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RELAP5-3D[TM] Simulations for HTGR at the Canadian Nuclear Laboratories

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Outline

- Introduction, Facility Description
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- Pressurized Conduction Cooldown Results
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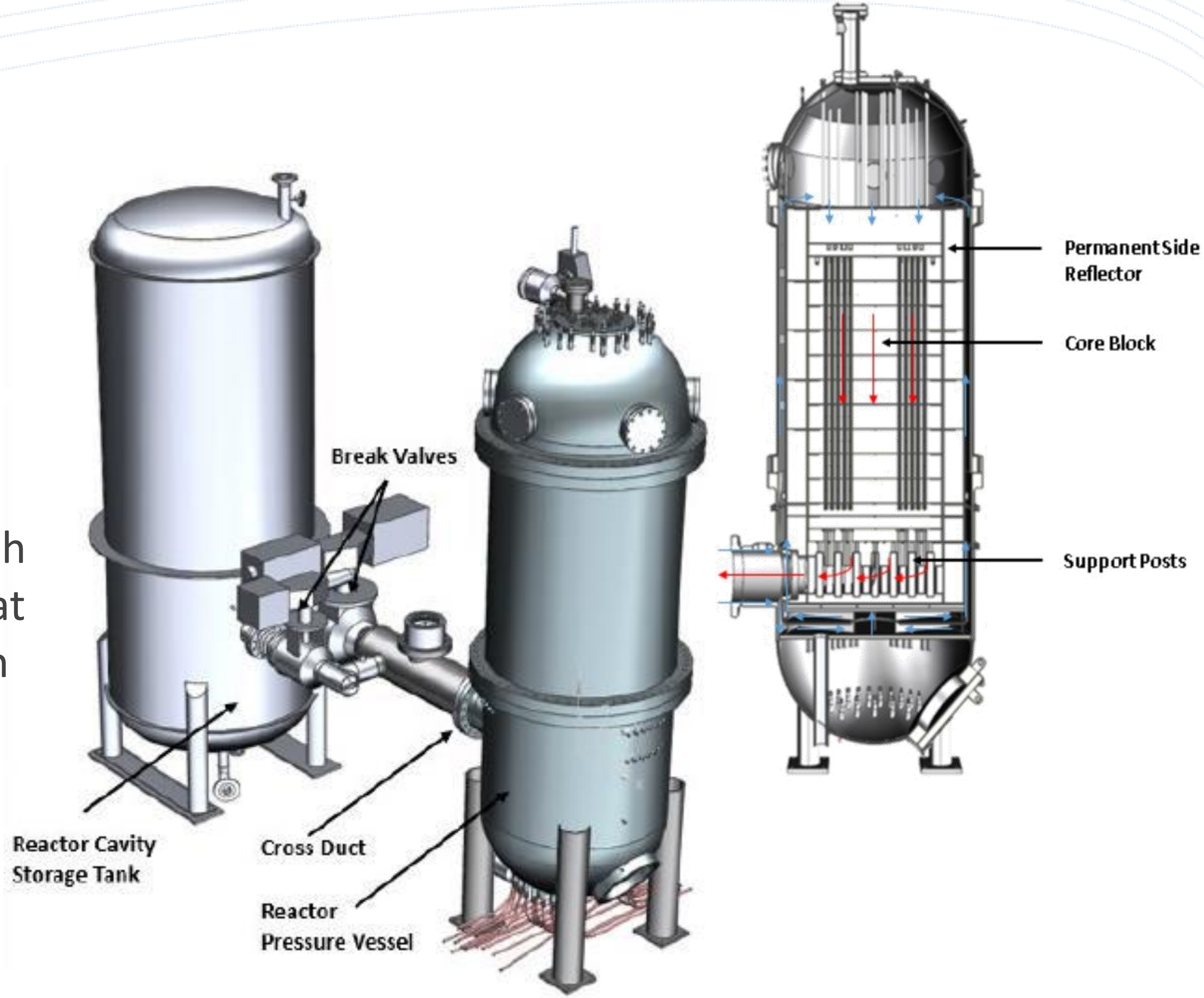
Introduction

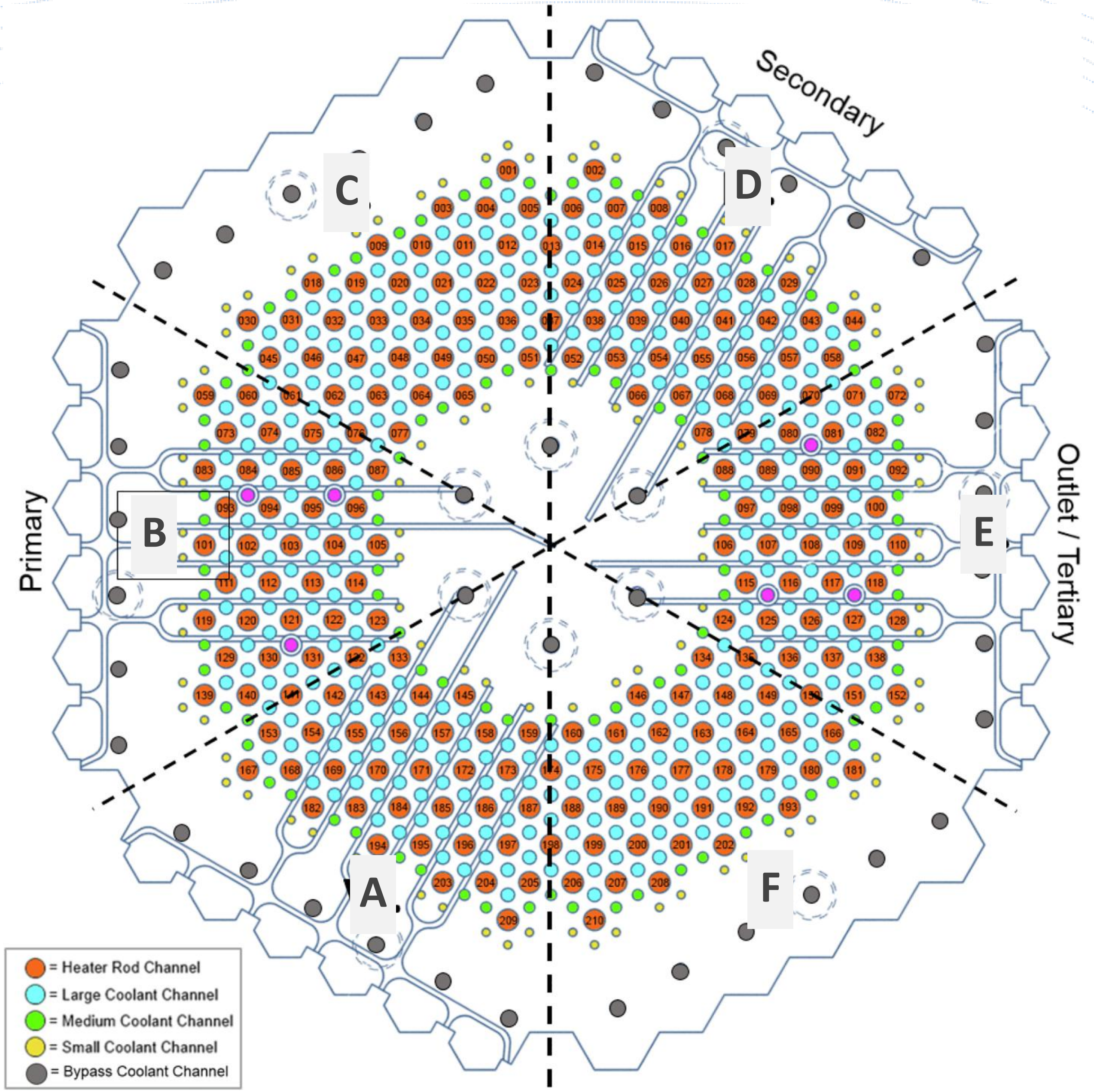
Canadian Nuclear Laboratories (CNL) is developing modelling and simulation capabilities for small High-Temperature Gas-cooled Reactors (HTGRs).

- The applicability of the system thermalhydraulics code RELAP5-3D to HTGR analysis is being assessed through simulation of experiments performed at the Oregon State University (OSU) High Temperature Test Facility (HTTF).
- CNL is participating in the OECD-NEA HTGR T/H Benchmark based on HTTF data [1].



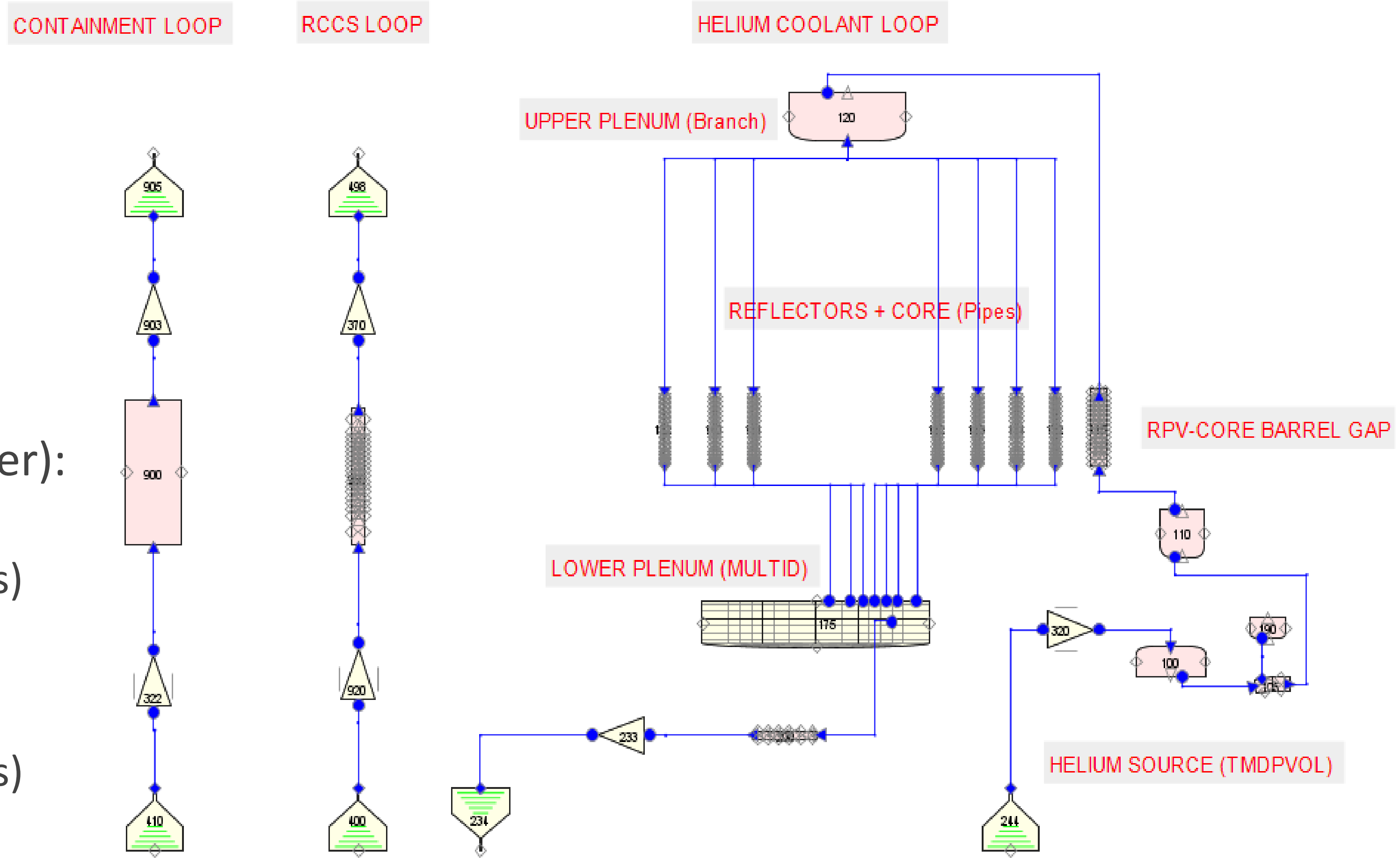
HTTF Experiments and Instrumentation

- Nominal power 2.2 MW, He flow 1 kg/s
- OSU performed various Facility Characterization, Pressurized Conduction Cooldown (PCC) and Depressurized Conduction Cooldown (DCC) tests
- Core divided into six sectors (labelled A to F)
- Sectors identified as primary, secondary or tertiary, based on degree of instrumentation
- Core is heated by 210 graphite rods (red circles)
- Helium coolant flows through 516 channels (yellow, green and blue circles represent different sizes, gray for bypass channels)

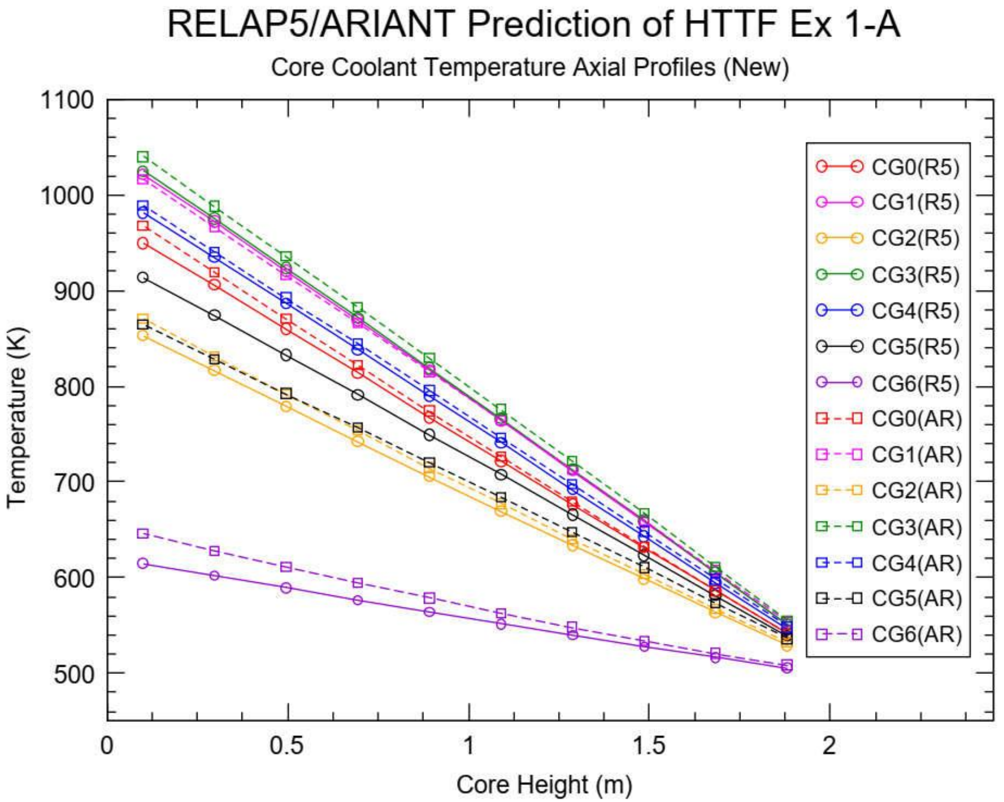


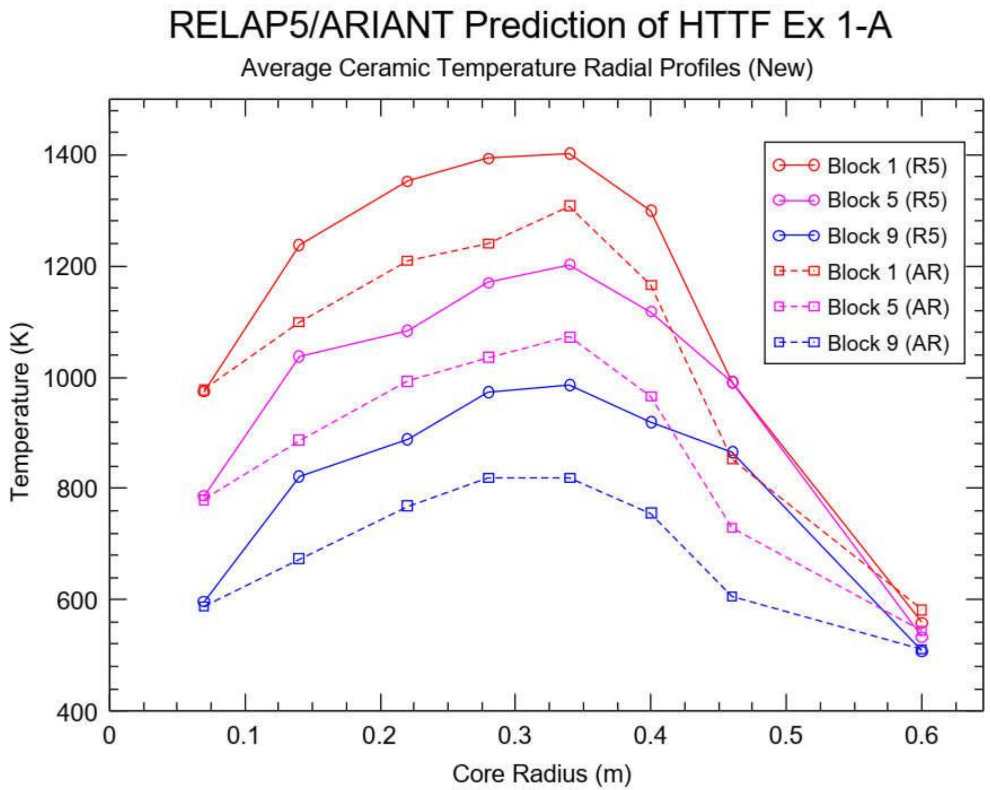
RELAP5-3D Model for HTTF Full Power Simulations

- Three once-through loops, fixed BCs
- Primary Loop (Helium):
  - Reactor core (1+1+5 coolant rings model)
  - Core Inlet/Upper plenum BRANCH
  - Lower Plenum MULTID component
  - Up-riser pipe
  - Lower Plenum support structures
- Reactor Cavity Cooling System (RCCS, water):
  - Reactor cavity (pipe)
  - Cavity upper and lower outlet (reservoir BCs)
- Containment Loop (Nitrogen):
  - Single Volume
  - Cavity upper and lower outlet (reservoir BCs)
  - Has insignificant impact



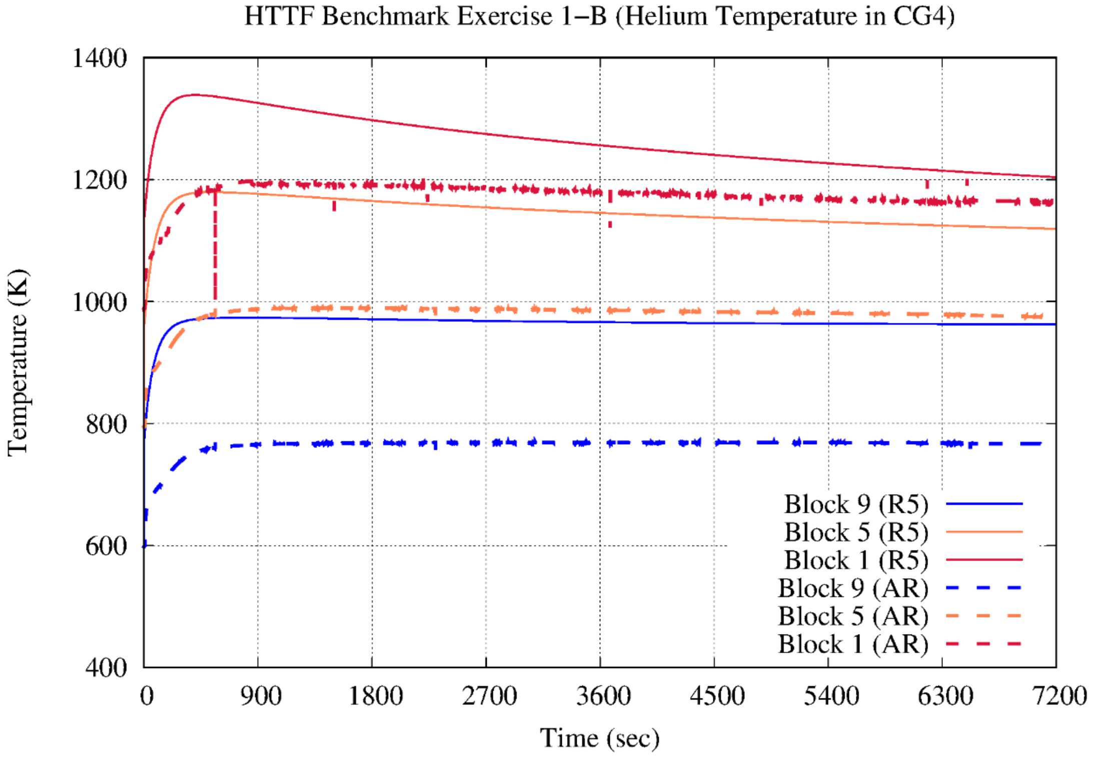
HTTF Full Power, Steady State: He and Ceramic Temperatures

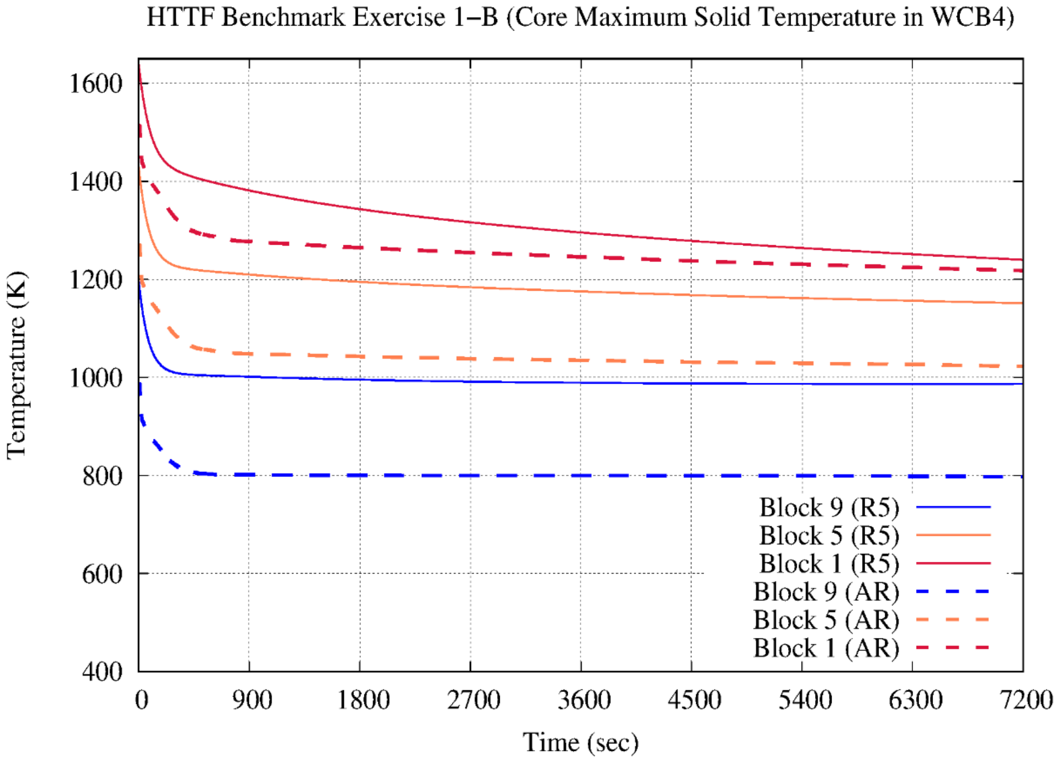




- HTTF nominal design (i.e., full power, steady-state) conditions
- Left: RELAP5-3D (solid) and ARIANT (dashed) He coolant (CG) temperature predictions at ten core axial locations
- Right: Average Ceramic (CB) temperature predictions for Blocks 1, 5, and 9 (measured from bottom-up); RELAP5-3D predicts higher solid temperatures

Full Power PCC; CG4 He and Max. Solid Temperatures





- Pressurized conduction cooldown (PCC) from full power steady-state
  - Coolant flow to zero over first second, decay heat power
- Left: He temperature predictions for CG4 at blocks 1, 5, 9
- Right: Maximum solid temperature predictions for CB4 at blocks 1, 5, 9
- RELAP5-3D-predicted coolant and solid temperatures slightly higher than ARIANT

PG-28 Lower Plenum Mixing Test

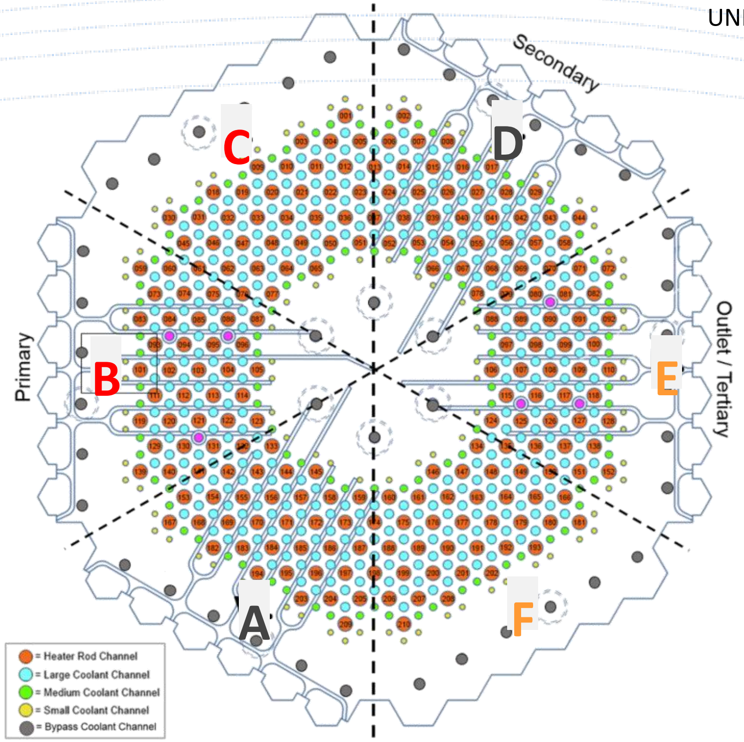
- Test selected to study 3-D effects within the lower (outlet) plenum (using CFD). The RELAP5-3D model provides boundary conditions to the CFD code.
- Four (B, C, E, F) of the six sectors are heated
  - 42 of 210 heater rods active: 14 in each in sectors B and C, 7 each in sectors E and F

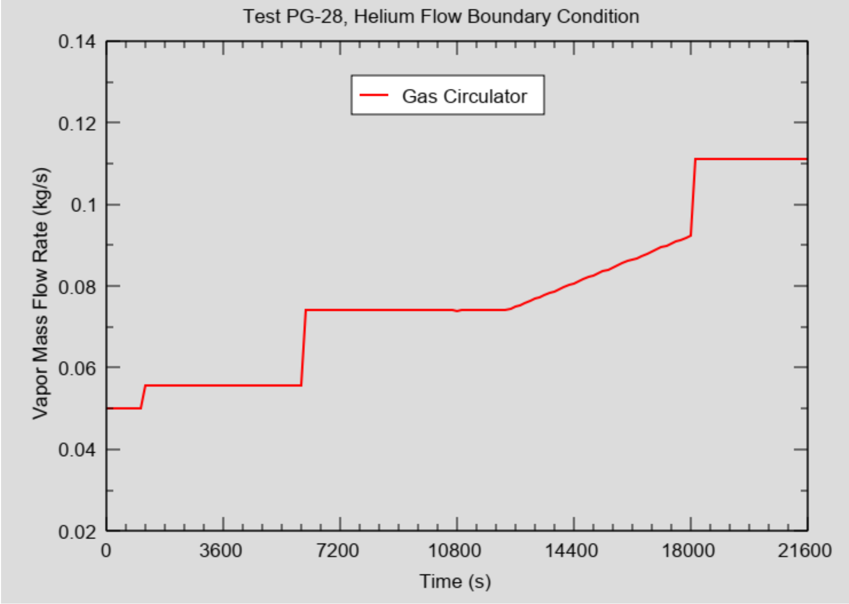
Transient boundary conditions:

- Total heater power: constant 24.5 kW
- He coolant flow rate: starts at 0.05, then increases in steps to 0.11 kg/s
- Initial conditions from steady-state simulation

Steady-state conditions:

- Constant values from time zero



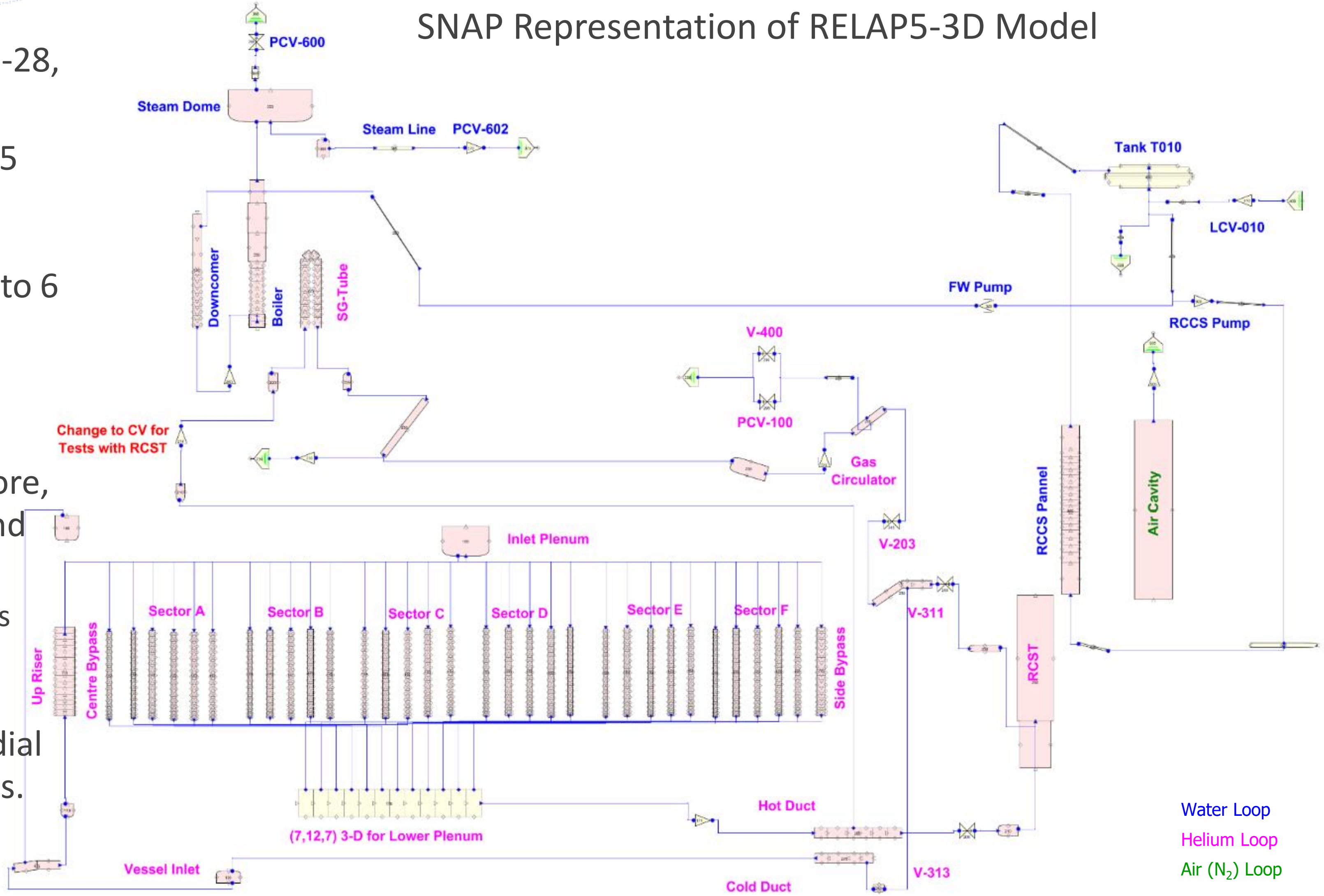


RELAP5-3D PG-28 Model

CNL developed a RELAP5-3D model of test PG-28, based on an INL RELAP5-3D pre-test model.

- Helium coolant channels were modelled as 5 concentric radial rings. Core blocks were modelled using 6 concentric rings. Channel groups and block structures were divided into 6 azimuthal sectors (asymmetric heating).
- Lower plenum was modelled using a 3-D cylindrical MULTID component.
- Heat Structures model conduction within core, core barrel, pressure vessel, coaxial duct, and steam generator.
  - Convective heat transfer coefficients applied as boundary conditions between solid and fluid component models
- Radiation/Conduction Enclosures model radial conduction between concentric core models.
  - Azimuthal conduction is neglected

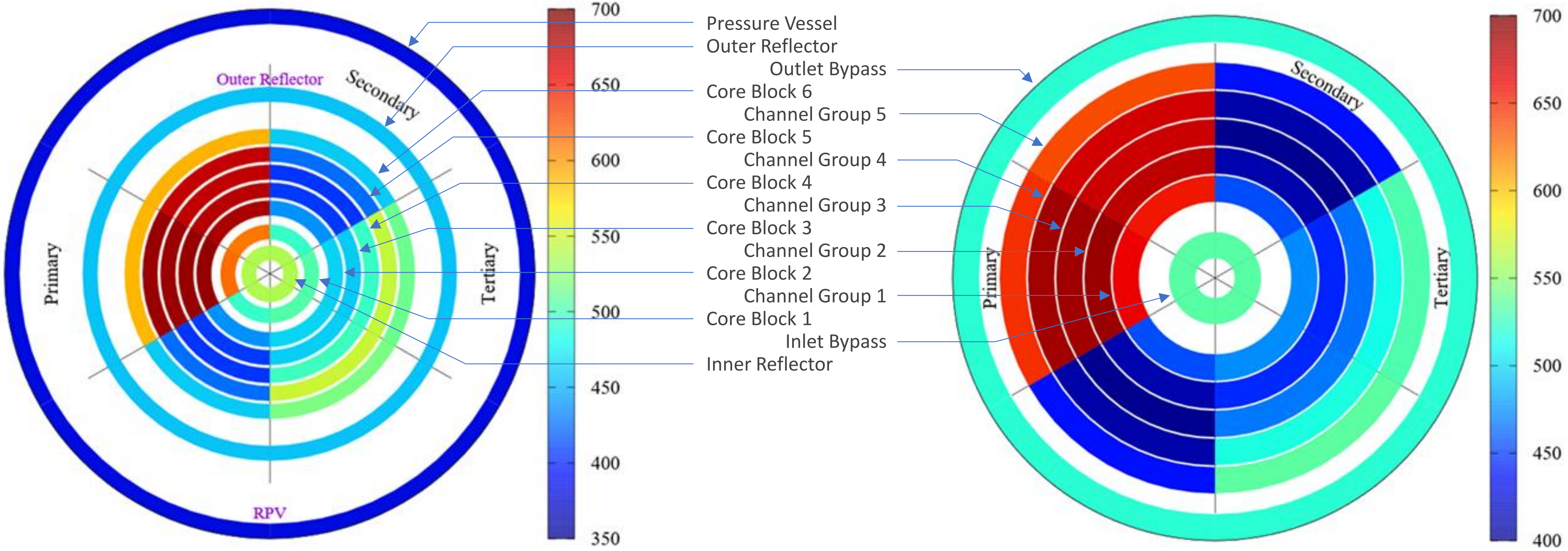
SNAP Representation of RELAP5-3D Model



PG-28 Six-sector Steady-State Results

Predicted solid temperatures (K) at core outlet

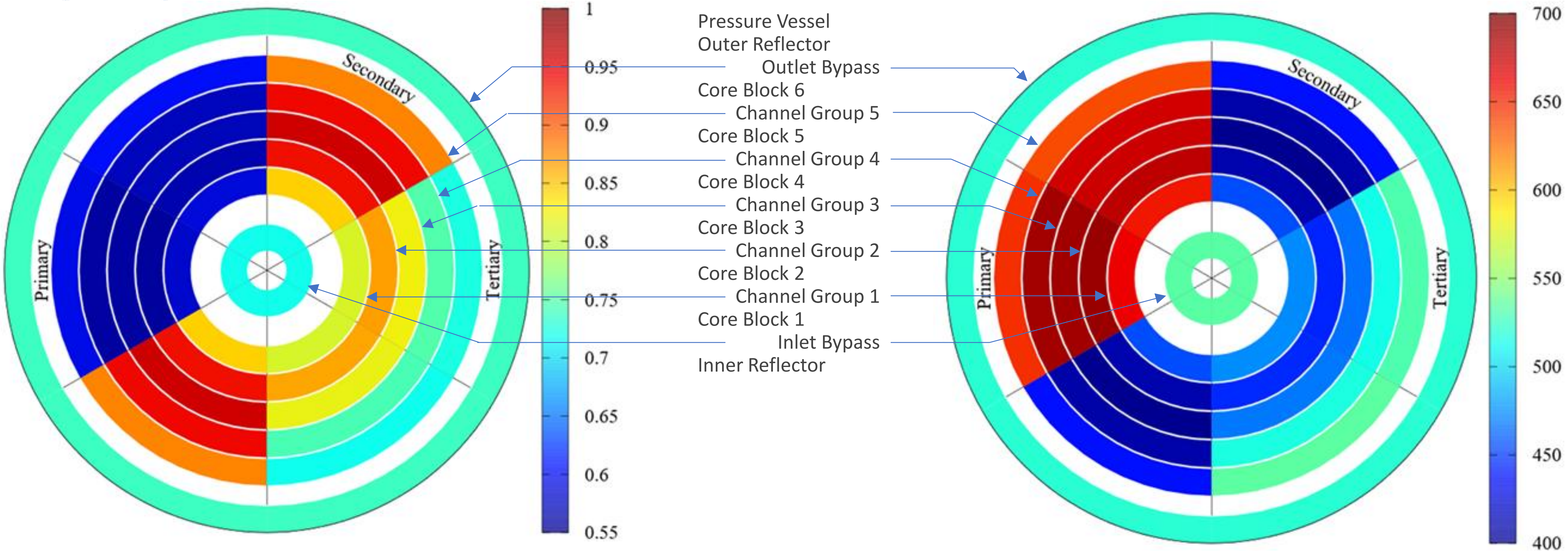
Predicted He temperatures (K) at core outlet



PG-28 Six-sector Steady-State Results

Predicted He velocities (m/s) at core outlet

Predicted He temperatures (K) at core outlet



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PG-28 Transient Results

In heated sectors, RELAP5-3D results in good agreement with measured core solid and He coolant temperatures:

- Simulation captures magnitude of temperature decreases (due to increases in He flow rate) well

In unheated sectors, RELAP5-3D underpredicts measured temperatures:

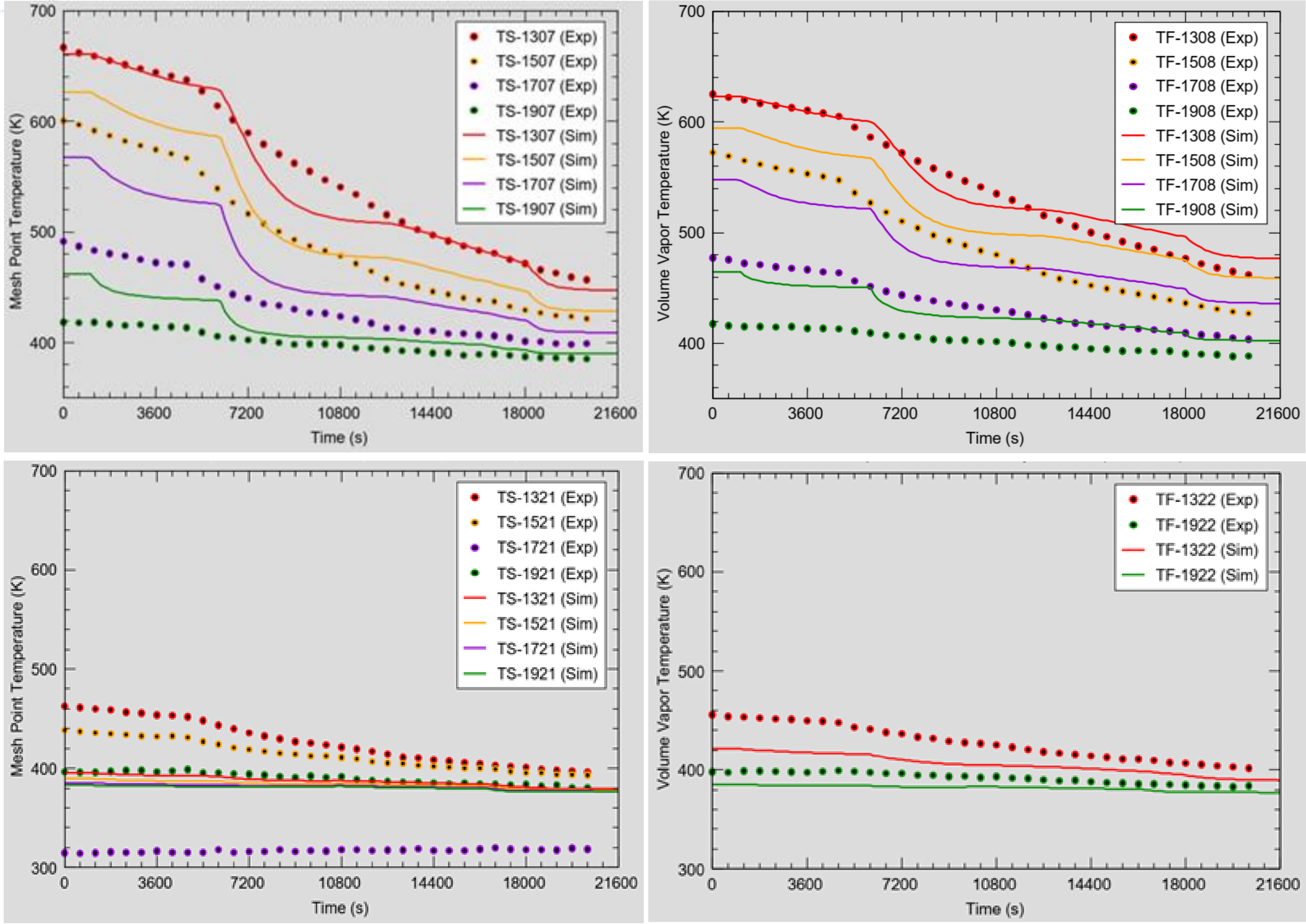
- Conduction between azimuthal sectors ignored

Solid Temperatures

Helium Temperatures

Heated Sector B

Unheated Sector D



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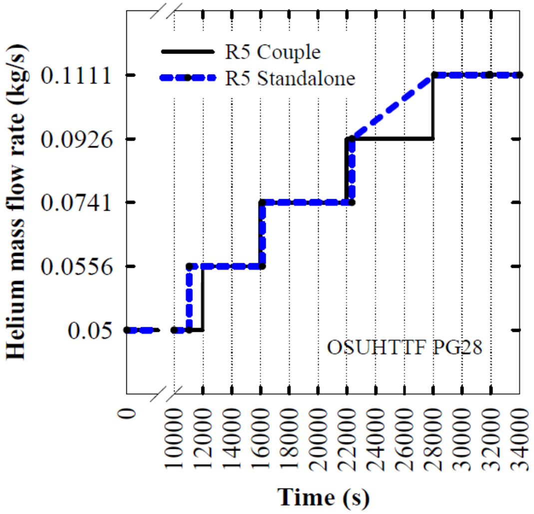
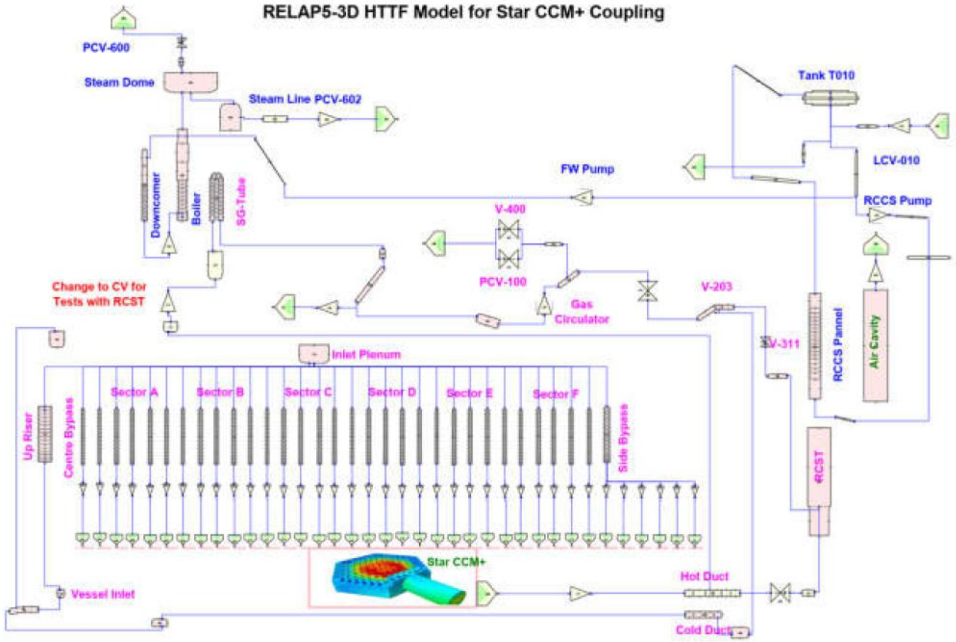
PG-28 Coupled TH-CFD Simulations

- STAR-CCM+ simulates 3-D details within the lower (outlet) plenum
  - mixing of coolant from core channels in plenum may result in heat streaking
- RELAP5-3D provides boundary conditions to the CFD code
- Data exchange between RELAP5-3D and STAR-CCM:
  - He coolant pressure, mass flow and temperature
  - at 234 core channel outlets (CFD model inlets)
  - occurs every 2000 s
  - He mass flow ramp slightly modified to align with data exchange
- Results presented in Nuc. Eng. Des. paper [3]





Summary

- CNL is developing modelling and simulation capabilities for small modular reactors, including HTGR (also MSR and BWR)
- For HTGR applications, code applicability has been assessed through code-to-code benchmarking and assessment against experiments from the OSU HTTF (also HTTR)
- CNL using system thermalhydraulics codes RELAP5-3D and ARIANT
  - RELAP5-3D and ARIANT predictions are similar
  - Agreement with measurement data is reasonable, given challenge of modelling 3D system (e.g., asymmetric heating) with 1D codes
- CNL is participating in the OECD-NEA HTGR T/H Benchmark based on HTTF data

Acknowledgements

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- HTTF test data was provided by OSU, and a RELAP5-3D pre-test model was provided by INL, through the Cooperative Action Plan between the Department of Energy of the United States, the Department of Natural Resources of Canada and Atomic Energy of Canada Limited on nuclear energy research and development.

References

1. A.S. Epiney et al., “Overview of HTTF Modeling and Benchmark Efforts for Code Validation for Gas-cooled Reactor Applications”, 4th International Conference on Generation IV and Small Reactors (G4SR-4), Toronto, Ontario, Canada, October 3-6, 2022.
2. X. Huang, T. Jafri, G. Waddington, “RELAP5-3D Simulation of Oregon State University High Temperature Test Facility Lower Plenum Mixing Test”, 4th International Conference on Generation IV and Small Reactors (G4SR-4), Toronto, Ontario, Canada, October 3-6, 2022.
3. K. Podila et al., “Coupled simulations for prismatic gas-cooled reactor”, Nucl. Eng. Des. 395 (2022) 111858. https://doi.org/10.1016/j.nucengdes.2022.111858.

Thank you

Questions?

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