UC Berkeley Nuclear Engineering
Thermal Hydraulics Laboratory

Verification and Validation of a Single-Phase Natural Circulation Loop Model in RELAP5-3D

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FHR
Fluoride Salt Cooled High Temperature Reactor

NEUP Nuclear Energy University Programs
U.S. Department of Energy

Research Objectives

- **Develop accurate models of the thermal-hydraulics behavior of the Pebble-Bed Fluoride-salt-cooled, High-temperature Reactor (PB-FHR)**
  - Identify characteristic phenomena in the system
  - Identify gaps in existing modeling tools to replicate these phenomena
  - Develop the missing validation basis for the thermal-hydraulics models
- **Use the developed models to enhance the design of the PB-FHR**

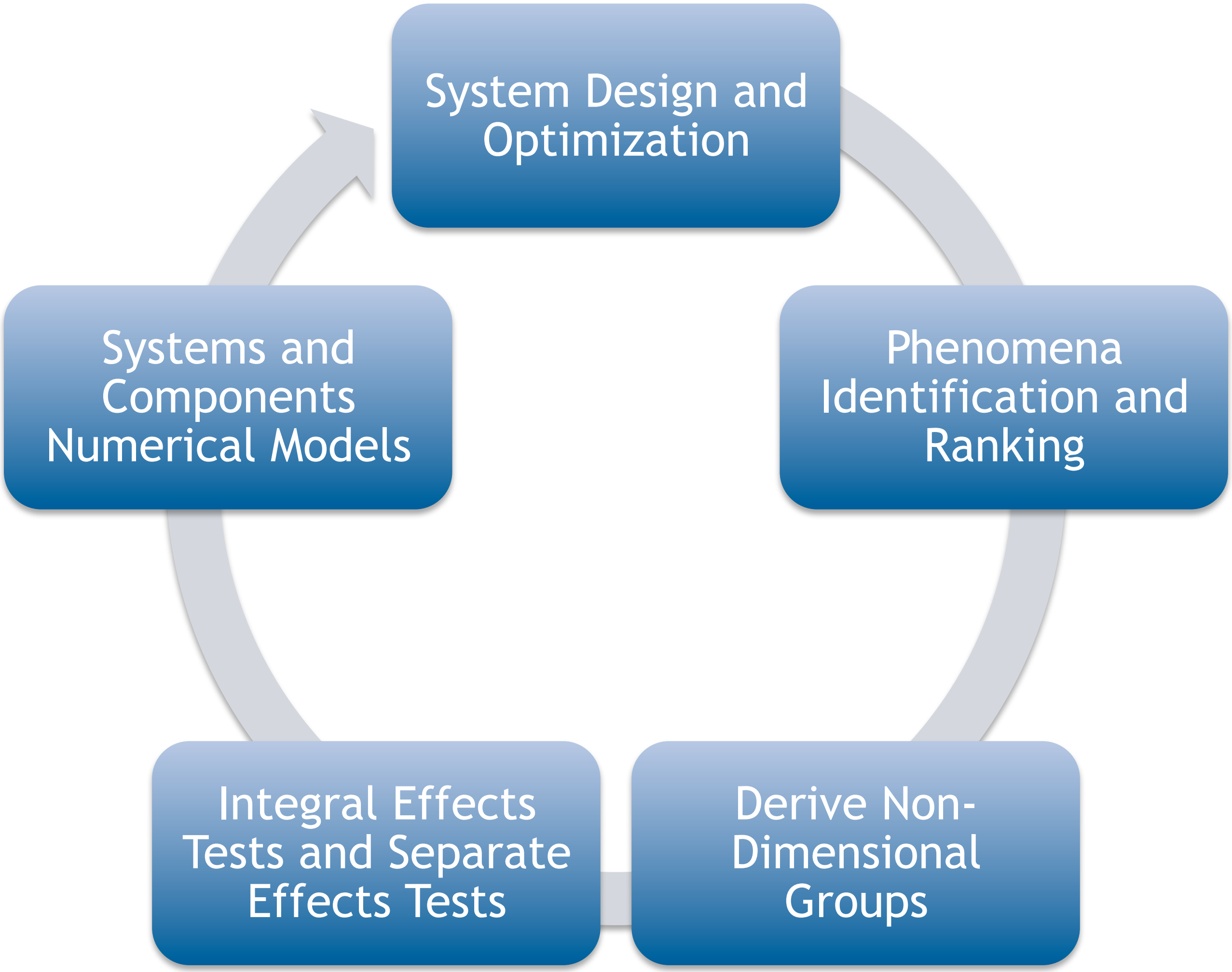
Presentation Outline

1. Introduction of Research Methodology, PB-FHR Concept and Applicability of RELAP5-3D
2. IETs for Natural Circulation Heat Transfer: the Compact Integral Effects Test (CIET) Test Bay
3. Solution and Code Verification for Natural Circulation
4. Code and Model Validation
5. Conclusions and Future Plans

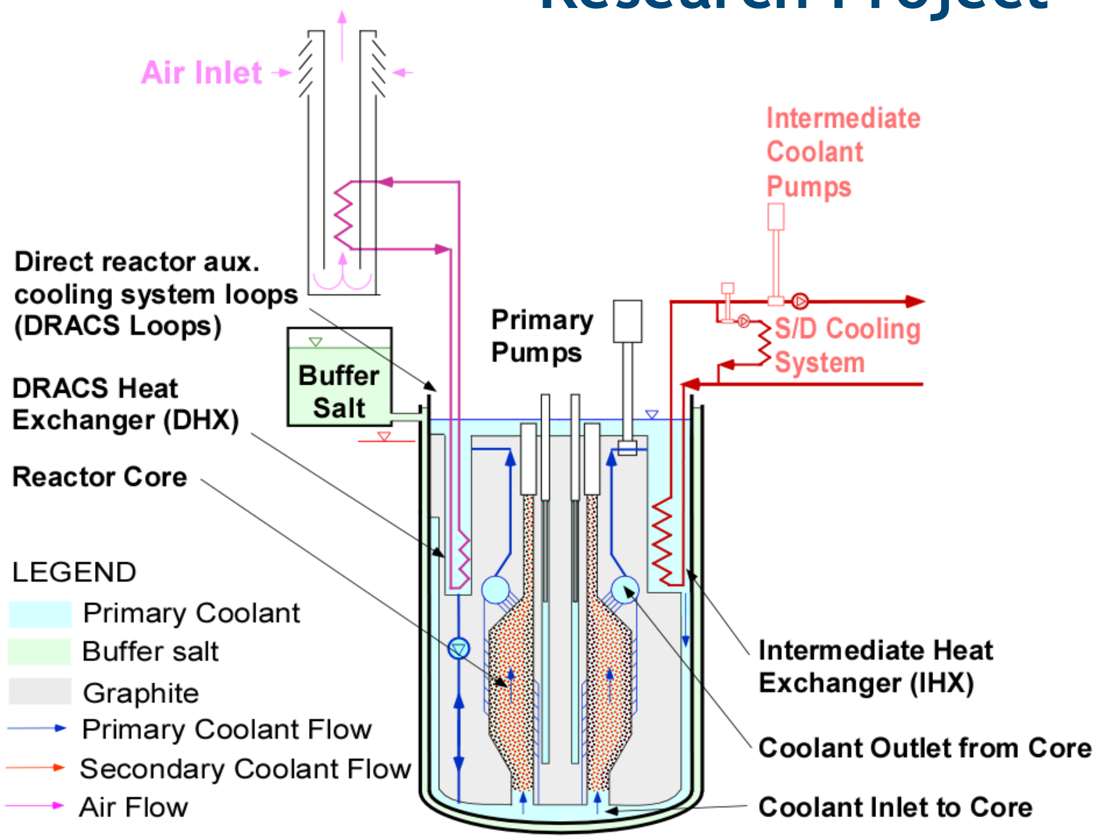
1. Introduction of Research Methodology, PB-FHR Concept and Applicability of RELAP5-3D

Research Methodology

- **Top-down and bottom-up approach:**



The PB-FHR: a DOE-Funded, 3-Year Long Integrated Research Project



- **Liquid salt coolant**
- **Passive safety mechanisms**
- **Mobile fuel (pebble compacts)**

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Applicability of RELAP5-3D

- **Modeling and validation gaps for the PB-FHR:**

Key PB-FHR phenomena	Existing LWR basis
Liquid salt (high Pr fluid) coolant	Water coolant
Natural circulation decay heat removal	Limited natural circulation decay heat removal
Pebble bed core (flow dynamics & heat transfer)	Fuel pin assemblies
Potential for coolant freezing	Potential for coolant boiling
Significant radiative heat transfer to structural materials at high temperature	-

- **IETs and SETs must be developed to characterize key phenomena, and serve as a validation basis for RELAP5-3D (or any other system code) thermal-hydraulics models**

2. IETs for Natural Circulation Heat Transfer: the Compact Integral Effects Test (CIET) Test Bay

Scaling Methodology: Natural Circulation

- Prandtl number dictates the selection of the simulant fluid and its average operating temperature for scaled experiments where heat transfer phenomena are important:

$$Pr = \frac{\nu}{\alpha} = \frac{\text{momentum diffusivity}}{\text{thermal diffusivity}}$$

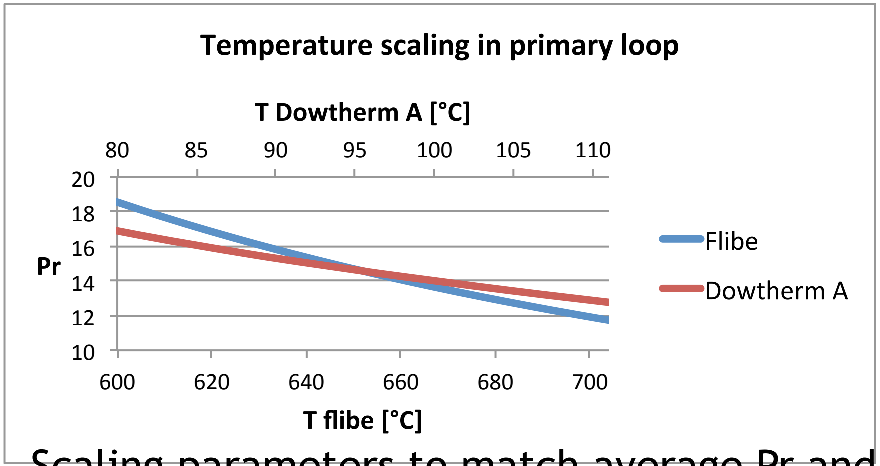
- For buoyancy-driven flow, the Grashof number must also be matched:

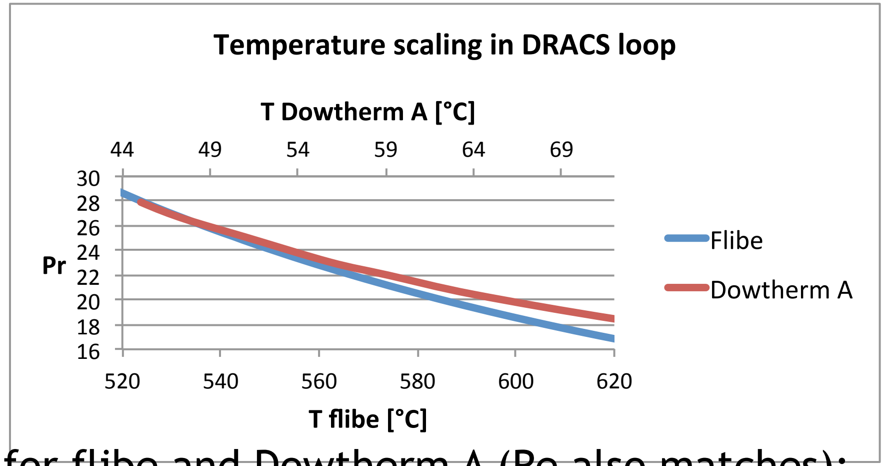
$$Gr = \frac{\beta \Delta T g L^3}{\nu^2} = \beta \Delta T \cdot \frac{g L^3}{\nu^2} = \frac{\text{buoyancy forces}}{\text{viscous forces}}$$

$$(\beta \Delta T)_m = (\beta \Delta T)_p \Leftrightarrow \frac{\beta_m}{\beta_p} = \frac{\Delta T_p}{\Delta T_m}$$

$$\left(\frac{g L^3}{\nu^2}\right)_m = \left(\frac{g L^3}{\nu^2}\right)_p \Leftrightarrow \left(\frac{L_m}{L_p}\right)^{3/2} = \frac{\nu_m}{\nu_p}$$

Applicability to the PB-FHR: Integral Effects Testing for PB-FHR Transients Using Dowtherm A Simulant Fluid

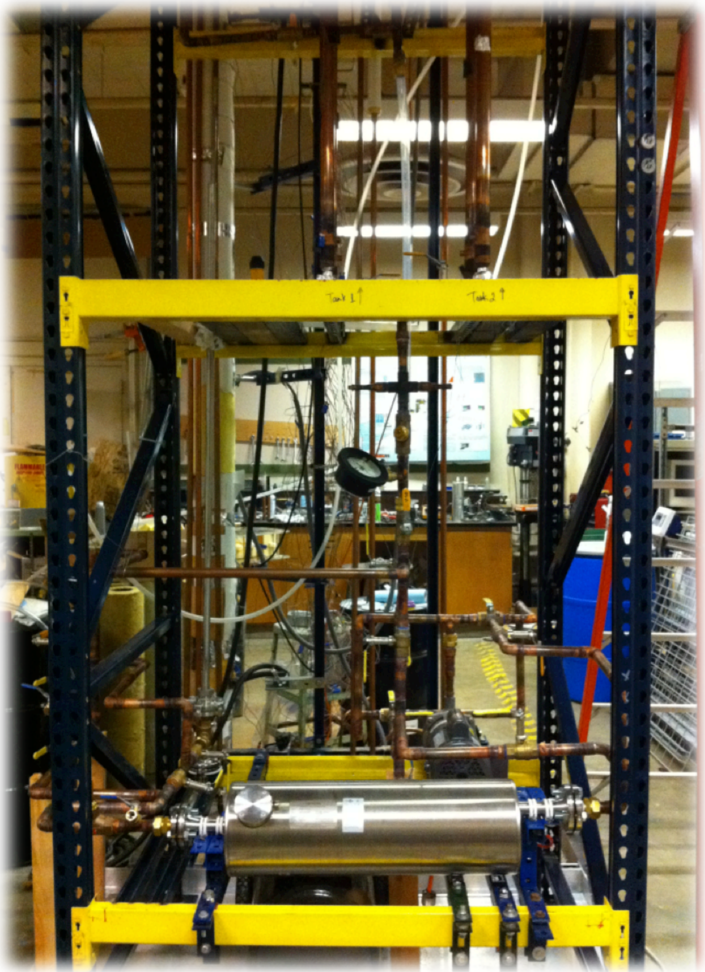




Scaling parameters to match average Pr and Gr for flibe and Dowtherm A (Re also matches):

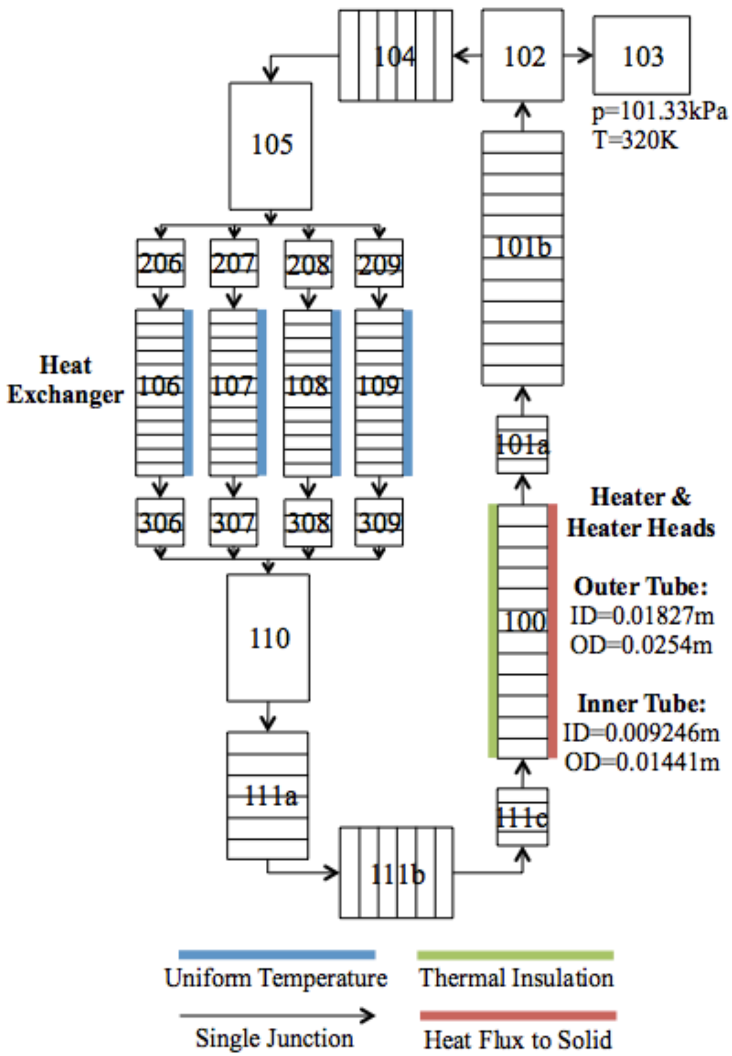
		DRACS, normal operation	DRACS, natural circulation	Primary loop
Flibe Temperature [˚C]		543	567	652
Dowtherm A Temperature [˚C]		**51**	**59**	**95**
Length scale	L_m/L_p	**0.49**	**0.48**	**0.45**
Velocity scale	U_m/U_p	0.70	0.69	0.67
ΔT scale	$\Delta T_m/\Delta T_p$	0.31	0.31	0.30
Transient time scale	τ_m/τ_p	0.70	0.69	0.67
Pumping power	$P_{p,m}/P_{p,p}$			**3.1%**
Heating power	$P_{q,m}/P_{q,p}$			**1.6%**

The CIET Test Bay
Single Phase Natural Circulation Loop Using Dowtherm A



- **Research objectives:**
  - Demonstrate natural circulation phenomenology (single loop) and decay heat removal capability
  - Use experimental data to validate numerical models
- **Experimental configuration:**
  - Square loop with vertical heater, heat exchanger and connected piping
  - Annular heater with needle valve to vary friction factor
  - Tube-in-tube water-cooled heat exchanger
  - Instrumentation: Coriolis flowmeter, type-T thermocouples and manometer lines

RELAP5-3D Model of the CIET Test Bay



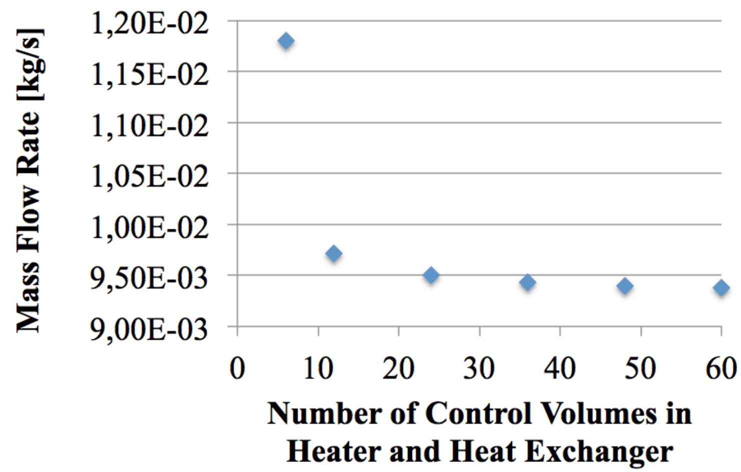
- Working fluid: Dowtherm A
- Boundary conditions:
  - Adiabatic on stainless steel inner tube of the annular heater
  - Uniform heat flux to solid on stainless steel outer tube of annular heater
  - Copper piping with 5-cm-thick fiberglass insulation on hot and cold legs
  - 10°C uniform temperature on outer wall of inner heat exchanger tube (25°C in RELAP)
  - 20°C ambient temperature around rest of loop
  - 101.33 kPa pressure at free surface of expansion tank
- More details on hydrodynamic component and heat structure parameters in paper

3. Solution and Code Verification for Natural Circulation

Solution Verification: Sensitivity of Natural Circulation Mass Flow Rate to a Range of Input Parameters

Model input parameter	Parameter range	Sensitivity of solution*
Expansion tank temperature [°C]	25 - 180	Not sensitive
Loop initial temperature [°C]	25 - 180	Not sensitive
Loop initial pressure [kPa]	100 - 200	Not sensitive
Loop initial mass flow rate [kg/s]	0.01 - 1	Not sensitive
Form losses	0 - 10	Not sensitive
Wall radial discretization [number of meshes]	2 - 20	Not sensitive
Hot leg and cold leg axial discretization [number of control volumes]	10 - 50	Not sensitive
Heater and heat exchanger axial discretization [number of control volumes]	**6 - 60**	**Sensitive**

**Not sensitive*: solution varies by less than 0.1% for any value of the parameter



- **Solutions converge for a number of control volumes above 30 for the heater and heat exchanger**
- **Conservative number of 60 control volumes for the heater and heat exchanger used for subsequent models**

Code Verification: Comparison of RELAP5-3D Solutions to Analytical Solutions

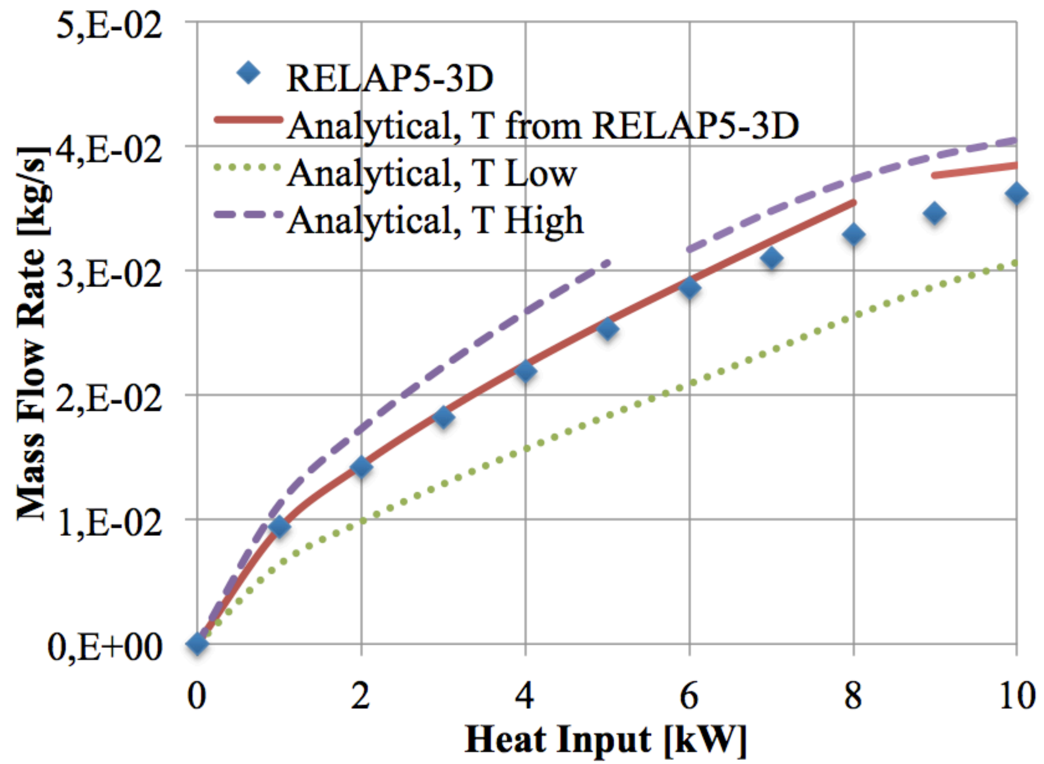
- **Analytical solution for natural circulation mass flow rate:**

$$\dot{m}^3 = \frac{2\rho_{av}{}^2 g\beta}{c_{p,av}} \cdot \frac{\Delta z_{NC} Q_h}{F'}$$

$$F' = \sum_{i=1}^{N} \left(\frac{1}{A_i{}^2} \cdot \frac{L_i}{D_i} \right) f_i$$

$$f = \frac{64}{Re} \text{ for } 0 < Re < 2000$$

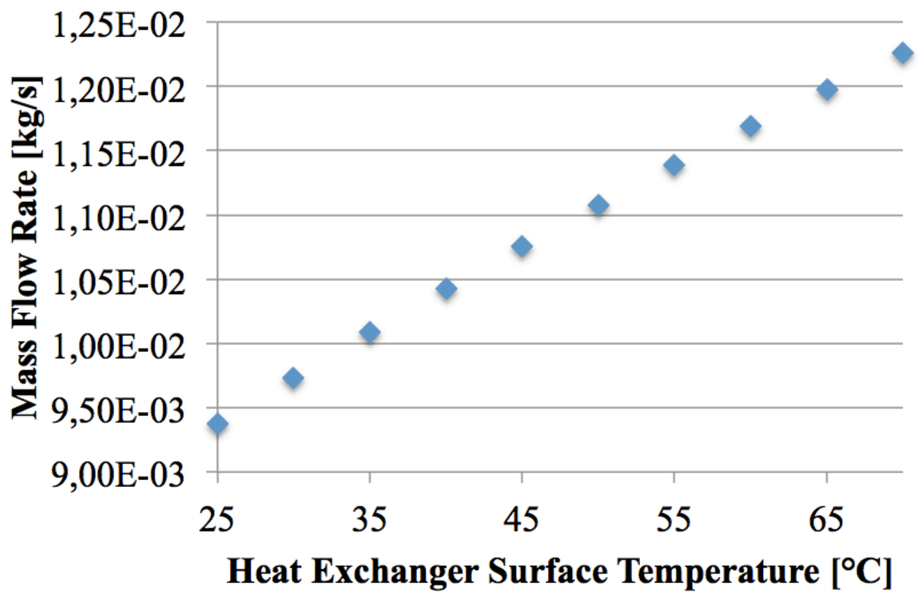
$$f = \frac{Re^{1/3}}{381} \text{ for } 2000 < Re < 4000$$



- **Potential explanations to discrepancy in high end of laminar flow region and transition region:**
  - Use of average fluid thermophysical properties for analytical solution
  - Use of different correlations for transition regime

Code Verification: Sensitivity to Heat Exchanger Wall Temperature

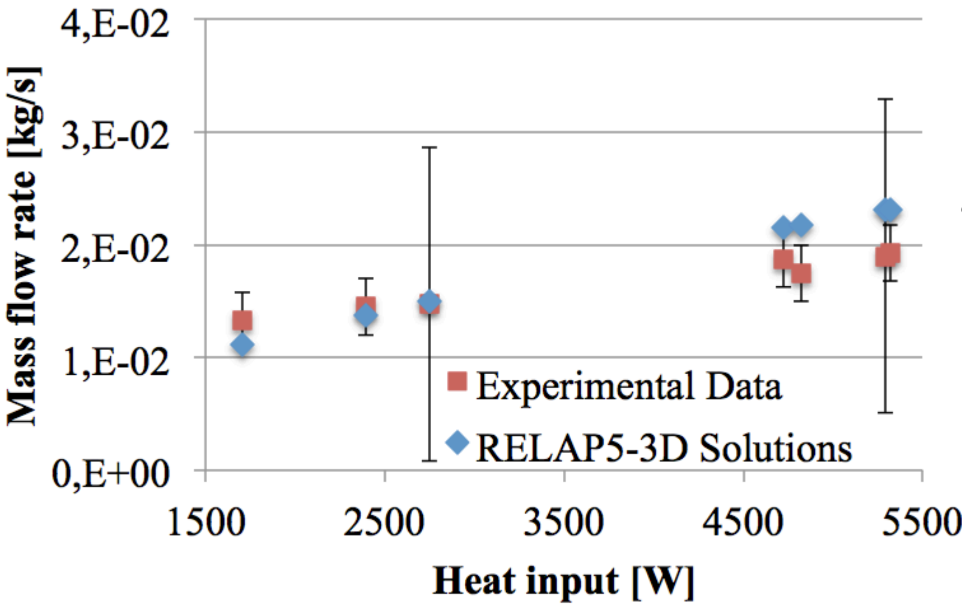
- Higher heat exchanger wall temperature leads to higher fluid average temperature
  - Leads to higher natural circulation mass flow rate
  - Important effect to take into account for future studies



- Conclusions of verification effort:
  - Agreement between RELAP5-3D results and analytical solutions is within 5% in the laminar regime and within 8% in the transition regime
  - RELAP5-3D solutions lie between the low and high values of analytical solutions
  - Model has been developed to a point where it is only sensitive to relevant physical parameters for our application

4. Code and Model Validation

Direct Comparison of RELAP5-3D Solutions to Experimental Data



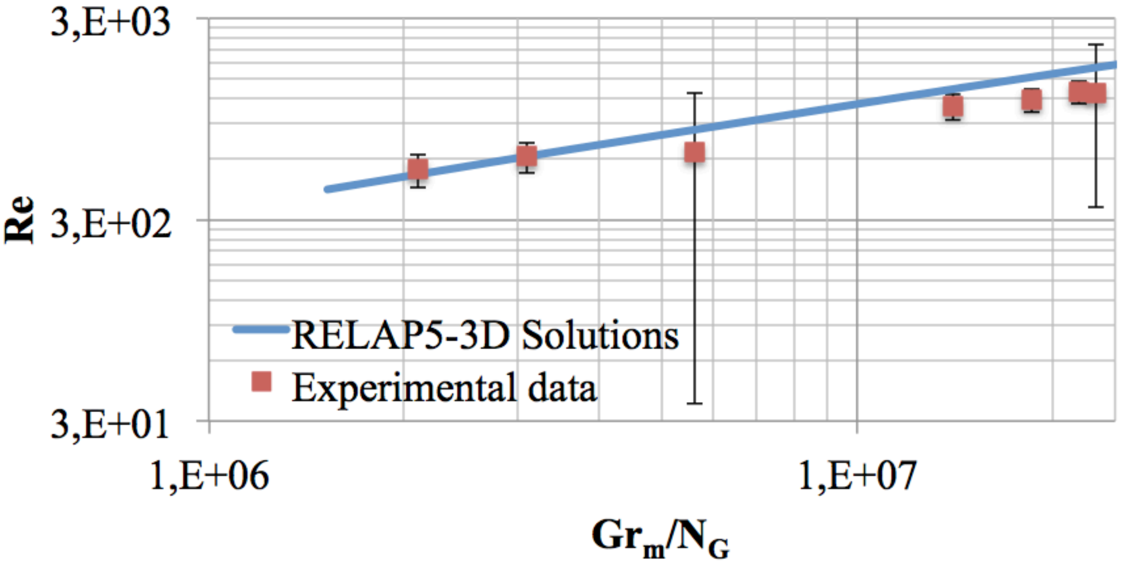
- **Low heat inputs:**
  - Agreement between RELAP5-3D results and experimental data within 10%
  - RELAP5-3D solutions inside uncertainty bands of the data
- **Higher heat inputs:**
  - Major trend of the data correctly predicted by RELAP5-3D
  - Agreement between RELAP5-3D results and experimental data within 20%
  - Calculation results outside but near uncertainty bands of the data
- **Observed overprediction of mass flow rate for a given heat input not conservative for this application**

Non-Dimensional Comparison of RELAP5-3D Solutions to Experimental Data

$$Re = C\left[\frac{(Gr_m)_{\Delta z_{NC}}}{N_G}\right]^r \qquad Re = \frac{D_r \dot{m}}{A_r \mu_{av}}$$

$$(Gr_m)_{\Delta z_{NC}} = \frac{{D_r}^3 {\rho_{av}}^2 \beta_{av} g Q_h \Delta z_{NC}}{A_r {\mu_{av}}^3 c_{p,av}}$$

$$N_G = \frac{L_t}{D_r}\sum_{i=1}^{N}\left(\frac{l_{eff}}{d^{1+b} a^{2-b}}\right)_i$$



- Same conclusions
- Literature suggests using an alternate friction coefficient in the transition regime, based on experimental data:

$$f = \frac{1.2063}{Re^{0.416}} \text{ for } 898 < Re < 3196$$

- This could be the main explanation to observed discrepancies between RELAP5-3D calculations and CIET Test Bay data, but no way to implement alternate laminar friction factor in RELAP5-3D

5. Conclusions and Future Plans

Conclusions and Future Plans

- **Conclusions:**
  - First step towards predicting performance of passive decay heat removal system of FHRs
  - Excellent agreement with analytical solutions and experimental data in laminar regime
  - Reasonable agreement with analytical solutions and experimental data in transition regime
  - Overprediction of natural circulation mass flow rates in transition regime, probably due to a discrepancy between friction factor correlations as implemented in the code and what they actually are in the experimental loop

- **Future work:**
  - Collect additional data with better accuracy
  - Use current data as calibration data for future models
  - Find way to implement alternate friction factor correlations in laminar and transition regime
  - Code-to-code comparisons with other system codes (Flownex)

Questions? Suggestions?