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# Computational Modeling & Verification of MSR Transients via MSRE Reactivity Insertion Tests

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# Introduction

- MSRs are among the selected concepts for Gen IV reactors.
- They have unique features arising from adopting circulating fuel.
- New computational tools are needed for the analysis of MSRs.
- Evaluated experimental data is needed for verification and validation (V&V).

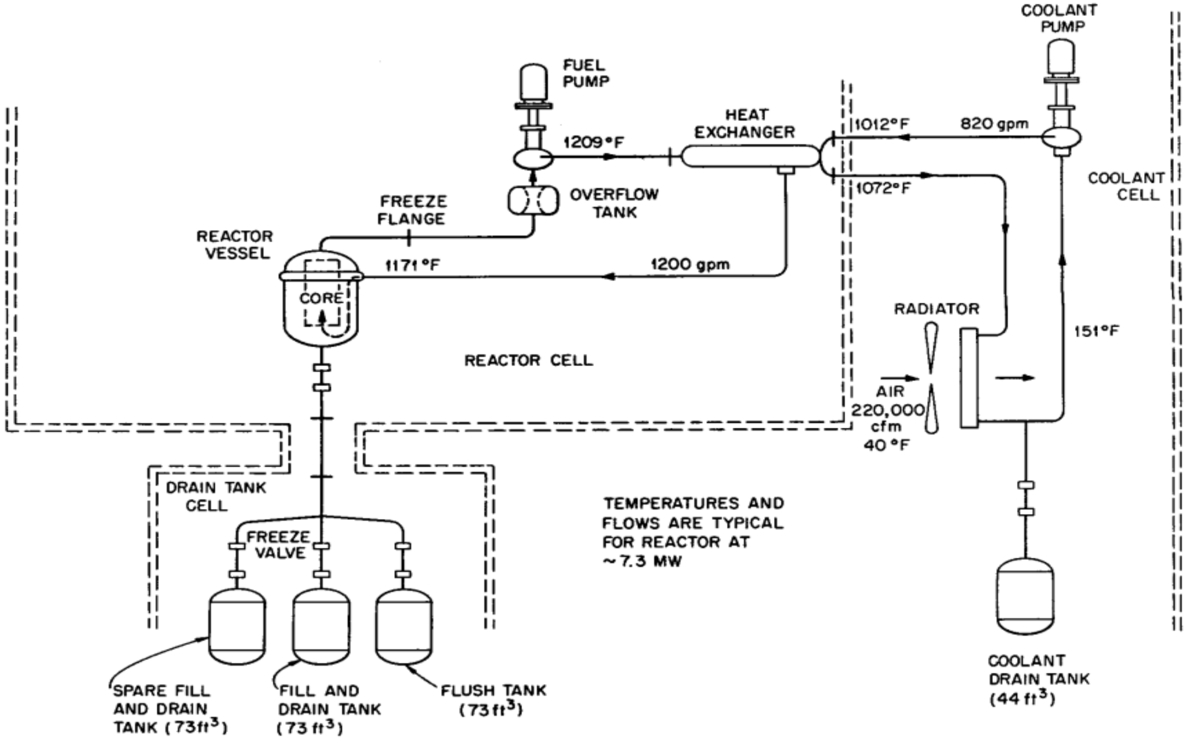
## ➢ Objectives of current work

- Developing a Multiphysics computational toolset for MSR analysis.
- Evaluating transient tests from the historical MSRE.
- Preparing a benchmark for the IRPhE handbook.

# Molten Salt Reactor Experiment (MSRE)

- Performed at ORNL (1965-1969 ).
- The objective was to verify the safety, and practicality of molten-fluoride, circulating-fuel reactor system.

| | |
|---|---|
| **Design thermal power** | 10 MW |
| **Maximum operation power** | 7.4 MW |
| **Fissile material** | $^{235}$U then $^{233}$U |
| **Coolant and fuel solvent** | FLiBe |
| **Moderator** | Graphite |
| **Design fuel temperature** | 1175-1225 $^{o}$F (635-663 $^{o}$C) |
| **Design flow rate** | 1200 gpm (0.0757 m$^3$/s) |
| **Fuel circulation time** | ~25 sec |



# Mathematical Model for MSR Analysis

- Three physics components are considered in the model:
  - Neutronics
  - Transport of diluted species (i.e., precursors)
  - Thermal hydraulics (T/H)
- A multiphysics model is developed and implemented in COMSOL Multiphysics.
- Fully coupled numerical scheme is employed in the calculations

# Neutronics Model

- The multigroup (MG) neutron diffusion equation is used to obtain the power shape and to calculate the effective delayed neutron fractions.

$$-\nabla D_g \nabla \varphi_g + \Sigma_{rg}\varphi_g = \chi_{p,g}\frac{(1-\beta)}{k}\sum_g \nu\Sigma_{fg}\varphi_g + \sum_{g'\neq g}\Sigma_{g'\to g}\varphi_{g'} + \chi_{d,g}\sum_{k=1}^{6}\lambda_k C_k$$

- A PKE customized for circulating fuel is used for the power magnitude.

$$\frac{dn}{dt} = \frac{\rho(t)-\beta_M}{\Lambda}n(t) + \frac{1}{\Lambda}\sum_{k=1}^{6}\beta_{M,k}\frac{\tilde{C}_k(t)}{\tilde{C}_{k0}}$$

$$\beta_{M,k} = \frac{\lambda_k \int c_k^{ss}\,dV}{(1-\beta)\int\sum_g \Sigma_{f,g}\varphi_g^{ss}\,dV + \int\sum_k \lambda_k c_k^{ss}\,dV}$$

$$\rho(t) = \rho_{ext}(t) + \alpha_f\left(\tilde{T}_f - \tilde{T}_{f0}\right) + \alpha_m\left(\tilde{T}_m - \tilde{T}_{m0}\right)$$

# Transport of Diluted Species

- Transport of delayed neutron precursors (DNP).

$$A\frac{\partial c_k}{\partial t}+Au\frac{\partial c_k}{\partial z}=\frac{\partial}{\partial z}\left(AD_k\frac{\partial c_k}{\partial z}\right)+A\beta_i\sum_g \nu\Sigma_{fg}\varphi_g-A\lambda_k c_k,\qquad k=1,\cdots,6.$$

- Transport of decay heat precursors (DHP).

$$A\frac{\partial h}{\partial t}+Au\frac{\partial h}{\partial z}=\frac{\partial}{\partial z}\left(AD_h\frac{\partial h}{\partial z}\right)+A\left(1-E_m\right)e_d\varepsilon_f\sum_g \Sigma_{fg}\varphi_g-A\lambda_h h$$

- The DHP in MSRE can be modeled using one group with a generation fraction of 0.53% and decay constant of 0.066 [1/s].

# T/H Model

- Incompressible flow in pipes.

$$A\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial z}(A\rho u)=0,$$

$$\rho\frac{\partial u}{\partial t}+\rho u\cdot\frac{\partial u}{\partial z}=-\frac{\partial p}{\partial z}-f_D\frac{\rho}{2d_h}u|u|+F,$$

- Heat transfer in fluids.

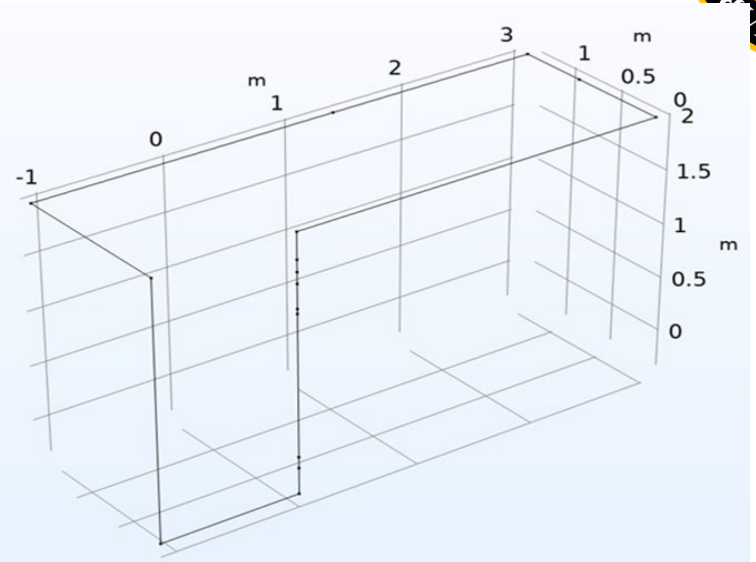
$$\rho_f c_p^f A\left(\frac{\partial T_f}{\partial t}+u\frac{\partial T_f}{\partial z}\right)=(1-E_{\mathrm{m}})(1-e_d)A\varepsilon_f\sum_g\Sigma_{f,g}\varphi_g+P_w h(T_m-T)+A\lambda_h h+A\frac{\partial}{\partial z}\left(k_f\frac{\partial T_f}{\partial z}\right)$$

- Heat transfer in solids.

$$\rho_m c_p^m\frac{\partial T_m}{\partial t}=E_{\mathrm{m}}A\varepsilon_f\sum_g\Sigma_{f,g}\varphi_g-P_w h(T_m-T)+\frac{\partial}{\partial z}\left(k_m\frac{\partial T_m}{\partial z}\right)$$

# Boundary Conditions & Others

- **BCs:**
  - Albedo BC for neutronics
  - The two ends of the moderator matrix are treated as insulated boundaries.
  - The flow is sustained using a point B.C. with a predefined flow rate.
- Active regions: Lower plenum, Core, and Upper plenum.
- The heat transfer coefficient in the core is modeled using The Dittus–Boelter equation.
- Ultimate heat sink is molded using fixed air temperature in the radiator.




Primary loop geometry in COMSOL model

$$\mathrm{Pr} = \frac{c_p \mu_f}{k_f}, \; Nu = \frac{hL}{k_f}$$

$$Nu = 0.023\, \mathrm{Re}^{0.8}\, \mathrm{Pr}^{0.3}$$

K. O. Lee, et. al., "Heat and mass Transfer Coefficients in the Molten Salt Reactor Experiment," The ANS Winter Meeting, Washington D.C., November 12–15 (2023).

# Model Verification and Validation (V&V)

## Reactivity Insertion Tests

- Set of three tests conducted at power operation.
- The fuel is 91% enriched $^{233}U$.
- At each power level, a predefined reactivity is inserted to initiate the transient.
- No operation action was carried out after initiating the transient.
- Large noise existed in the measured response due to large salt void percentage.
- Power change was calculated from the flux signal.

| Power $[MW]$ | External reactivity $\rho_{ext}$ $[pcm]$ |
|---|---|
| 1 | 24.8 |
| 5 | 19 |
| 8 | 13.9 |

ORNL-DWG 70-2921

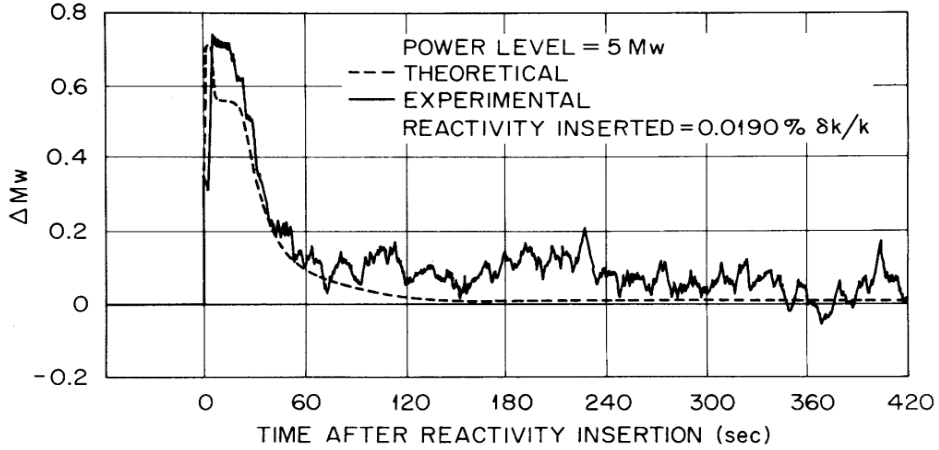


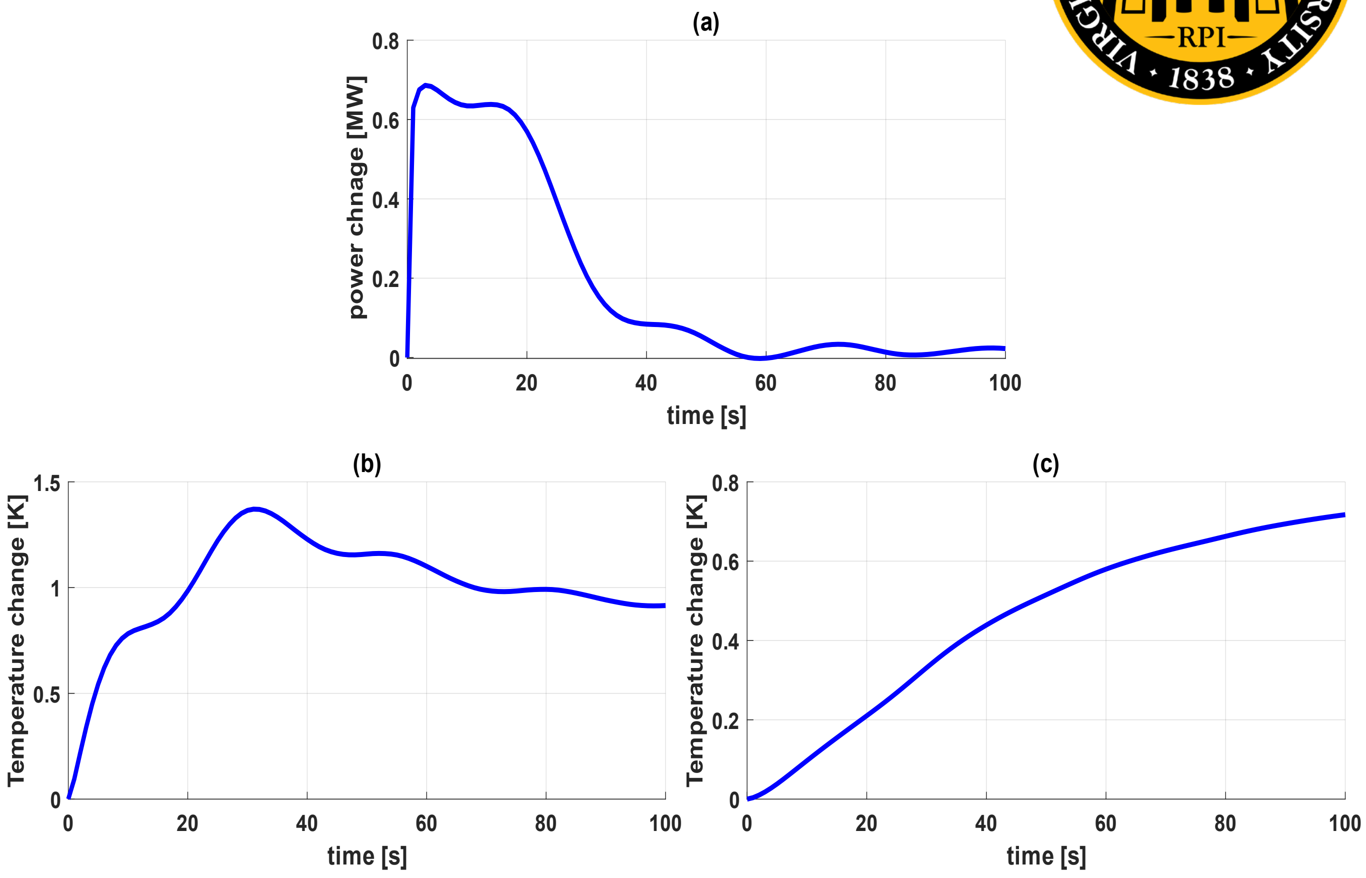

Fig. 3. Response of the Neutron Flux to a Step Change in Reactivity of 0.0190% δk/k with the Reactor Initially at 5 MW.

R.C. Steffy Jr., "Experimental Dynamic Analysis of the MSRE with U-233 Fuel," ORNL-TM-2997, Oak Ridge National Laboratory, April 1970.

# Modeling Results & Discussion

# 8 MW Test Modeling Results

- After prompt rise, the hot lump of salt leaves the core casing the fuel temperature to plateau.
- After 25 s, the hot lump reenters the core causing the temperature to peak and the power to drop sharply.
- The effect of the circulation of this hot lump vanishes gradually.
- The graphite temperature rises gradually until steady state.



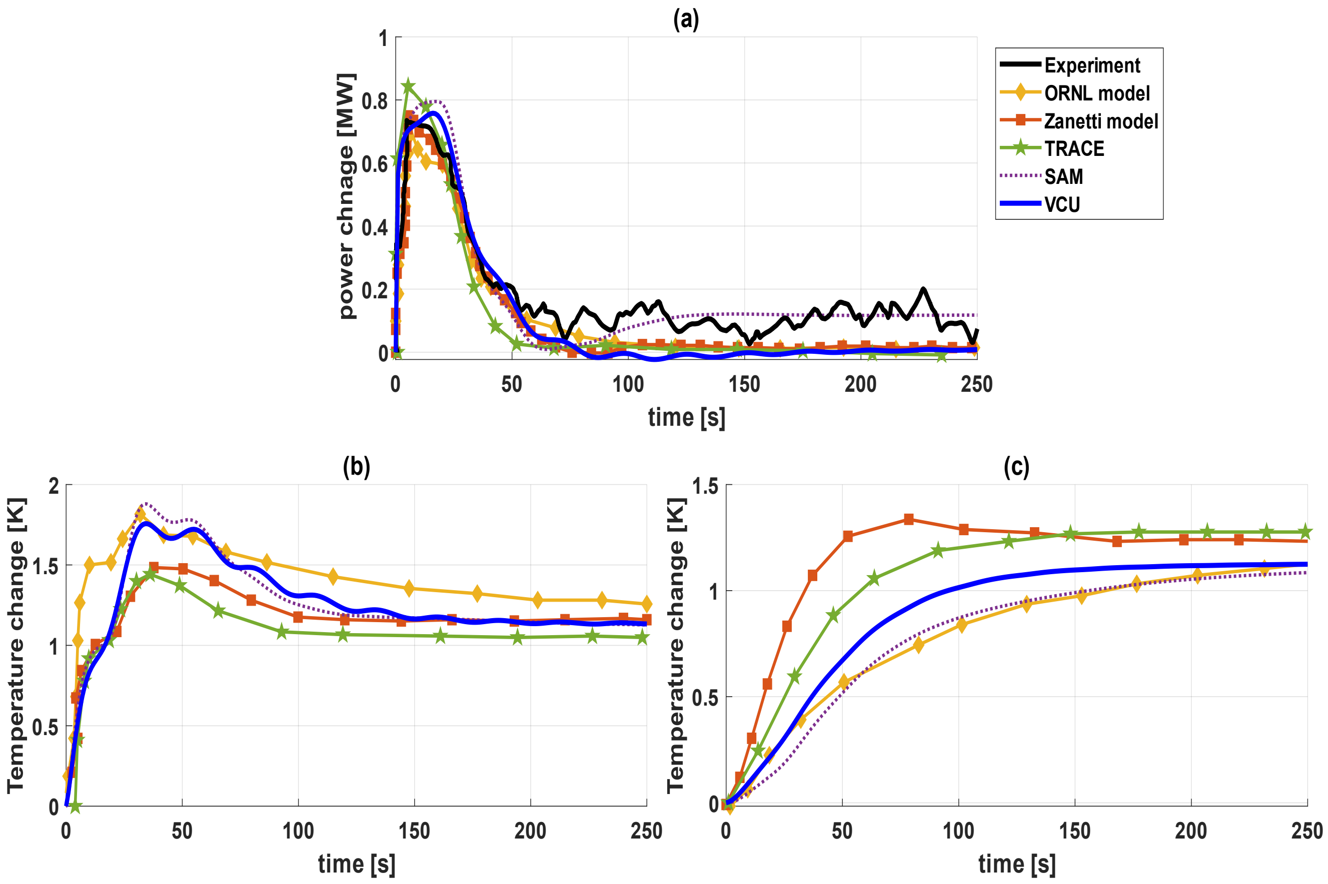

change in (a) Power, (b) fuel temperature, (c) moderator temperature.

# Various Verification Models from Others

- Four different set of results from literature are used for code verification, and compared to our results
  - ORNL model multi-region lumped representation of the MSRE with both primary and secondary loops modeled.
  - Zanitte model used a Multiscale representation of the MSRE, where the core is divided into three radial regions each with a 3D model. The remaining components are modeled as 0D. The temperature and DNPs in the PKE are importance-weighted.
  - TRACE model uses a 1D representation and a customized PKE. The downcomer is considered an active area.
  - SAM model is limited to the primary loop, the secondary loop is modeled using a fixed temperature.

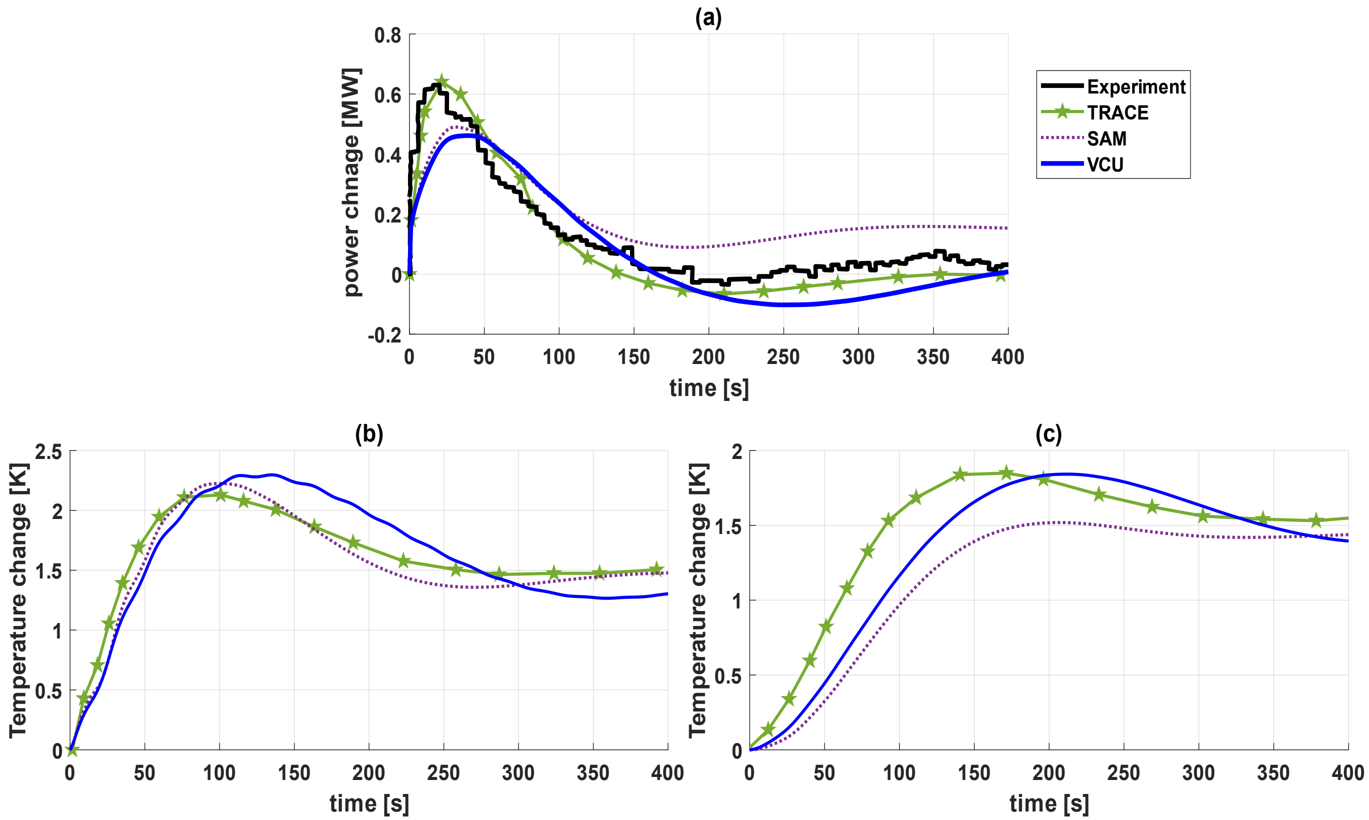
# 5 MW Test Results

- The prompt salt temperature rise is similar for all models except ORNL model.
- The rate of graphite temperature rise in Zanetti and TRACE models is higher than other models.
- Relative error in the power peak for current work 0.8%



# 1 MW Test Results

- The deviation between SAM results and the current model can be attributed to the adoption of different BCs for the heat equation.
- Relative error in the power peak for current work 10.4%



# Conclusions & Future Work

- A Multiphysics model for MSRs is developed based the PKE and flow in pipes.
- The MSRE reactivity insertion tests are used for V&V.
- The model achieved good agreement with experimental data and other models.

➢ <u>Future work</u>

- Sensitivity and Uncertainty Analysis (SA/UQ)
- Natural Circulation Test.

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# Thank you!

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