ANS Annual Conference 24

Uncertainty Analysis on the Pump Flow Transient Phenomena in the Molten Salt Reactor Experiment

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Introduction

- Molten Salt Reactors (MSR) are among selected concepts for Gen-IV reactors.
- MSR have unique features arising from adopting circulating fuel.
- Evaluated experimental data is needed for verification and validation (V&V).

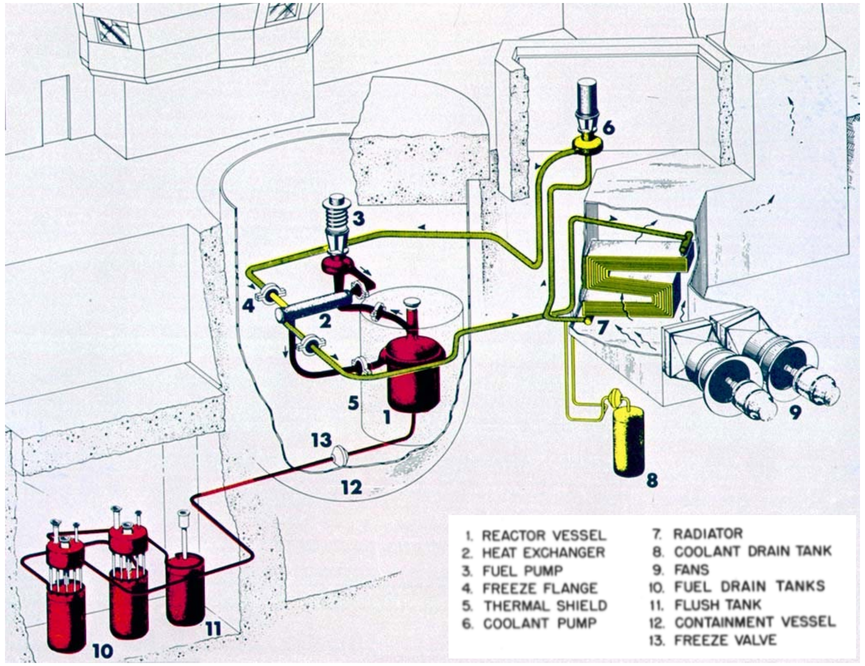
➢ Objectives of this work

- Evaluate the uncertainty in the experimental measurements for the Molten Salt Reactor Experiment (MSRE) pump transient test.
- Modeling the MSRE pump transient using a 1D coupled N/TH model.
- Evaluating the uncertainty in the model predictions due to uncertainty in model input parameters.

Molten Salt Reactor Experiment (MSRE)

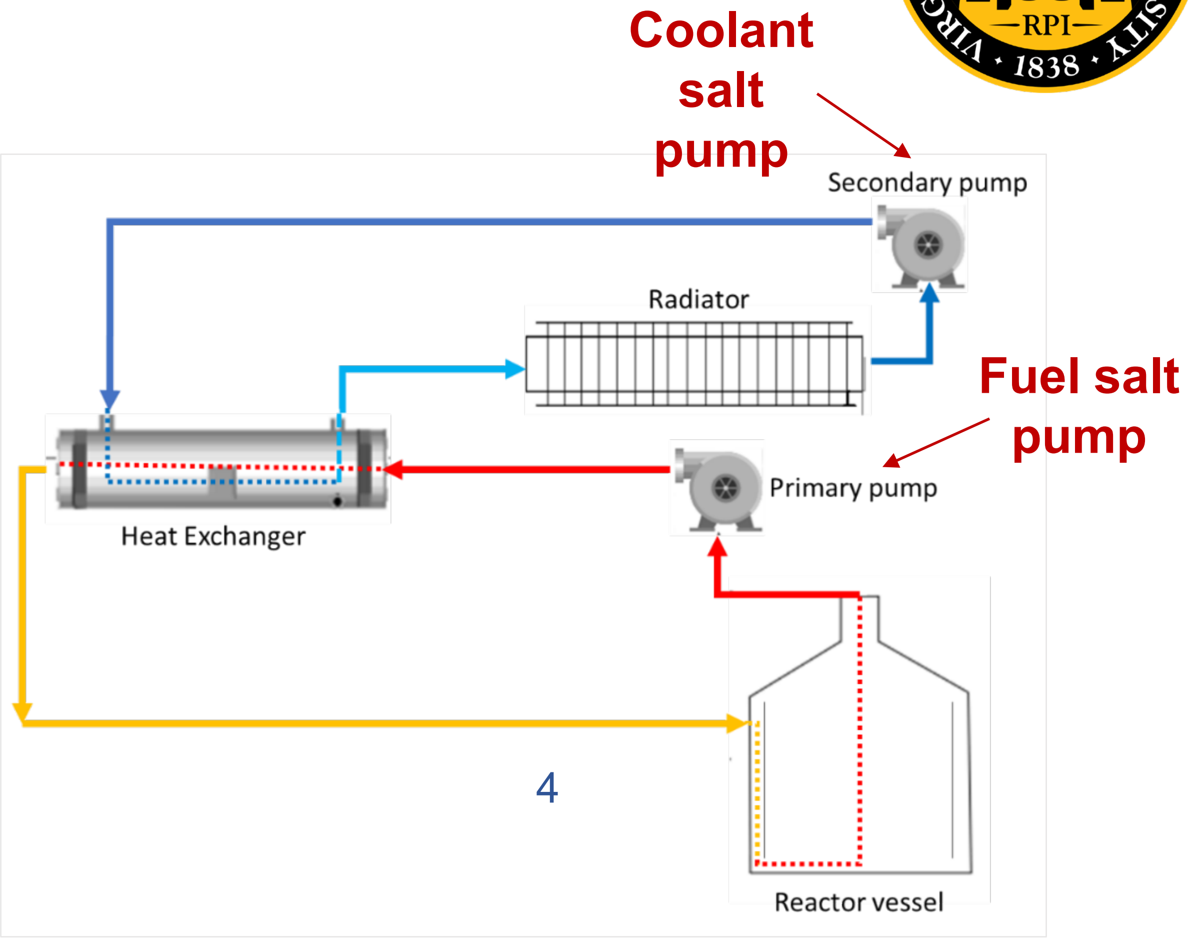
- Performed at ORNL in 1960s – 1970s
  - June 1965 - March 1968, ^{235}U fueled core;
  - August 1968 - January 1970, ^{233}U fueled core.
- The objective of MSRE was to verify the safety and practicality of molten-fluoride, circulating-fuel reactor system.

Design thermal power	10 MW
Maximum operation power	7.4 MW
Fissile material	^{235}U then ^{233}U
Coolant and fuel solvent	FLiBe (2LiF-BeF_2)
Moderator	Graphite
Design fuel temperature	1175-1225 °F (635-663 °C)
Design flow rate	1200 gpm (0.0757 m^3/s)
Fuel circulation time	~25 sec



MSRE Pump Transient Tests

- **Conducted at zero power (no significant thermal feedback)**
- **The aims are to:**
  - Examine **the fuel pump and coolant pump startup and coastdown characteristics;**
  - **Infer fuel salt flow rate characteristics during the** pump startup and **coastdown;**
  - **Determine transient effects of fuel flow rate changes on reactivity.**
- **The transient procedure:**
  - **When the pump speed was changed, a flux servo controller is actuated to keep the power constant;**
  - **The reactivity response is estimated from the control rod position;**
  - **Reactivity response is** entirely **due to fluctuations in delayed neutron precursors (DNPs) concentration.**



Schematics of the MSRE salt circulation loops.

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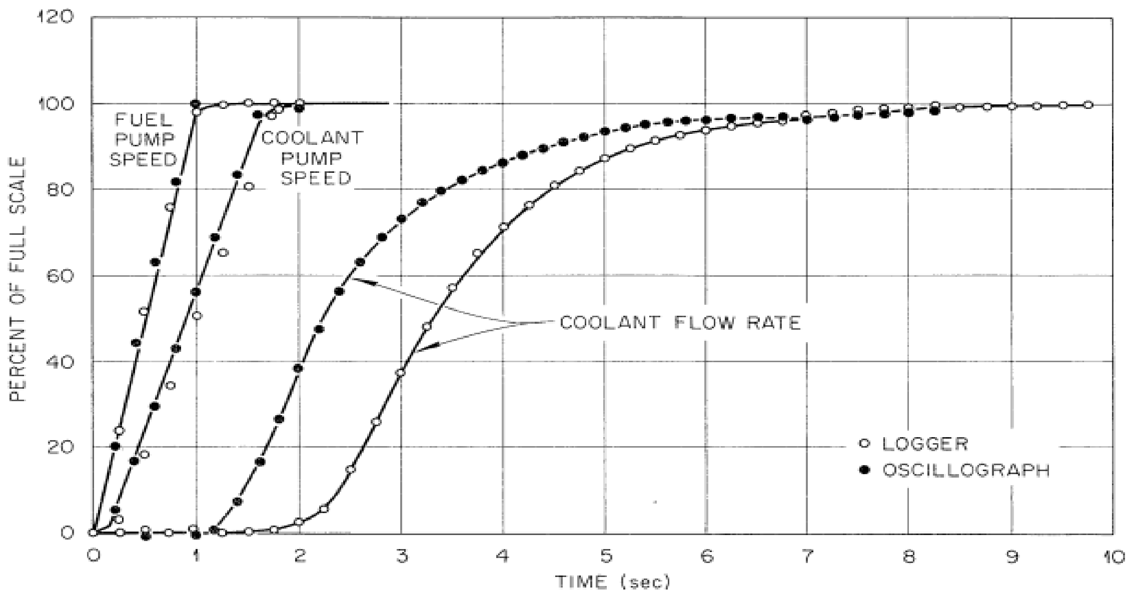
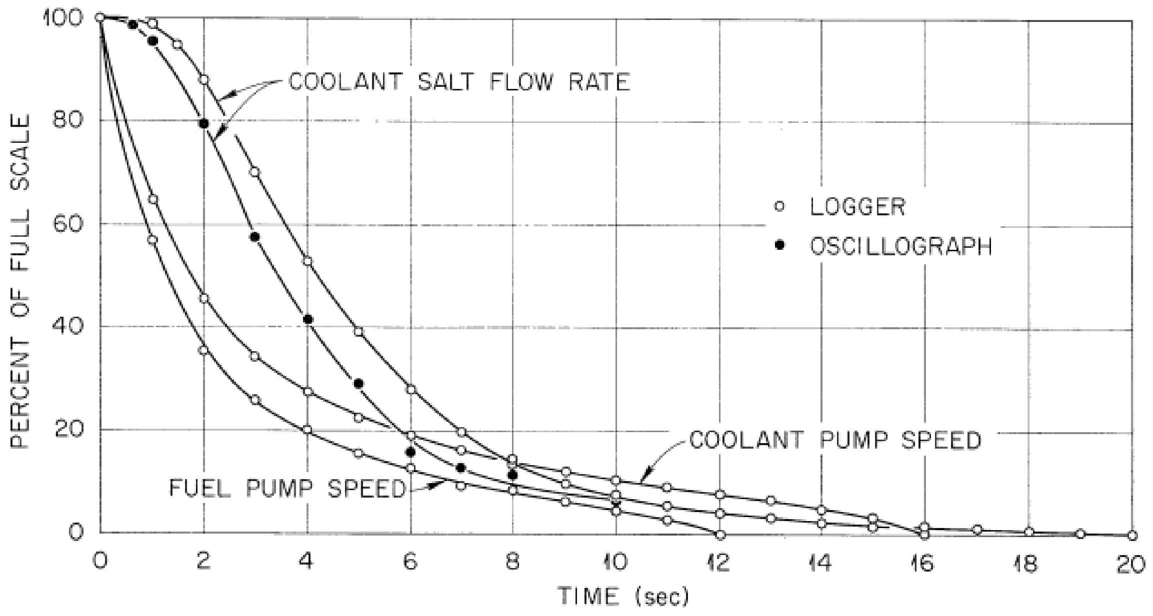
Pump Transient Test Data (1/2)

- **Pump startup test**



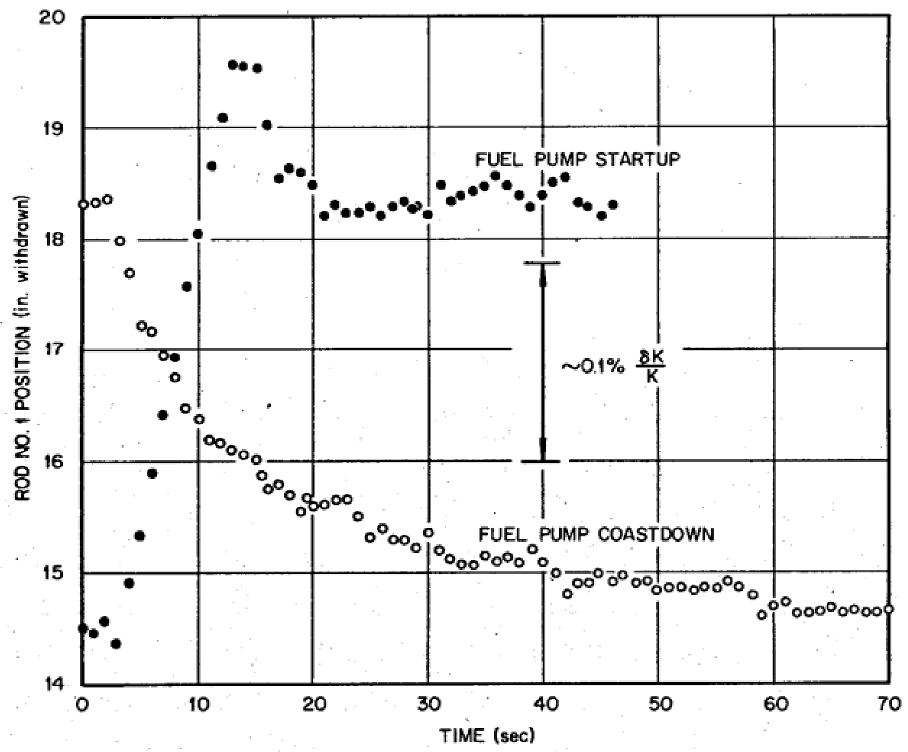
- **Pump coastdown test**



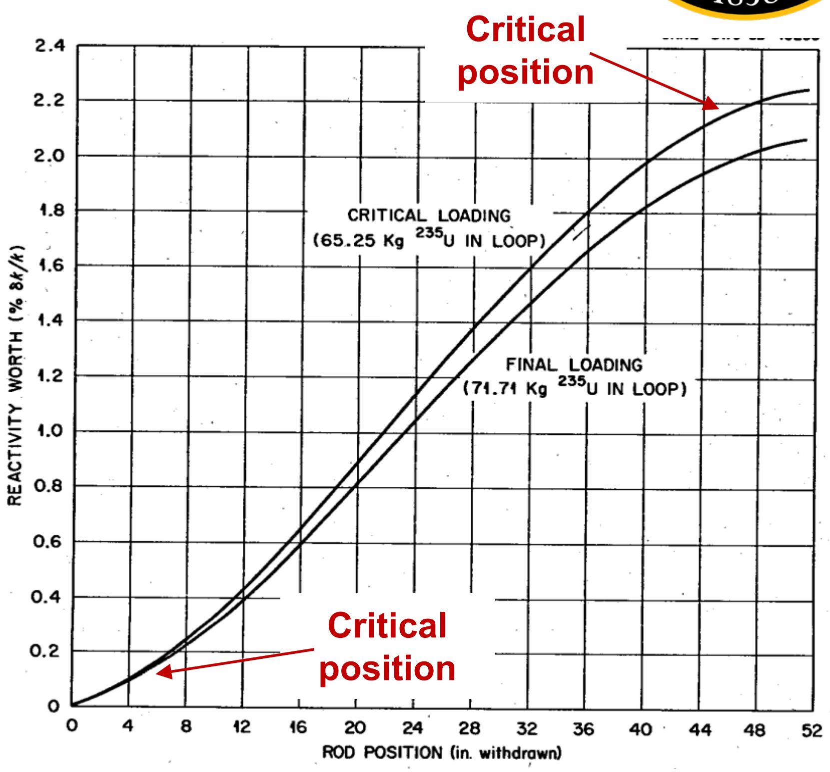
- R. B. Briggs, MOLTEN-SALT REACTOR PROGRAM. Semiannual Progress Report for Period Ending August 31, 1965, **ORNL-3872**, ORNL (1966).
- B. E. Prince, et al., "Zero-Power Physics Experiment on the Molten Salt Reactor Experiment," **ORNL-4233**, ORNL (1968).

Pump Transient Test Data (2/2)

- Control rod response for the pump transient tests



- The measured integral rod worth curve is used to calculate the inserted reactivity at each measured control rod position.
- The control rod position fine indicator has a sensitivity of **0.05** inches.
- The worth integral curve has uncertainty of **5%**.



Control rod worth curves of MSRE

- R. B. Briggs, MOLTEN-SALT REACTOR PROGRAM. Semiannual Progress Report for Period Ending August 31, 1965, **ORNL-3872**, ORNL (1966).
- B. E. Prince, et al., "Zero-Power Physics Experiment on the Molten Salt Reactor Experiment," **ORNL-4233**, ORNL (1968).

Multiphysics Computational Models

- **Multigroup (MG) diffusion-based space-energy dependent neutron kinetics model**

$$\frac{1}{v_g}\frac{\partial \phi_g(t,\mathbf{r})}{\partial t} - \nabla \cdot D_g \nabla \phi_g + \Sigma_{r,g}\phi_g = \frac{\chi_{pg}}{\theta(t)}\sum_g \nu_p \Sigma_{f,g}\phi_g + \sum_{g'\neq g}\Sigma_{s,g'\to g}\phi_{g'} + \chi_{dg}\sum_{k=1}^{6}\lambda_k C_k$$

$$A\frac{\partial C_k(t,\mathbf{r})}{\partial t} + \nabla \cdot \left[A\mathbf{u}C_k \right] = \frac{A}{\theta(t)}\sum_g \nu_{dk}\Sigma_{f,g}\phi_g - A\lambda_k C_k, \qquad k = 1,\cdots,6.$$

- **A quasi-static approach to estimate the reactivity response:**

$$\rho(t) = \frac{\theta_0 - \theta(t)}{\theta(t)} \qquad \rho_{insrted} = -\rho(t)$$

- **1D fluid flow in pipes**

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0,$$

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

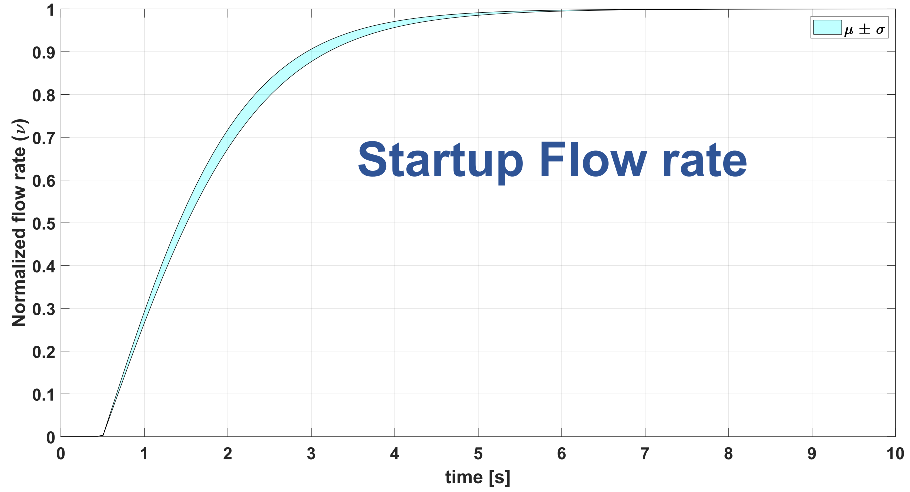
Transient Flow Rate Prediction

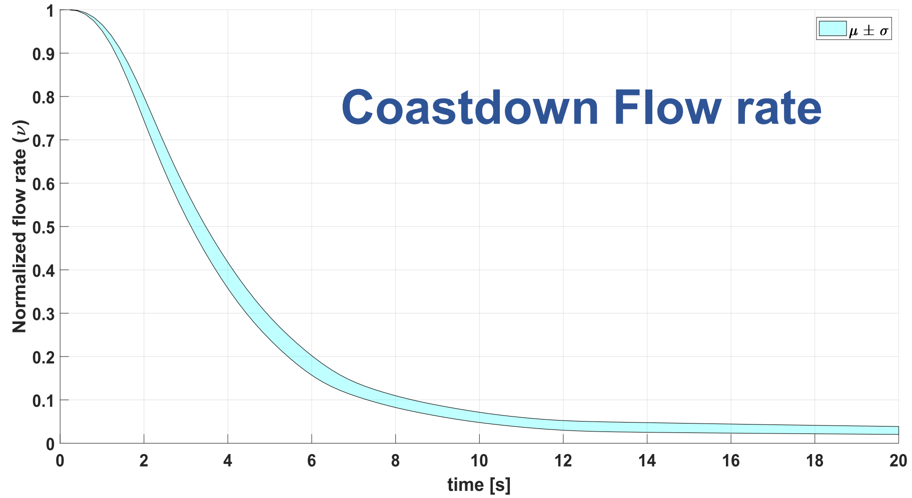
- **Primary pump (i.e., fuel pump) flow rate is not recorded!**
- **The momentum balance model for centrifugal pumps in closed loops is solved for the primary pump flow rate.**

$$\sum \frac{L_i}{A_i}\frac{d\dot{m}}{dt} = -\rho g \frac{\dot{m}^2}{\dot{m}_0^2} h_{p0} + \rho g h_p$$

$$I\frac{d\omega}{dt} = M_{em} - \pi$$

- M. H. Elhareef and Z. Wu, “A New Approach to Predict Pump Transient Phenomena in Molten Salt Reactor Experiment (MSRE) by Missing Data Identification and Regeneration,” *Nuclear Engineering and Design*, **424**, 113292 (2024).





Model Input Parameters of Interest

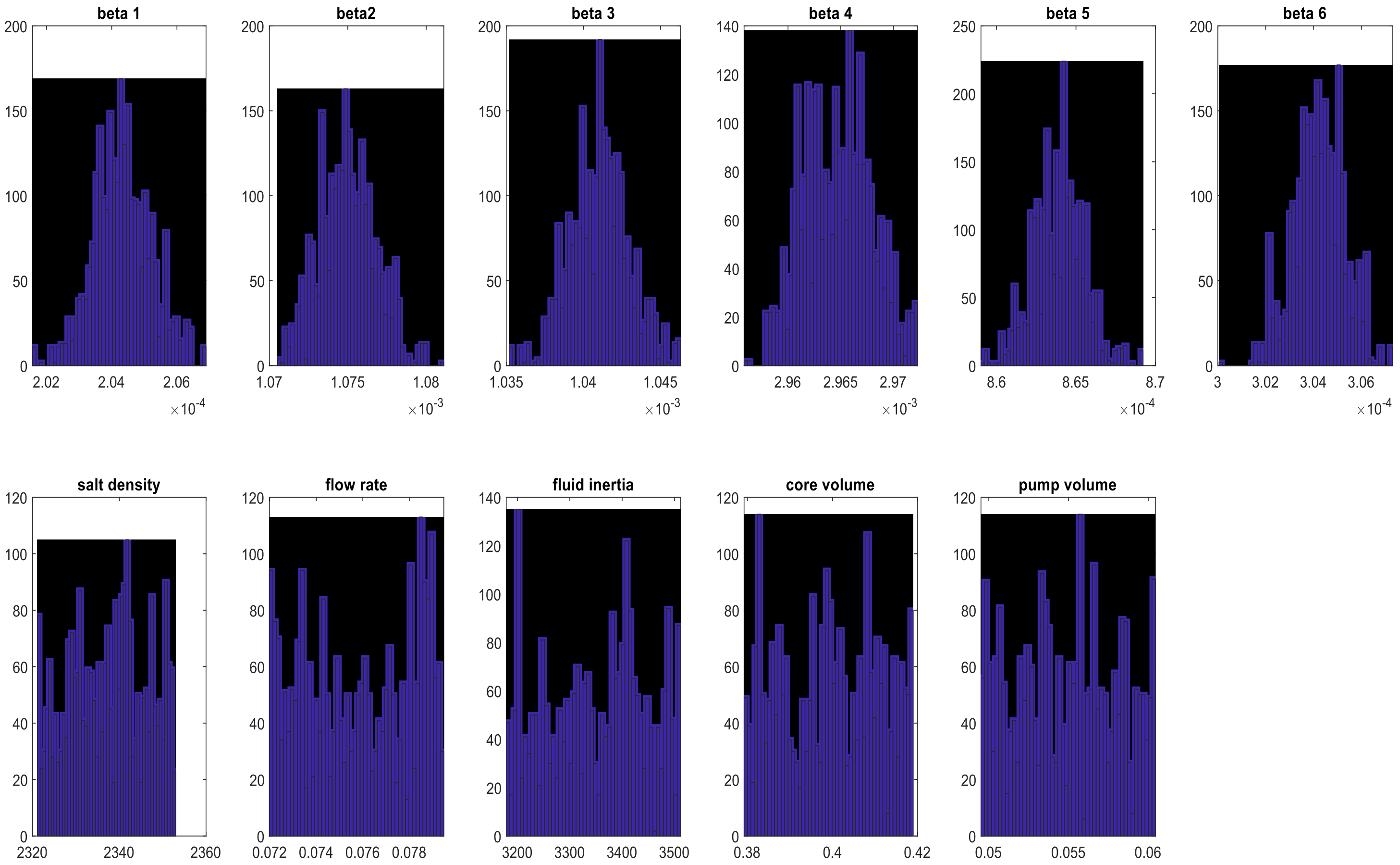
- **Eleven** input parameters are considered in this study.
- Uncertainty in DNF (***β***) is assumed to be equal the statistical uncertainty evaluated by Serpent.
- The reported salt density is **2337 ± 16** kg/m^3
- The uncertainty in flow rate ***Q***, loop flow inertia $\sum \frac{L_j}{A_i}$, core volume is assumed to be **5%.**
- The uncertainty in salt volume in the pump bowl is assumed to be **10%.** This choice is based on the uncertainty in the salt level inside the pump during the test.

Group	Decay constant $\lambda_i\left[s^{-1}\right]$	DN fraction $\beta_i\left[\times 10^{-4}\right]$	STD of DN fraction $\sigma_{\beta_i}\left[\times 10^{-6}\right]$
1	0.0124	2.04	0.84
2	0.0318	10.74	1.87
3	0.1093	10.41	1.88
4	0.3171	29.65	3.20
5	1.3538	8.64	1.01
6	8.6405	3.04	1.01

Parameter	Nominal value	Lower limit	Upper limit
Salt density [kg/m^3]	2337	2321	2353
Flow rate [m^3/s]	0.0757	0.0719	0.0795
Flow inertia $\sum L_i/A_i$ [m^{-1}]	3345	3178	3512
Core flow area [m^2]	0.399	0.379	0.419
Pump flow area [m^2]	0.055	0.050	0.061

Perturbations on the Input parameters

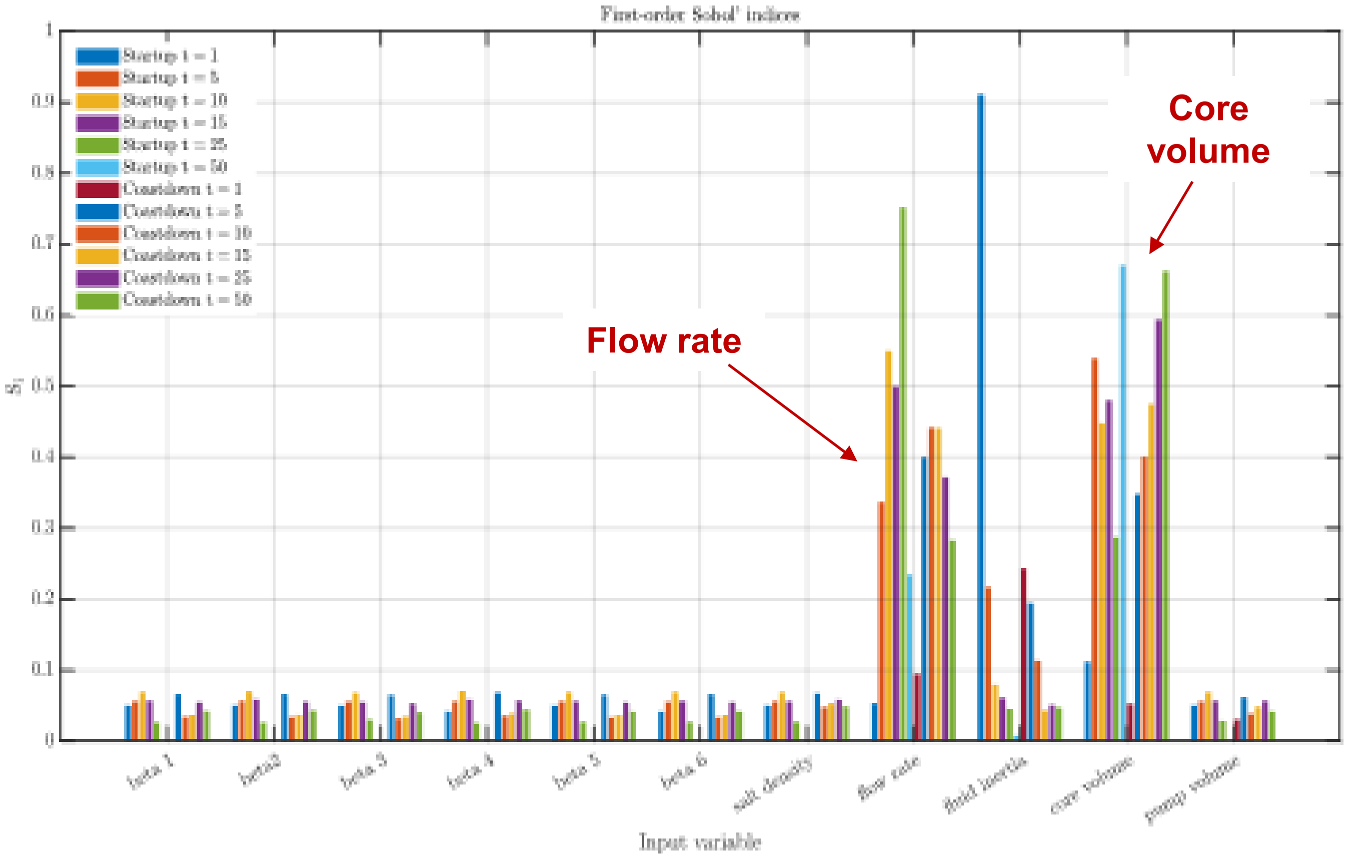
- **Uncertainty in DNF is assumed to follow a *Gaussian distribution* with a STD equal to the statistical uncertainty**
- **The uncertainty in all other parameters are assumed to follow uniform distribution**
- **2600 samples are drawn from the respective distribution of each parameter**



Histogram of the sample used for S/U analysis

Sensitivity Analysis & Results

- **Sobol's method is used to evaluate the 1st and total effect of the uncertainty in each parameter**
- **MATLAB package UQLab-V2.0 is used to evaluate *Sobol's indices***
- **Uncertainties in the DNF estimated by Serpent have a *small* contribution to the output variability**
- **Flow rate and core volume have the *largest* impact on output variability**



First-order **Sobol's indices** for each parameter. Each colored bar represents the index evaluated at a specific time point.

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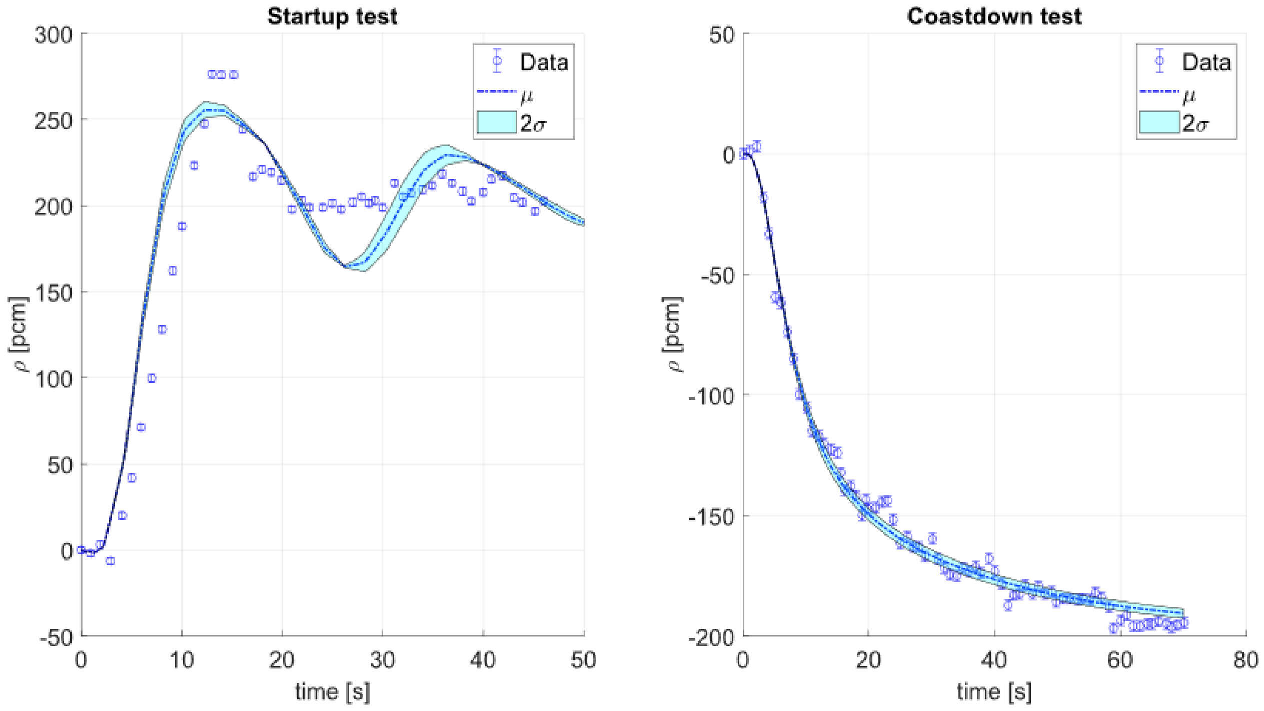
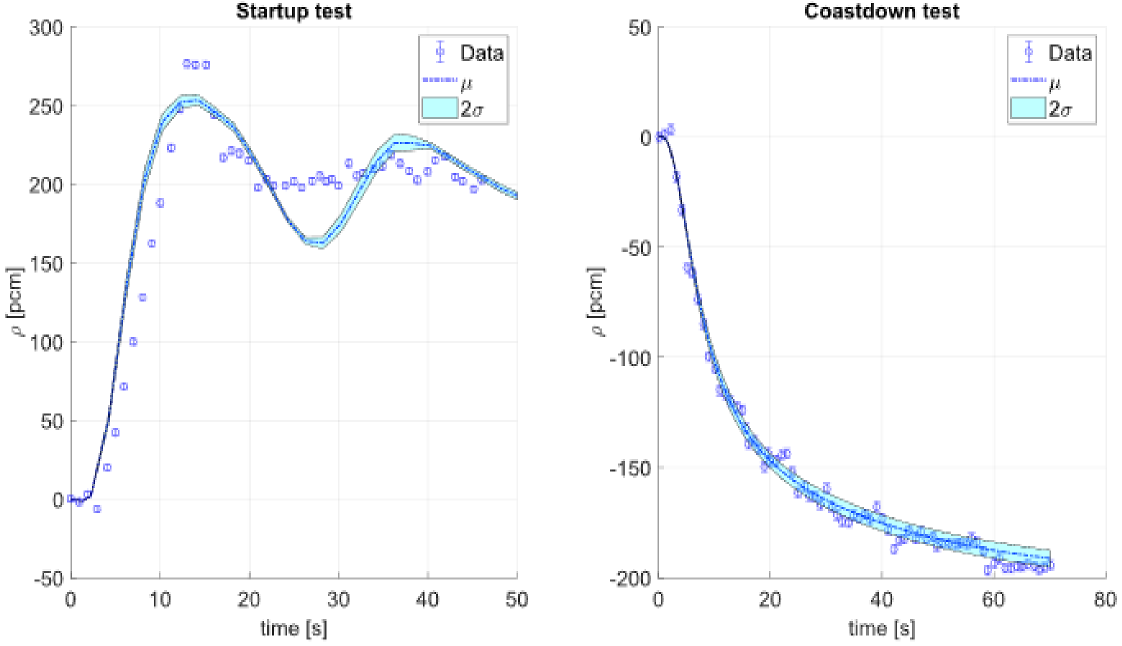
Results on Uncertainty Propagation (1/3)

- The uncertainty in the model output due to the uncertainty in single input is evaluated.
- The model predictions are evaluated for each of the 2600 sample while fixing all other inputs at nominal value
- The uncertainty in the model output is presented in terms of mean and STD (i.e., 1-σ uncertainty)

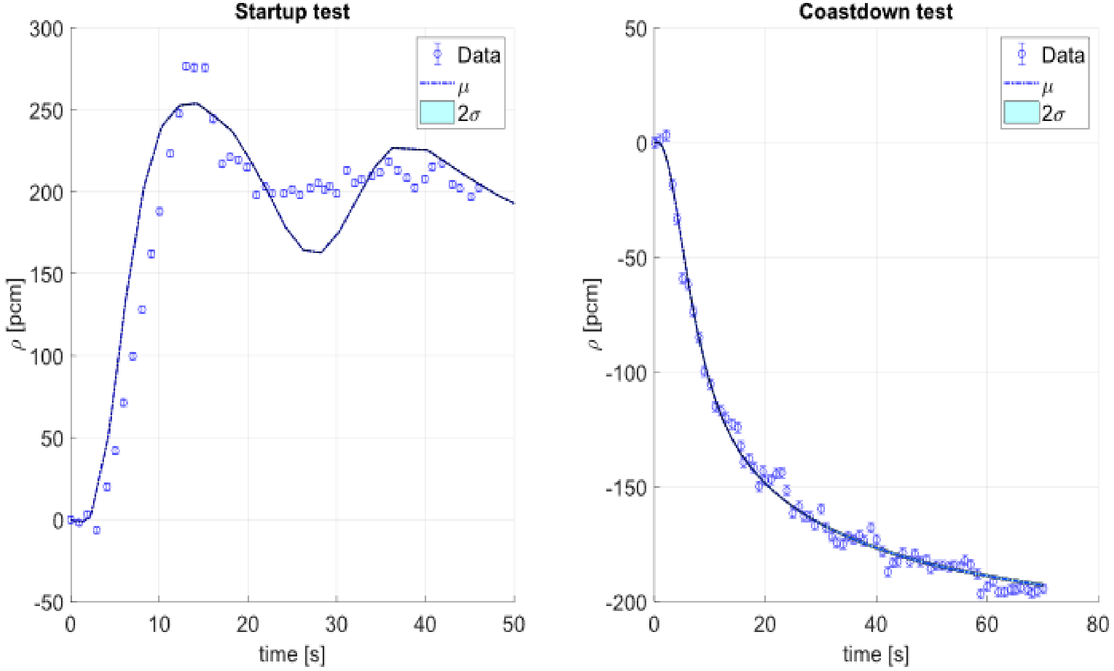


Uncertainty interval of the reactivity response due to uncertainty in **the flow rate**.

Results on Uncertainty Propagation (2/3)



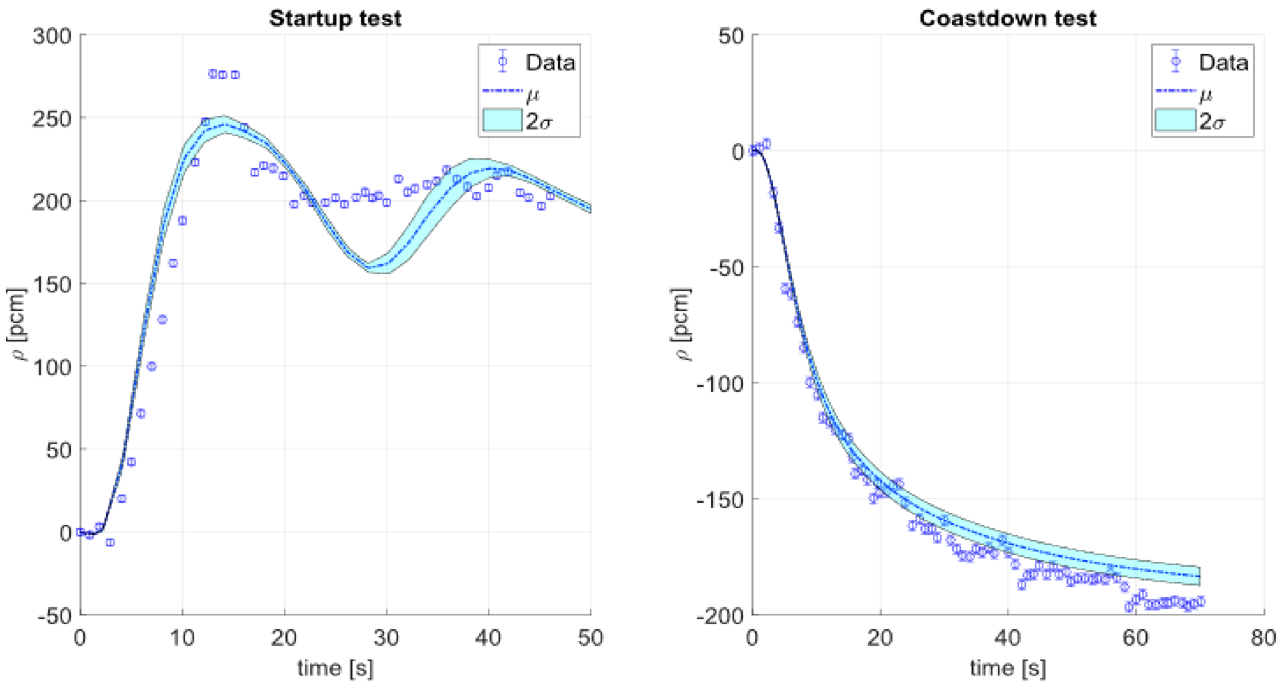
Uncertainty interval of the reactivity response due to uncertainty in **the salt volume** inside the core.



Uncertainty interval of the reactivity response due to uncertainty in **DNF**.

Results on Uncertainty Propagation (3/3)

- **The predictions in the 1D model for coastdown are in relatively good agreement with the experimental data (mean relative error 8%)**
- **The error in the predictions for the startup test are slightly larger (mean relative error 16%)**
- **The uncertainty in the input parameters does not fully explain the discrepancy with the experimental data and computational predictions, which indicates the model approximation may play a more pivoting role in uncertainties.**



Uncertainty interval of the reactivity response due to uncertainty in **all input parameters**.

More Observations & Future Work

- There is generic difference between the startup and coastdown phenomena arising from the initial conditions.
- For startup, the test starts from stationary conditions and only the salt filling the core contains DNPs that are distributed according to the power distribution. Using a 1D model results in under prediction of the DNPs dispersion, which results in larger oscillations in reactivity due to the circulation of the salt bulk initially filled the core.
- For the coastdown, the test starts from circulation configuration and there is no bulk of salt containing higher concentration of DNPs. The solution does not have oscillatory nature.
- For future work, we will extend the analysis to 2D axisymmetric geometry to accurately model the flow mixing and DNPs dispersion.

Acknowledgements

U.S. Department of Energy

Nuclear Energy University Program (NEUP)

Project 21-24286: "Regenerate Undocumented Data in Historical Experiments for MSRE Transient Benchmark Development"

Thank you!

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2024 ANS Annual Conference, June 16–19, 2024, Las Vegas, NV