134</td>
<td>198</td>
<td>149</td>
<td>305</td>
<td>112</td>
<td>128</td>
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</tbody>
</table>

• Validation basis
  • 1% +/- 2% bias in decay heat based on burst-fission experiments
  • 200 pcm +/- 400 pcm bias in eigenvalue based on 24 critical experiments with similarity index $c_k > 0.9$ compared to BOL cold zero power
Unit Cell Verification

- INL reported sensitivity study results of k-inf on pitch and clad thickness changes using infinite unit cell models in MCNP
- These models were replicated in SCALE
  - Using identical explicit isotopics with ENDF/B-VII.0 library used in the INL report
  - Using the SCALE standard composition library with ENDF/B-VII.1 library
- SCALE k-inf results differed by roughly 50 pcm with identical models
- Updating library and material definitions added, on average, 50 pcm to the SCALE results

<table>
<thead>
<tr>
<th>Case</th>
<th>Outer SS Clad (cm)</th>
<th>Pitch (cm)</th>
<th>$k_{\text{inf}}$ (MCNP)</th>
<th>$k_{\text{inf}}$ (SCALE) ENDF 7.0, Isotopics</th>
<th>$k_{\text{inf}}$ (SCALE) ENDF 7.1, Std Comp</th>
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<tbody>
<tr>
<td>1</td>
<td>0.1</td>
<td>2.786</td>
<td>1.25953</td>
<td>1.259937 (40.7)</td>
<td>1.260461 (93.1)</td>
</tr>
<tr>
<td>2</td>
<td>0.05</td>
<td>2.786</td>
<td>1.27496</td>
<td>1.275447 (48.7)</td>
<td>1.275798 (83.8)</td>
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<tr>
<td>3</td>
<td>0.05</td>
<td>2.686</td>
<td>1.28830</td>
<td>1.288864 (56.4)</td>
<td>1.289494 (119.4)</td>
</tr>
</tbody>
</table>

1. "Preliminary Assessment of Two Alternative Core Design Concepts for the Special Purpose Reactor", NL/EXT-17-43212, May 2018
Full Core Verification

• Reactivity control devices were tested in different configurations
  • All Poisons Out – Both shutdown rods were withdrawn, and control drums (CDs) were turned away
  • All Poisons In – Both shutdown rods were inserted, and CDs were turned in

• Comparisons were done using both the explicit isotopics with ENDF/B-VII.0 library and standard composition library with ENDF/B-VII.1

• Reactivity worth calculations were performed and compared to reference results
  • Identical models agree well with < 200 pcm k-eff differences and < 3.5% reactivity worth differences

<table>
<thead>
<tr>
<th>Control Condition/Parameter</th>
<th>Design A MCNP</th>
<th>Design A SCALE ENDF 7.0, Isotopics</th>
<th>Design A SCALE ENDF 7.1, Std Comp</th>
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</thead>
<tbody>
<tr>
<td>All Poisons Out</td>
<td>1.02825</td>
<td>1.029816 (156.6)</td>
<td>1.02989 (164.0)</td>
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<tr>
<td>All Poisons In</td>
<td>0.84594</td>
<td>0.846039 (9.9)</td>
<td>0.84526 (-68.5)</td>
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<tr>
<td>Control Drums In</td>
<td>0.95042</td>
<td>0.95067 (25.0)</td>
<td>0.950304 (-11.6)</td>
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<tr>
<td>Annular Shutdown Rod In</td>
<td>0.94555</td>
<td>0.947445 (189.5)</td>
<td>0.94725 (170.0)</td>
</tr>
<tr>
<td>Solid Shutdown Rod In</td>
<td>0.95933</td>
<td>0.960734 (140.4)</td>
<td>0.960660 (133.0)</td>
</tr>
<tr>
<td>$\beta=0.007$</td>
<td></td>
<td>$\beta=0.0072 (20)$</td>
<td>$\beta=0.0072 (20)$</td>
</tr>
<tr>
<td>BOL Excess Reactivity ($)</td>
<td>3.925</td>
<td>4.021 (2.5%)</td>
<td>4.025 (2.6%)</td>
</tr>
<tr>
<td>Total Drum Worth ($)</td>
<td>11.377</td>
<td>11.228 (-1.3%)</td>
<td>11.278 (-0.9%)</td>
</tr>
<tr>
<td>Individual Drum Worth ($)</td>
<td>0.970</td>
<td>0.985 (1.5%)</td>
<td>0.990 (2.1%)</td>
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<tr>
<td>Annular Shutdown Rod Worth ($)</td>
<td>12.151</td>
<td>11.725 (-3.5%)</td>
<td>11.749 (-3.3%)</td>
</tr>
<tr>
<td>Solid Shutdown Rod Worth ($)</td>
<td>9.981</td>
<td>9.698 (-2.8%)</td>
<td>9.705 (-2.8%)</td>
</tr>
</tbody>
</table>

Effect of control drum rotation on eigenvalue
Control Drum Rotation Flux Animations

Shutdown rods out

Shutdown rods in
Validation Basis: Short-Term Decay Heat

- Fissioning nuclides in INL A
  - 90% from $^{235}\text{U}$
  - 10% from $^{238}\text{U}$
  - Negligible from Pu
- Cumulative energy release following shutdown
  - ~90% by 0.3 days
  - ~92% by 1 day
  - ~96% by 10 days
- “Burst fission” experiments measure energy release over time ($t<1$ day) from a single fission of $^{235}\text{U}$
  - Most accurate measurements in the set have 1-sigma uncertainty in the 2–3% range
  - ORIGEN simulation is within 2-sigma uncertainty bounds shown in figure for almost all measurements
- Based on burst-fission data analyzed so far, 1% +/- 2% bias in instantaneous decay heat recommended for SCALE modeling of INL A
Decay Heat after Core Shutdown

Decay heat for select isotopes for the INL Design A at 2 GWD/MTU

- Top 10 decay heat producing isotopes in the first 10 days following shutdown
- Subtotal shows sum of top 10
Why Is Decay Heat So Much Lower than a Pressurized Water Reactor (PWR)?

- INL A has 2.7% specific power of PWR
- Comparing INL A fuel vs. PWR fuel per MTIHM
- PWR at 2 GWd/MTU
  - INL A has 2.9% of PWR decay heat at t=0
  - INL A has 4.8% of PWR decay heat at t=10 days
- PWR at 60 GWd/MTU
  - INL A has 3.1% of PWR decay heat at t=0
  - INL A has 2.6% of PWR decay heat at t=10 days
- Does this mean decay heat can be scaled with specific power?
• Comparing INL Design A with PWR decay heat curve scaled down
  • INL A differs by
    ▪ 13.2% at t=0
    ▪ -10.0% at t=1.88
    ▪ -5.2% at t=10

• Decay heat does not scale using specific power
Activity after Core Shutdown

Activity for selected Cs and I isotopes for the INL Design A at 2 GWd/MTU
Power Distribution

- Axial-normalized power peaking factors agree well with distribution from LANL and INL documents
  - INL reference gives hottest pin power profile while the LANL and ORNL are core averages
- Peaks at the top and bottom are due to axial reflection
  - Not as much reflection in the top due to heat pipes
  - MCNP models did not use fine enough mesh to capture bottom reflector peak fully
- Axial peaking does not fluctuate over core lifetime due to low burnup
Reactivity Feedback Effects

- Four negative reactivity feedback effects reported
  - Doppler broadening (primary)
  - Fuel axial thermal expansion
  - Alumina reflector radial thermal expansion
  - Outer clad radial thermal expansion

- Modeled all radial effects simultaneously
  - Outer SS clad radial expansion
  - Gap closure and increased pitch
  - Alumina radial expansion
  - Control drum drift

<table>
<thead>
<tr>
<th>Feedback Effect (cents/°C)</th>
<th>INL</th>
<th>ORNL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doppler</td>
<td>-0.1074</td>
<td>-0.1113</td>
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<tr>
<td>$\text{UO}_2$ Fuel Axial Elongation</td>
<td>-0.0422</td>
<td>-0.0437</td>
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<tr>
<td>Alumina Reflector Radial Thermal Expansion</td>
<td>-0.0225</td>
<td>-0.0284</td>
</tr>
<tr>
<td>Outer SS Fuel Clad Thermal Expansion</td>
<td>-0.0323</td>
<td>-</td>
</tr>
<tr>
<td>All Radial Expansions (Clad, Reflector, and CDs)</td>
<td>-</td>
<td>-0.0636</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>-0.2044</td>
<td>-0.2185</td>
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</tbody>
</table>
Neutronics Summary

- Eigenvalue bias was assessed for BOL cold zero power
  - 200 pcm +/- 400 pcm based on 24 critical experiments with similarity $c_k > 0.9$
- Decay heat bias 1% +/- 2% based on burst-fission measurements
- New 302-group structure was developed
  - Demonstrates a ~150 pcm bias over core lifetime compared to CE
- Axial refinement study shows higher reflector peaks at top and bottom of core compared with reference documents
- Using SCALE gives a more realistic representation of decay power than scaling PWR decay power
  - 13.2% at shutdown
  - -5.2% after 10 days
MELCOR Heat Pipe Reactor Model
When present, HPs replace conventional convective heat transfer between the fuel and coolant channel with the energy transfer from the fuel to the evaporative region of the HP.

HP models are special components within the COR package.

Heat rejection from the HP model at the condensation interface is transferred to the CVH package.

Basic geometry of a heat pipe is assumed to be a circular cylinder characterized by a relatively small set of geometric values, e.g.:

- \( R_O \) outside radius of heat pipe wall (m),
- \( R_I \) inside radius of heat pipe wall (m),
- \( D_{\text{wick}} \) thickness (or depth) of the wick (m), and
- \( \phi_{\text{wick}} \) porosity of the wick (-).

Axial lengths of the condenser, adiabatic, and evaporator sections are implicitly defined by the COR package cells that these regions are associated with.
HP modeling approaches within MELCOR reflect the purpose and constraints of the systems-level integrated code that it is.

MELCOR accommodates HP models of different fidelity through a common interface and a specified wall and working fluid region nodalization.

- Model 1: working fluid region modeled as high thermal conductivity material.
  - Accepts experimental or design-specific performance limit curves
  - Flexible implementation allows for multiple HP definitions in the same MELCOR input deck and multiple HP regions

Time-dependent conservation-of-energy equations are solved within the HP component and include boundary conditions linking them with the neighboring fuel (evaporator region) and coolant (condenser region)
MELCOR Heat Pipe Reactor Modeling: 3

- Core region modeled as a 2-D multi-ring representation

- Ring-to-ring radiative exchange implemented through the generalized core heat transfer pathway modeling in MELCOR
HP limits of operation

Steady-state operational limits modeled in MELCOR

• Sonic limit
  • Choked flow of vapor through the central core

• Capillary flow limit
  • Liquid flow rate at maximum capillary pressure difference

• Boiling limits
  • As heat flux increases, both nucleate and film boiling related issues can disrupt heat transfer. Film boiling can lead to a sudden drop in heat transfer efficiency.

• Condenser HX limit
  • The heat exchanger absorbing heat from the condenser may have operation limits of its own.

Each of these limits depend on the HP details (geometry, materials, type of wick, working fluid etc.) and can independently vary in magnitude based on operational conditions.

Estimated HP SS limits for a design considered in a 2018 INL report INL/EXT-17-43212
Several failure modes considered

- HP wall or end-cap failure due to time-at-temperature if the HP is subjected to high operating temperatures and associated pressures, such as might occur in a complete loss of heat sink (e.g., the HX fails)
- Local melt-through of the HP wall due to a sudden influx of heat
- HP wall or micro-imperfections in end-cap welds or HP wall materials after being subjected to time-at-operating temperatures and pressures.
MELCOR HP failure modeling

• HP temperature excursion leads to working fluid pressurization and HP wall creep failure
  o Larson-Miller model used for wall failure
  o Subsequent response includes HP failure and depressurization

• Alternate user-specified criteria for HP wall failure
  o HP wall failure can be a specified event (e.g., initiating event) or as an additional failure following a creep rupture failure (i.e., creep failure is predicted before wall melting)

• Optional user features to dynamically control or disable HP evaporator or condenser wall heat transfer and to start the fuel cell radionuclide leakage
MELCOR cascading HP failure modeling

HPR model can be subdivided into an arbitrary number of rings

- Generalized input matrix for fuel element connectivity governs heat flows
- Cascade region shown with 4 zones but could be larger
- User specifies HP failure(s)
- Bulk HP response modeled outside of the cascade region
- Consequences of initial failure(s) on adjacent ring responses

Zone modeling approach used in SFP applications for cascading fuel assembly ignition [NUREG/CR-7216]
Heat Pipe Reactor Plant Model and Source Term Analysis
MELCOR model of INL Design A – Reactor

Reactor modeling

- 2-D reactor nodalization
  - 14 axial levels
  - 15 radial rings
- 14 concentric rings of heat pipes (width of ~1 fuel assembly)
- Center ring models the emergency control rod guides
- Top and bottom reflectors are in axial levels 1 and 13
- Heat pipes transfer heat to the secondary Brayton air cycle in axial level 14
- Core region is surrounded by stainless steel shroud, alumina reflector, core barrel, and B₄C neutron shield
Reactor vessel – release pathways

Release from fuel to reactor vessel
   • Stainless-steel cladding failure at 1650 K

Release from reactor vessel to reactor building
   • Assumed reactor vessel leakage

Heat-pipe release path
   • Requires heat-pipe wall failure in two places
     o Creep rupture followed by melting
   • Creep rupture failure in the heat-pipe condenser region (secondary system region) could lead to reactor building bypass
Enclosure building nodalization

LANL and INL HPR descriptions did not address the enclosure building

Modeling includes internal building circulation flow paths

- Natural circulation into and out of the reactor cavity
- Natural circulation within the building

Building leakage addressed parametrically

- Base leakage similar to the reactor building surrounding the BWR Mark I containment
MELCOR input model attributes

Radionuclide inventory and decay heat at start of accident predicted with SCALE
  • End-of-cycle inventory at 5-yr

Point kinetics model for transient power calculation

Heat transfer between adjacent fuel elements modeled using radiative exchange
  • Heat transfer efficiency is parametrically varied

Potential for heat pipe creep rupture monitored in the evaporator and the condenser regions

Heat pipe limits estimated using LANL HTPIPE code
  • MELCOR accepts sonic, capillary, entrainment and boiling limit curves
  • Potassium and sodium limit curves were developed
  • MELCOR can also accept proprietary performance curves when available
Description of the TOP scenario

Transient Overpower (TOP) scenario selected for demonstration calculations

- Control drums malfunction and spuriously rotate “outward”

Modeled as linear reactivity insertion rate in $/second

- Safety control rods assumed to insert when peak fuel temperature exceeds 2200 K
- Strong feedback coefficient creates linear power increase

Performed sensitivity analysis to show how MELCOR could be used to gain insight into key source term drivers

- Sensitivities focused on source term and HPR parameters
- Previous LWR parameters do not necessarily translate to HPR uncertainties
Transient Overpower (TOP) scenario timeline

Steady-State
- Initialization
- Fuel temperature stabilizes

Reactivity Insertion
- Power increase
- Temperature rise
- Heat pipe failure
- Core damage
- Fission product release

Post-SCRAM
- Radial cooling by natural processes
- Fission product release and transport

$t = -5000 \text{ s}$
$t = 0 \text{ s}$
$t = 24 \text{ h}$
$T_{\text{max}} = 2200 \text{ K}$
Transient Overpower (TOP) base scenario (1/7)

The control drums start rotating at t=0 sec, which leads to an increase in the core power over 0.9 hr
  • Negative fuel temperature reactivity feedback limits the rate of power increase

The core steadily heats until the maximum heat flux location reaches the boiling limit
  • The heat transfer rate is limited above the boiling limit, which leads to a rapid heatup rate
  • The SS cladding is assumed to fail at 1650 K (just below its melting point), which starts the fission product releases into the reactor
  • The reactor is assumed to trip at 2200 K

Radial heat dissipation and heat loss to the reactor cavity passively cools the core
  • No active heat removal (secondary system trips and isolates)
The HP performance limits at the highest heat flux location show a steady heatup to the boiling limit

- Once the boiling limit is reached, there is a rapid heatup over the next minute
  - The fuel rapidly heats to melting conditions
  - SS cladding fails at 1650 K
  - SS HP wall also fails at 1650 K
- The start of the fission product release occurs through the failed cladding locations
Cladding failure at 1650 K resulting in fission product release

- HPs that exceeded the boiling limit rapidly heat to cladding failure (1650 K)
- ~20% of the 1134 HPs and fuel elements failed
- HP depressurization on failure drive release from the vessel

Iodine releases also depend on time at temperature

- Fuel release – 1.4% of core inventory
- Environmental release – 0.0008% of core inventory

- Vessel leakage is 1.6 in²
- Building leakage is 1.8 in²
Transient Overpower (TOP) base scenario (4/7)

The HPs could be challenged by creep failure at high temperature and pressure
- The HP gas heats and pressurizes during the TOP scenario
- The HP depressurizes after the wall fails shortly after reaching the boiling limit
  - Creep accumulation effectively stops upon HP wall failure without ΔP stress
- For HPs that do not reach the boiling limit, the HP pressure initially drops due to secondary system removing heat

HP creep failure is monitored using Larson-Miller correlations
- TOP base scenario shows maximum creep is ~0.07 (failure = 1)
- Creep failures in the condenser can create a bypass leak path to the environment
Fission products are retained in the fuel or deposit on their way to the environment

- The cladding remained intact for ~80% of the fuel elements
- 98.4% of the iodine fission product inventory is retained in the fuel due to limited time at high temperature

- The vessel retains 89% of the released iodine radionuclides
  - HP depressurization after failure is primary release mechanism
- The reactor building retains 11% of the radionuclides in the base case
  - BWR reactor building leak tightness used for the base case
  - No strong driving pressure to cause leakage
A series of calculations were performed to investigate the sensitivity of the source term magnitude to reactor building leakage effects:

- The design specifications of the reactor building were assumed:
  - The base result (1X) assumed a BWR reactor building value
  - 10X and 100X reflect higher design leakage and/or building damage
- Building leakage is driven by a very small temperature gradient to the environment (~5-7 °C)
  - Leakage is approximately linear with leakage area (1X is ~1.8 in²)
A series of calculations were performed to investigate the impact of an external wind

- External wind effects are included in DOE facility safety analysis where there also are not strong driving forces
  - Wind increases building infiltration and exfiltration
  - Upwind and downwind leakage pathways
- Wind effects are modeled as a Bernoulli term
  - \( dP = \frac{1}{2} \rho C_p v^2 \)
  - ASHRAE building wind-pressure coefficients

External wind modeling ref:
Building wind pressure coefficients.
Heat Pipe Reactor MELCOR Uncertainty Analysis
Role of MELCOR in Resolving Uncertainty

Uncertainty

Event Scenario Uncertainty
Phenomenological Model Uncertainty
Plant Initial/Boundary Condition Uncertainty
SSC Failure Modes
Simulation Uncertainty

Engineering Performance

Probability Density

Risk-Informed Assessment

Applied Load / SSC Capacity (Arbitrary Units)

- Load
- Safety Limit
- Capacity

- Ops Enhancements
- Power Uprates
- Inc. Fuel Burnups
- Design Changes
- SSC Aging
Evolution from MELCOR LWR Uncertainty Analysis

MELCOR application to LWR severe accident uncertainties

- Range of uncertainty studies under SOARCA
- PWR and BWR plant uncertainty studies
- Resolved role of uncertainty in a number of critical severe accident issues of high impact

General commonalities between LWR and HPR accident uncertainties

- Chemical form of key elements
- Aerosol physics parameters (e.g., shape factor)
- Operating time before accident happens
- Containment leakage hole size

Parameter selection emphasized potential HPR-specific uncertainties

- Ran samples of uncertainty calculations to explore role of uncertainty in evolution of HPR accident scenario class
## Parametric Uncertainties – Capability Demonstration

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<tr>
<th>Component</th>
<th>Parameter</th>
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<td><strong>Heat Pipes</strong></td>
<td>Heat Pipe Failure Location</td>
<td>Condenser (50%) / Evaporator (50%)</td>
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<td>Initial non-functional HPs</td>
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<td><strong>Core</strong></td>
<td>Gaseous Iodine Fraction (-)</td>
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<td>Reactivity Insertion Rate ($/s)</td>
<td>0.5x10^{-4} - 1.0x10^{-3}</td>
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<td>Vessel Emissivity (-)</td>
<td>0.125 - 0.375</td>
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<td>Total Leak Area (m$^2$)</td>
<td>2x10^{-5} - 2x10^{-3}</td>
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<td>Vessel and Vessel Upper Head HTC (W/m-K)</td>
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<td><strong>Confinement</strong></td>
<td>Cavity entrance open fraction</td>
<td>100% (90%) - 1% (10%)</td>
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<td>Wind Loading (m/s)</td>
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<td>Total Leak Area Multiplier (-)</td>
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<td><strong>Scenario</strong></td>
<td>Peak fuel temperature for safety rod insertion (K)</td>
<td>1300 – 2200</td>
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Traditional event scenario evolution for LWRs dominated by active system performance

Event scenarios evolved based often on binary decisions

- SSC performance often characterized as success or failure
- Risk profile could be adequately characterized or bounded by success or failure of SSCs

HPR accident scenario evolution will be unique, like other advanced non-LWRs

- Limited operational experience
- Broader range of operation for passive systems
- Consideration of degraded modes of operation
- What is the true margin to failure under accident conditions?

Realizations with greater reactivity insertion rates
Overall Timing of Event Evolution

- Fission product release commences with cladding failures
  - Continued fuel heatup can occur as deposited energy diffuses following reactor trip
Evaluating Heat Pipe Response

Spectrum of accident scenarios give rise to range of plant conditions

- Relevant to assessing potential and magnitude of consequences

Evaluation of SSC performance and margin in performance under accident conditions

HPRs rely on passive heat removal through capillary flows in heat pipes

- Sensitive to operating range of heat pipes
- Operating limits could for example be challenged under overpower conditions
Fuel Response by Ring

Highest powered rings off-center

Energy deposited in reactor during reactivity transient diffuses to lower power rings after reactor trip

Heatup of fuel in peripheral rings influenced by

- Lower decay heat levels
- Energy loss to confinement through vessel wall

Heatup of fuel in central rings influenced by

- Diffusion of energy from hottest fuel rings
- Limited heat sinks to which to dissipate energy
Thermal Inertia in Fuel Response

Most realizations dominated by early energy deposition into fuel prior to reactor trip

Diffusive heat flux from hottest rings to periphery
• Dominates heatup of fuel in peripheral rings
Thermal Inertia in Fuel Response

**Centrally Peaked Core**

- Ring 2
- Ring 4
- Ring 6

**Time to Peak Fuel Temperature [h]**

- Ring 8
- Ring 9
- Ring 10
- Ring 11
- Ring 12
- Ring 15

**Higher powered rings off-center**

- Ring 2
- Ring 4
- Ring 6

- Ring 8
- Ring 9
- Ring 10
- Ring 11
- Ring 12
- Ring 15
Heat Pipe Response

Lower peak fuel/clad temperatures promote potential for creep failure
Fission Product Release from Fuel Characterization

- In-vessel Iodine Release
  - Percent of Initial Inventory (%)
  - Time [h]

- In-vessel Cesium Release
  - Percent of Initial Inventory (%)
  - Time [h]

- In-vessel Iodine Release
  - Peak Fuel Temperature [K]

- In-vessel Cesium Release
  - In-vessel Iodine Release
  - Percent of Initial Inventory (%)
  - In-vessel Cesium Release
  - Percent of Initial Inventory (%)
Fission Product Transport Characterization

Iodine: Reactor Building

Cesium: Reactor Building

Iodine: Reactor Building

Cesium: Reactor Building

Peak Fuel Temperature [K]
Fission Product Release to Environment

Iodine Environment Release

Percent of Initial Inventory (%)

Cesium Environment Release

Percent of Initial Inventory (%)

Peak Fuel Temperature [K]

Iodine Environment Release Percent of Initial Inventory (%)
Summary
Conclusions

Added HPR modeling capabilities to SCALE & MELCOR for HPR source term analysis to show code readiness

Modeling demonstrated for a Transient Overpower Scenario with delayed scram

- Input of detailed ORIGEN radionuclide inventory data from ORNL
- Input radial and axial power distributions from ORNL neutronic analysis
- Develop MELCOR input model for exploratory analysis
- Fast-running calculations facilitate sensitivity evaluations (600 realizations included in the exploratory calculations)

Developed an understanding of non-LWR beyond-design-basis-accident behavior and overall plant response
What Is It?
The SCALE code system is a modeling and simulation suite for nuclear safety analysis and design. It is a modernized code with a long history of application in the regulatory process.

How Is It Used?
SCALE is used to support licensing activities in NRR (e.g., analysis of spent fuel pool criticality, generating nuclear physics and decay heat parameters for design basis accident analysis) and NMSS (e.g., review of consolidated interim storage facilities, burnup credit).

Who Uses It?
SCALE is used by the U.S. Nuclear Regulatory Commission (NRC) and in 61 countries (about 10,000 users and 33 regulatory bodies).

How Has It Been Assessed?
SCALE has been validated against criticality benchmarks (>1000), destructive assay of fuel and decay heat for PWRs and BWRs (>200)
Data to generate for MELCOR: QOIs

Code strategy for source term
MELCOR for Accident Progression and Source Term Analysis
MELCOR Development for Regulatory Applications

What Is It?
MELCOR is an engineering-level code that simulates the response of the reactor core, primary coolant system, containment, and surrounding buildings to a severe accident.

Who Uses It?
MELCOR is used by domestic universities and national laboratories, and international organizations in around 30 countries. It is distributed as part of NRC’s Cooperative Severe Accident Research Program (CSARP).

How Is It Used?
MELCOR is used to support severe accident and source term activities at NRC, including the development of regulatory source terms for LWRs, analysis of success criteria for probabilistic risk assessment models, site risk studies, and forensic analysis of the Fukushima accident.

How Has It Been Assessed?
MELCOR has been validated against numerous international standard problems, benchmarks, separate effects (e.g., VERCORS) and integral experiments (e.g., Phedus FPT), and reactor accidents (e.g., TMI-2, Fukushima).
Source Term Development Process

**Experimental Basis**
- Oxidation/Gas Generation
- Melt Progression
- Fission Product Release
- Fission Product Transport

**PIRT process**

**MELCOR**

**Accident Analysis**
- Scenario # 1
- Scenario # 2
- Scenario # n-1
- Scenario # n

**Synthesize timings and release fractions**

**Design Basis Source Term**

Fission Product Classes | Firing | 0.1 hr | 1.0 hr | Avg | Std. Dev. |
--- | --- | --- | --- | --- | --- |
Noble Gases | 5% | 95% | 95% | 0% | 0% |
Iodine, bromine | 5% | 95% | 25% | 1% | 1% |
Cesium | 5% | 95% | 35% | 1% | 1% |
Tellurium | 0% | 5% | 25% | 0.5% | 0.5% |
Ba, Sr | 0% | 2% | 15% | 0% | 0% |
Ru, Mo, Pd, etc. | 0% | 0.25% | 0.25% | 0% | 0% |
Lanthanides | 0% | 0.8% | 0.5% | 0% | 0% |
Cerium group | 0% | 0.85% | 0.5% | 0% | 0% |
SCALE/MELCOR/MACCS

**SCALE**
- **Neutronics**
  - Criticality
  - Shielding
  - Radionuclide inventory
  - Burnup credit
  - Decay heat

**MELCOR**
- **Integrated Severe Accident Progression**
  - Hydrodynamics for range of working fluids
  - Accident response of plant structures, systems and components
  - Fission product transport

**MACCS**
- **Radiological Consequences**
  - Near- and far-field atmospheric transport and deposition
  - Assessment of health and economic impacts

---

**Nuclear Reactor System Applications**

**Safety/Risk Assessment**
- Technology-neutral
  - Experimental
  - Naval
  - Advanced LWRs
  - Advanced Non-LWRs
  - Accident forensics (Fukushima, TMI)
  - Probabilistic risk assessment

**Regulatory**
- License amendments
- Risk-informed regulation
- Design certification (e.g., NuScale)
- Vulnerability studies
- Emergency preparedness
- Emergency Planning Zone Analysis

**Design/Operational Support**
- Design analysis scoping calculations
- Training simulators

**Fusion**
- Neutron beam injectors
- Li loop LOFA transient analysis
- ITER cryostat modeling
- He-cooled pebble test blanket ($H^3$)

**Spent Fuel**
- Risk studies
- Multi-unit accidents
- Dry storage
- Spent fuel transport/package applications

**Facility Safety**
- Leak path factor calculations
- DOE safety toolbox codes
- DOE nuclear facilities (Pantex, Hanford, Los Alamos, Savannah River Site)

---

**Non-Reactor Applications**
MELCOR Attributes
Foundations of MELCOR Development

Fully integrated, engineering-level code
• Thermal-hydraulic response of reactor coolant system, reactor cavity, reactor enclosures, and auxiliary buildings
• Core heat-up, degradation and relocation
• Core-concrete interaction
• Flammable gas production, transport and combustion
• Fission product release and transport behavior

Level of physics modeling consistent with
• State-of-knowledge
• Necessity to capture global plant response
• Reduced-order and correlation-based modeling often most valuable to link plant physical conditions to evolution of severe accident and fission product release/transport

Traditional application
• Models constructed by user from basic components (control volumes, flow paths and heat structures)
• Demonstrated adaptability to new reactor designs – HPR, HTGR, SMR, MSR, ATR, Naval Reactors, VVER, SFP, …
Validated physical models
• International Standard Problems, benchmarks, experiments, and reactor accidents
• Beyond design basis validation will always be limited by model uncertainty that arises when extrapolated to reactor-scale

Cooperative Severe Accident Research Program (CSARP) is an NRC-sponsored international, collaborative community supporting the validation of MELCOR

International LWR fleet relies on safety assessments performed with the MELCOR code
Common Phenomenology
MELCOR Modeling Approach

Modeling is mechanistic consistent with level of knowledge of phenomena supported by experiments

Parametric models enable uncertainties to be characterized

- Majority of modeling parameters can be varied
- Properties of materials, correlation coefficients, numerical controls/tolerances, etc.

Code models are general and flexible

- Relatively easy to model novel designs
- All-purpose thermal hydraulic and aerosol transport code
MELCOR State-of-the-Art

MELCOR Code Development

- Models
  - Converging Molten Pool
  - Curved Lower Head
  - Stefan Model
  - Point Kinetics
  - Smart Restart
  - RN Activity (BONUS)
  - Turbulent Deposition
  - H2 Production
  - Mechanistic Fan Cooler
  - CORQFUCH
  - LHC Eutectics
  - Vector CFs
  - Homologous Pump
  - Resuspension
  - Radiation Enclosure

- Emphasis
  - Conversion from F77 to F95
  - Code Performance Improvements
  - HTGR Models
  - N4 Fire Models
  - Non-LWR Models
  - MELCOR 2.x Robustness & User Flexibility
  - SEP Models
  - Molten Pool / Lower Head

- Official Release
  - MELCOR 1.8.5
  - MELCOR 1.8.6
  - M2L.13643
  - M2L.1378
  - M2L.14803
  - M2L.16342
  - MELCOR 2.2

Version Date
- 2.2.18180 December 2020
- 2.2.14959 October 2019
- 2.2.11932 November 2018
- 2.2.9541 February 2017
- 2.1.6342 October 2014
- 2.1.4803 September 2012
- 2.1.3649 November 2011
- 2.1.3096 August 2011
- 2.1.YT August 2008
- 2.0 (beta) Sept 2006

Spent Fuel
- Spent fuel pool risk studies
- Multi-unit accidents (large area destruction)
- Dry Storage

Non-Nuclear Facilities
- Leak Path Factor Calculations (LPF)
  - Release of hazardous materials from facilities, buildings, confined spaces
  - DOE Safety Toolbox code
  - DOE nuclear facility users
  - Pantex
  - Hanford
  - Los Alamos
  - Savannah River Site

HTGR Reactors
- Helium Properties
- Accelerated steady-state initialization
- Two-sided reflector (RF) component
- Modified Fuel components (PMR/PBR)
- Point kinetics
- Fusion product diffusion, transport, and release
- TRISO fuel failure

Sodium Reactors
- Sodium Properties
  - Sodium Equation of State
  - Sodium Thermomechanical properties

Containment Modeling
- Sodium pool fire model
- Sodium spray fire model
- Atmospheric chemistry model
- Sodium-concrete interaction

Molten Salt Reactors
- Properties for LiF-B2Li have been added
  - Equation of state
  - Thermomechanical properties

Accident Tolerant Fuels
- Performance improvements
- Improved safety margins

- Fusion
  - Neutron Beam Injectors (LOVA)
  - Li Loop LOFA transient analysis
  - ITER Cryostat modeling
  - Helium Lithium
  - Helium Cooled Pebble Bed Test Blanket (Trillium Breeding)
Emphasis is on Automation  
Affordable solutions  
Consistent solutions

Bug tracking and reporting  
- Bugzilla online

Code Validation  
- Assessment calculations  
- Code cross walks for complex phenomena where data does not exist.

Documentation  
- Available on ‘Subversion’ repository with links from wiki  
- Latest PDF with bookmarks automatically generated from word documents under Subversion control  
- Links on MELCOR wiki

Project Management  
- Jira for tracking progress/issues  
- Can be viewable externally by stakeholders

Sharing of information with users  
- External web page  
- MELCOR workshops  
- MELCOR User Groups (EMUG & AMUG)

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<th>OE</th>
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Table 1-1: Physics Package Coverage
MELCOR Verification & Validation Basis

Volume 1: Primer & User Guide
Volume 3: MELCOR Assessment Problems
[SAND2015-6693 R]

Analytical Problems
Saturated Liquid Depressurization
Adiabatic Expansion of Hydrogen
Transient Heat Flow in a Semi-Infinite Heat Slab
Cooling of Heat Structures in a Fluid
Radial Heat Conduction in Annular Structures
Establishment of Flow

LWR & non-LWR applications

Core Heatup & Degradation
Integral / Accidents

Specific to non-LWR applications

RN Release
Ex-Vessel Debris

Containment
A sensitivity study to examine fission product release from a fuel particle starting with a bare kernel and ending with an irradiated TRISO particle;
MELCOR Modernization

Generalized numerical solution engine

Hydrodynamics

In-vessel damage progression

Ex-vessel damage progression

Fission product release and transport