Analysis of the Versatile Test Reactor Using RELAP5-3D

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Outline

• Scope

• VTR main characteristics

• Suitability of RELAP5-3D for SFR simulation

• RELAP5-3D VTR Modeling & Simulation
  – Preliminary Safety Analysis for Protected/Unprotected Transients

• Conclusions
Scope

- US-DOE established the Versatile Test Reactor (VTR) program in February 2017
  - Reports indicated an existing gap between current fast neutron irradiation capabilities in US and needs of different stakeholders
  - 3-years R&D effort to enable an informed DOE decision on the further development of a fast neutron source
  - INL is leading the R&D program and it is the proposed hosting site
  - INL expanding its technical capabilities on SFR technology leveraging its staff expertise on experiments designs, reactors operation, codes development and assessment, nuclear safety analyses
Scope

• Reference VTR thermal-hydraulic (TH) design and model being developed by Argonne National Lab (ANL) using SAS4A/SASSY code

• INL developed an independent RELAP5-3D model
  – leveraging INL expertise in RELAP5-3D code development, modeling & simulation (M&S)
  – quicker learning process on SFR technology

• Following best practices outlined in IAEA SSG-2, “Deterministic Safety Analysis for Nuclear Power Plant”
  – “The operating organization shall ensure that an independent verification of the safety assessment is performed by individuals or groups separate from those carrying out the design, before the design is submitted to the regulatory body”. Additional independent analyses of selected aspects may also be carried out by or on behalf of the regulatory body.”
VTR main characteristics

- Remark: following information was developed before the selection of GE-Hitachi (GEH) Nuclear Energy PRISM technology by VTR program

- Conceptual core main characteristics

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Power (MWth)</td>
<td>300</td>
</tr>
<tr>
<td>Peak Fast Neutron Flux (n/cm² s)</td>
<td>&gt;4.0x10¹⁵</td>
</tr>
<tr>
<td>Number of Fuel Assemblies</td>
<td>66</td>
</tr>
<tr>
<td>Number of Radial Reflector Assemblies</td>
<td>114</td>
</tr>
<tr>
<td>Number of Shield Reflector Assemblies</td>
<td>114</td>
</tr>
<tr>
<td>Assembly Length (m)</td>
<td>3.53</td>
</tr>
<tr>
<td>Control Rods (Control + Safety)</td>
<td>6 + 3</td>
</tr>
<tr>
<td>Assembly pitch (cm)</td>
<td>12</td>
</tr>
<tr>
<td>Fuel Height (cm)</td>
<td>80</td>
</tr>
<tr>
<td>Plenum Height (cm)</td>
<td>80</td>
</tr>
</tbody>
</table>
**VTR main characteristics**

- Use of metallic fuel (U-20Pu-10Zr, 5% enriched U)
- Reactivity control by two independent systems
  - Primary system: 6 CR
  - Secondary system: 3 safety CR
- Pool type configuration
  - Primary Sodium Mass flow: 1566 Kg/s
  - 2 MCP, 2 IHX
  - Sodium Core Inlet/Outlet temp: 350/500 C
- Secondary side IHX dumping heat into atmosphere via air blowers
- Direct Reactor Auxiliary Cooling System (DRACS) remove heat from cold pool
  - 3 Na-K Natural Draft Heat Exchangers (NDHX)
VTR main characteristics

• Safety Limits:
  – Limits for Normal Operation (metallic fuel):
    • 650 ºC for fuel clad
    • 1,121 ºC for U-20Pu-10Zr
    • $q' < 450$ W/cm
  – DBA FOMs:
    • Peak Internal Cladding Temperature ($< 650$ ºC)
    • Bulk Coolant temperatures for Hot/Cold Pools ($< 650$ ºC)
    • Subcriticality
  – BDBA FOMs:
    • Peak Internal Cladding Temperature ($< 788$ ºC)
    • Fuel Centerline Temperature ($< 1119$ ºC)
    • Long-term Structural Materials Temperature ($< 704$ ºC)
VTR main characteristics

• Demonstrate the “inherent safety” of SFR w/ Metal Fuel (EBR-II experience) for BDBA → decrease the probability of severe accidents
  – **Inherent Shutdown**: use of negative reactivity feedbacks (fuel, core, CR expansions) generated by high temperature transients
  – **Passive shutdown heat removal**: use of Natural Circulation for removing decay heat
Suitability of RELAP5-3D for VTR M&S

- RELAP5-3D can model Liquid Metal circuits → Liquid Metal properties files available, Na, Na/K, Lead, Lead/Bismuth
- Dedicated correlation for core thermal heat exchange → Westinghouse/Cheng-Todreas correlation for wire-wrapped hexagonal rod bundles
- Several peer-reviewed journal articles showed successful application of RELAP5-3D code for simulating SFR sub-channels and plant transients (e.g., see IAEA EBR-II CRP)
Suitability of RELAP5-3D for VTR M&S

• Special RELAP5-3D modeling techniques for VTR
  – Use of Control Variables + Servo-valve for modelling wire-wrapped rod bundle friction losses in the laminar/transition region
  – VTR Fuel Pitch/Diameter (P/D) = 1.18 → Westinghouse correlation OK for heat transfer
  – Use of Control variables for modeling several reactivity feedbacks (e.g., Core axial and radial expansion, CR and Vessel expansion)

• Remark: scenarios involving sodium boiling and disruptive core events cannot be simulated using RELAP5-3D → use SAS4A/SASSY & other SA codes
RELAP5-3D VTR M&S

• Criteria for VTR M&S:
  – Preserve relevant elevation, masses, flow areas, flow paths \( \rightarrow \) ref.: ANL and INL design documentation
  – Modeling:
    • relevant components (core S/A, IHX, DRACS, pumps, NDHX, expansion tanks)
    • relevant flow paths (core, bypass, UIS, hot & cold pool, secondary and SHRS flows)
    • Important heat transfer mechanisms (core, core/bypass, IHX, CR and vessel expansion, cold pool – DRACS, heat sink with the atmosphere)
    • 0D Neutron Kinetics feedbacks
RELAP5-3D VTR M&S

- 7 channels core, 3 orifice zones
  - Average Channel (64 S/A), Hot Channel (1 S/A), Cold Channel (1 S/A)
  - CR/Test section channel (25 S/A)
  - Reflector/Shim/Shield channel (240 S/A)
  - Core Bypass (x 66)
  - Reflector Bypass (x 265)

- 2 Fuel materials describing different level of irradiations

- Primary side: Hot/Cold pools + IHX, Main Circulation Pump (MCP), DRACS shell

- Secondary side: IHX + pipelines + secondary MCP + Expansion Tank / DRACS+ pipelines + Expansion Tank + NDHX

- Heat Sink: Atmosphere & Blowers modeled as Boundary Conditions
RELAP5-3D VTR M&S

- RELAP5-3D Model stats
  - Number of Heat Structures: 237 (861 mesh points)
  - Number of Volumes: 656 (675 junctions)
  - 4,800 lines input deck
  - Control and Protection System Logic
  - 0D – Neutron Kinetics (NK)

- Steady State Results consistent with design specifications

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Core Power (MWh)</td>
<td>300.0</td>
</tr>
<tr>
<td>Core Inlet Temperature (°C)</td>
<td>350.0</td>
</tr>
<tr>
<td>Core Outlet Temperature (°C)</td>
<td>500.0</td>
</tr>
<tr>
<td>Peak Fuel Temperature (°C)</td>
<td>804.5</td>
</tr>
<tr>
<td>Peak Cladding Temperature (°C)</td>
<td>564.0</td>
</tr>
<tr>
<td>Peak Coolant Temperature (°C)</td>
<td>532.6</td>
</tr>
<tr>
<td>Core Mass Flow Rate (Kg/s)</td>
<td>1566.1</td>
</tr>
<tr>
<td>Core Pressure Drop – Total (MPa)</td>
<td>0.53</td>
</tr>
<tr>
<td>Primary Pump Head (MPa)</td>
<td>0.563</td>
</tr>
<tr>
<td>IHTS Mass Flow Rate – Total (Kg/s)</td>
<td>1558.4</td>
</tr>
<tr>
<td>IHX Intermediate Inlet Temperature (°C)</td>
<td>327.9</td>
</tr>
<tr>
<td>IHX Intermediate Outlet Temperature (°C)</td>
<td>478.3</td>
</tr>
</tbody>
</table>
RELAP5-3D VTR M&S

- Implementation of the Control & Protection System
  - Combination of logical trips and control variables
  - Regulate:
    - primary and secondary flows
    - heat sink rate (i.e., blower heat rejection) for secondary cold leg temperature control
    - NDHX heat rejection (i.e., atmosphere temperature) for Natural circulation in DRACS
  - Ref. ANL-VTR4 report for the Protection System actuation logic

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Threshold</th>
<th>Delay (s)</th>
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<tbody>
<tr>
<td>Reactor Power</td>
<td>115%</td>
<td>0.3</td>
</tr>
<tr>
<td>Power-to-Flow Ratio</td>
<td>115%</td>
<td>0.4</td>
</tr>
<tr>
<td>Average Core Outlet Temperature</td>
<td>+20°C</td>
<td>2.2</td>
</tr>
<tr>
<td>Average Core Inlet Temperature</td>
<td>+20°C</td>
<td>1.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Delay (s)</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPS Reactor Trip Signal Sent</td>
<td>0.1</td>
<td>Complete Control Rod Scram</td>
</tr>
<tr>
<td>Initiation of Control Rod Scram</td>
<td>0.2</td>
<td>PHTS &amp; IHTS Pumps Trip</td>
</tr>
<tr>
<td>Initiation of PHTS &amp; IHTS Pump Trips</td>
<td>2.0</td>
<td>DHX Heat Rejection Terminated</td>
</tr>
<tr>
<td>RPS Reactor Trip Signal Sent</td>
<td>10.0</td>
<td>SHRS Air Dampers Open</td>
</tr>
</tbody>
</table>
Transients calculations: PTOP

- Protected Transient Overpower (PTOP)
  - Assume CR Reactivity insertion step: 87 c in 175 seconds
  - Reactor scram at t=21 secs after core outlet temperature surges +20 °C
  - Cooldown after pump trip by DRACS → power removed = decay heat at t=10 hrs
  - Significant safety margins
Transients calculations: UTOP

- **Un-Protected Transient Overpower (UTOP)**
  - Assume CR Reactivity insertion step: 87 c in 175 seconds
  - No Reactor scram, no blower trips → Power surge at 161% $P_{nom}$
  - Negative reactivity coefficients bring reactor power back to $P_{nom}$ at $t=+15$ minutes
  - Peak Fuel Centerline Temp = 1074 °C → safety margin ~ 72 °C
**Transients calculations: UTOP**

- Monte Carlo calculations for a better understanding of UTOP safety margins → Use of RELAP5-3D/RAVEN
  - 5 input parameters, with normal distribution
  - 153 runs → get 95%/95% confidence/probability values
  - PICT = 716 °C and Peak Fuel Centerline temp = 1107 °C

### Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doppler Coefficient</td>
<td>20%</td>
</tr>
<tr>
<td>CR Driveline Expansion Coefficient</td>
<td>20%</td>
</tr>
<tr>
<td>Coolant Density Coefficient</td>
<td>20%</td>
</tr>
<tr>
<td>Radial Expansion Coefficient</td>
<td>20%</td>
</tr>
<tr>
<td>Hot Channel Conductivity</td>
<td>10%</td>
</tr>
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</table>
Transients calculations: PSBO

- Protected Station Blackout (PSBO)
  - Assume loss of all AC power → pumps trip and failsafe opening of DRACS HX
  - Reactor scram when power-to-flow ratio > 115 $P_{nom}$
  - Cooldown after pump trip by DRACS → power removed = decay heat at $t=10$ hrs
  - Significant safety margins
**Transients calculations: USBO**

- **Un-Protected Station Blackout (USBO)**
  - Assume loss of all AC power $\rightarrow$ pumps trip and failsafe opening of DRACS HX
  - No Reactor scram $\rightarrow$ temp increase $\rightarrow$ Power reduced by inherent negative reactivity feedbacks
  - Reactor remains critical ($k_{eff} = 1.0$), DRACS removes total power over long term (>~20 hrs)
  - Pools and Fuel temperatures below safety limits

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**Graphs:**

- **Reactor Power – Short term**
- **Reactivity Trend**
- **Reactor Power – Long term**
- **Cold and Hot Pool Temperatures**
- **Fuel and Coolant Max Temperatures**
Transients calculations: PLOHS

- Protected Loss of Heat Sink (PLOHS)
  - Loss of heat removal from IHXs $\rightarrow$ High inlet core temperature $\rightarrow$ power decrease for inherent negative feedbacks $\rightarrow$ reactor scram for high inlet temperature
  - Scram timing and final cold pool temperature depends by Cold Pool modeling
  - Significant safety margins
Transients calculations: ULOHS

- Un-Protected Loss of Heat Sink (ULOHS)
  - Loss of heat removal from IHXs → high inlet core temperature → power decrease for inherent negative feedbacks → no Reactor scram, MCPs continue to run → Negative reactivity coefficients bring reactor power down to ~ few % $P_{nom}$
  - Vessel Expansion causes return to criticality ($k_{eff}$ >=1.0) by $t = \sim 1$ hr
  - Primary system temps equalize, higher cold pool temp increases power removal by DRACS
  - DRACS remove Decay Heat at $t=\sim 5$ hrs
  - Pools and Fuel temperatures below safety limits
Conclusions

• Technical activities ongoing at INL, for developing necessary technical skills for the VTR hosting site

• State-of-the-art RELAP5-3D TH/0D NK VTR model developed

• RELAP5-3D code flexibility allowed M&S of main reactivity feedbacks and main plant components with an acceptable level of details

• Set of preliminary safety analyses developed → no safety limits violated

• Comparisons with reference code SAS4A/SASSY are satisfactory (not showed in this presentation)