Effect of Turbulent Diffusion on Delayed Neutron Precursors in the Molten Salt Reactor Experiment (MSRE)

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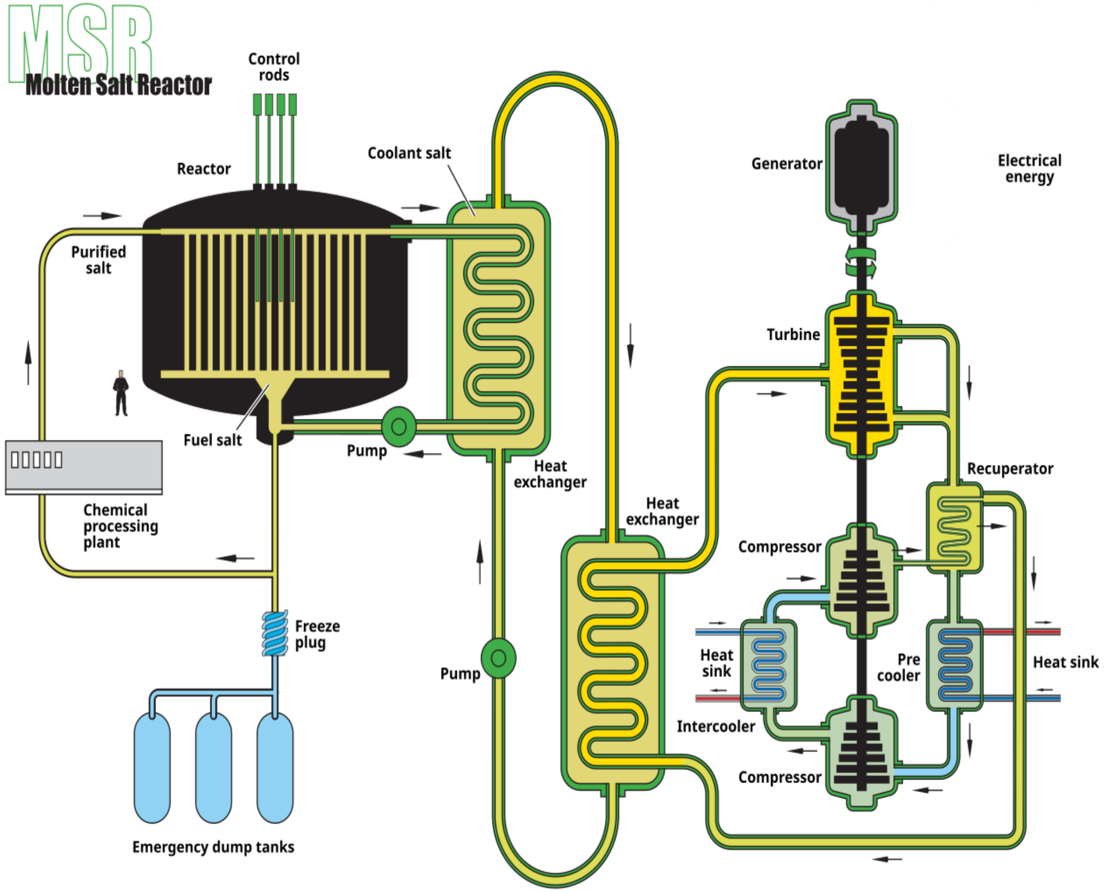
Fission Product Transport in MSRs

- **In MSRs, fission products (FP) are generated directly in the coolant.**
- **The transport of FP impacts the system's dynamic response and composition evolution.**
- **The FP and other species transport in MSRs may be governed by the equation**

$$\frac{\partial C}{\partial t} + \mathbf{U}\nabla \cdot C - \nabla \cdot \left(D \nabla C \right) = R$$



Diffusion Effect of the Species Transport

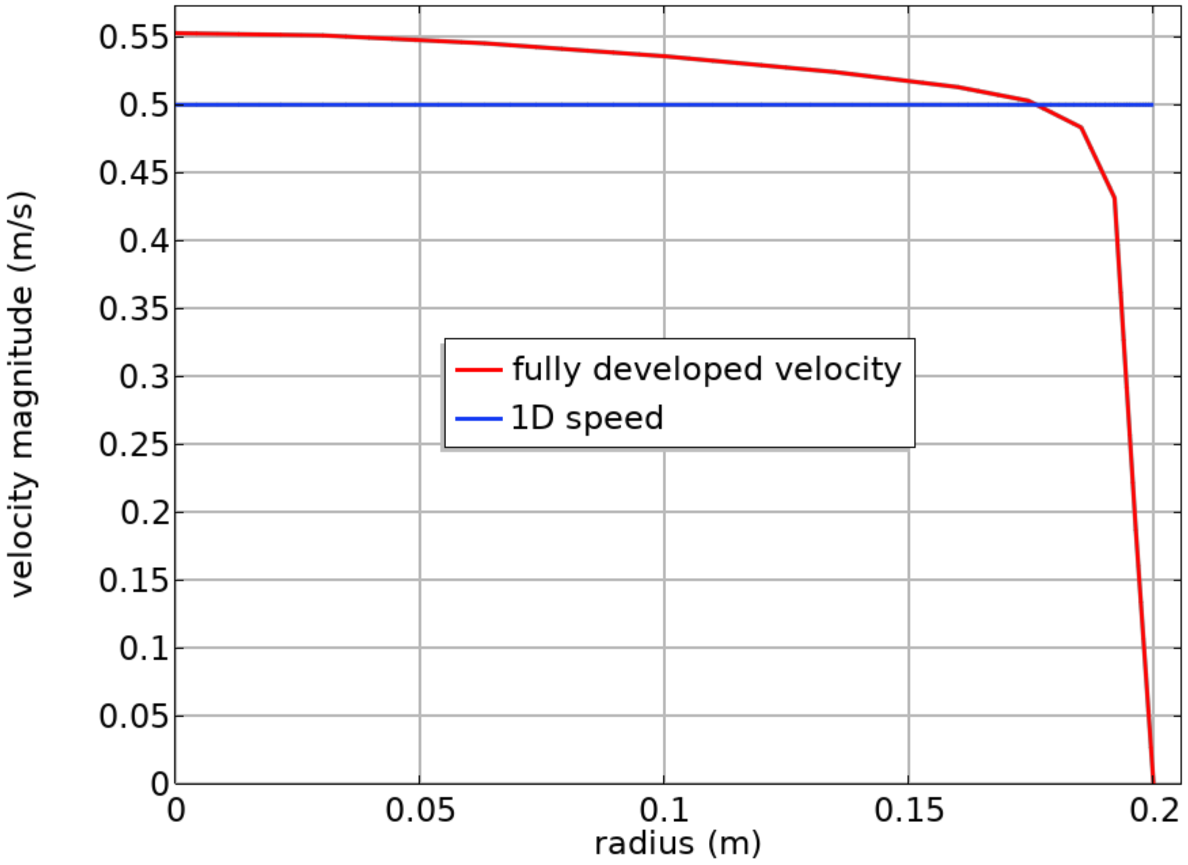
$$\frac{\partial C}{\partial t} + \mathbf{U}\nabla \cdot C - \nabla \cdot \left(D\nabla C \right) = R$$

- **The diffusion term accounts for molecular and turbulent diffusion effects, i.e., $D = D_c + D_T$, where molecular diffusion coefficient (D_c) is either obtained experimentally or using the Stokes–Einstein equation or the Wilke–Chang equations, and turbulent diffusion coefficient (D_T) requires turbulent CFD modeling.**
- **The diffusion term is typically much smaller than advection and is neglected in most dynamics analysis. However, this investigation reveals the diffusion effect is important in certain MSR transient scenarios.**

Diffusion Treatment in System-Level Models

$$\frac{\partial C}{\partial t} + \mathbf{U}\nabla \cdot C - \nabla \cdot \left(D \nabla C \right) = R$$

- **In system-level models, the velocity field is typically approximated as a 1D speed.**
- **This introduces bias in the transport model.**
- **As demonstration, the transport of a pulse of diffusing material is tracked inside a circular pipe.**



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Taylor Dispersion Coefficient*

$$\frac{\partial C}{\partial t} + \mathbf{U}\nabla \cdot C - \nabla \cdot \left(D\nabla C \right) = R$$

- **Taylor correlation defines a virtual diffusion coefficient that corrects for the use of the mean flow speed (i.e., 1D speed) for species transport instead of using the actual flow distribution.**

- **The derivation involved substituting the actual flow distribution in the transport equation and averaging over the cross section. For Turbulent flow regime**

$$D_T = 10.1 \frac{d_h}{2} u \sqrt{\frac{f_D}{2}}$$

*G. I. Taylor, "The dispersion of matter in turbulent flow through a pipe," *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, vol. 223, no. 1155, pp. 446–468, Jan. 1997, doi: 10.1098/rspa.1954.0130.

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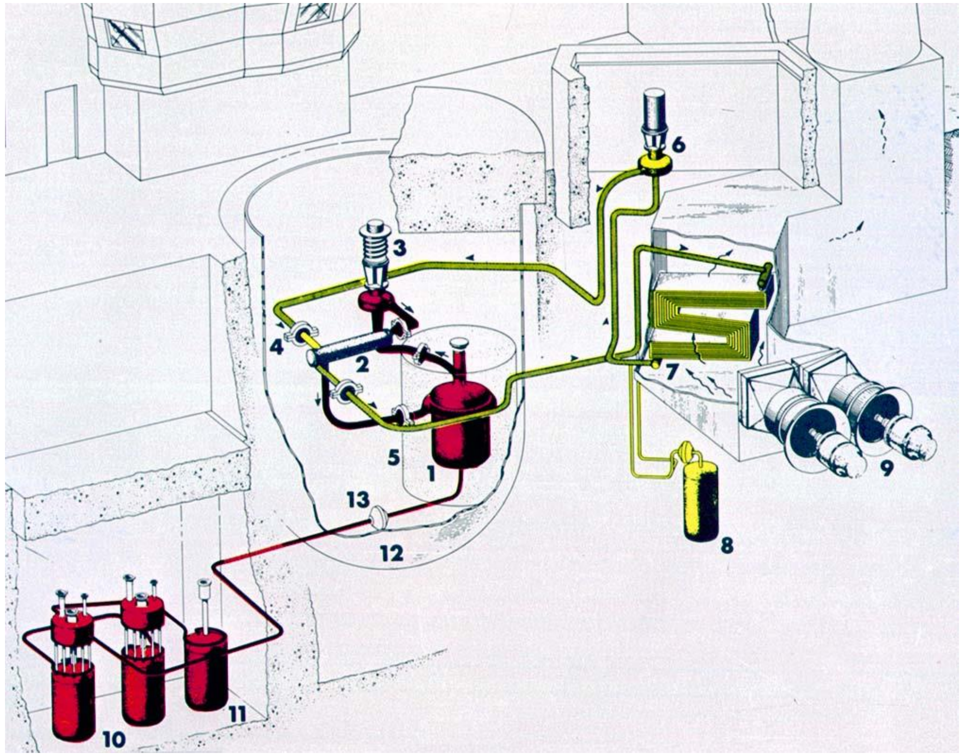
Molten Salt Reactor Experiment (MSRE)

- **Performed at ORNL (1965-1969).**
- **MSRE provides a reliable source for experimental data for circulating-fuel MSRs.**

Design thermal power	10 MW
Maximum operation power	7.2 - 8.0 MW
Fissile material	^{235}U then ^{233}U
Coolant and fuel solvent	FLiBe ($2LiF\text{-}BeF_2$)
Moderator	Graphite
Design fuel temperature	1175-1225 ^oF (635-663 ^oC)
Design flow rate	1200 gpm (0.0757 m^3/s)



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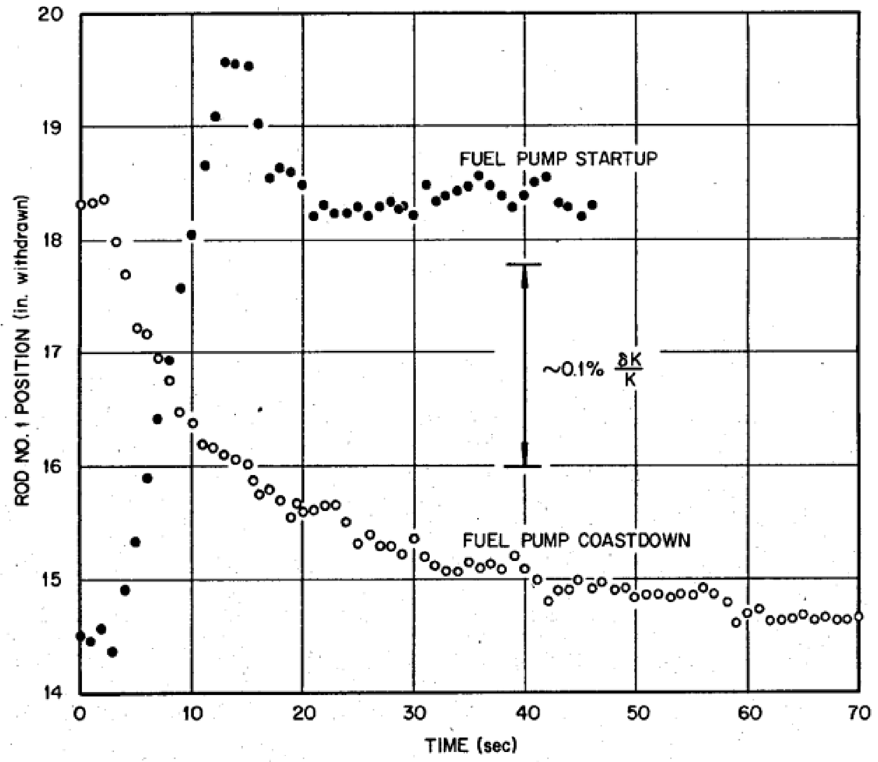
MSRE Pump Startup and Coastdown Tests

- **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.**



Control rod response for the pump startup and coastdown tests.

Computational Models on MSRE Transients

- **Neutronics behavior is described by the two-group diffusion model**

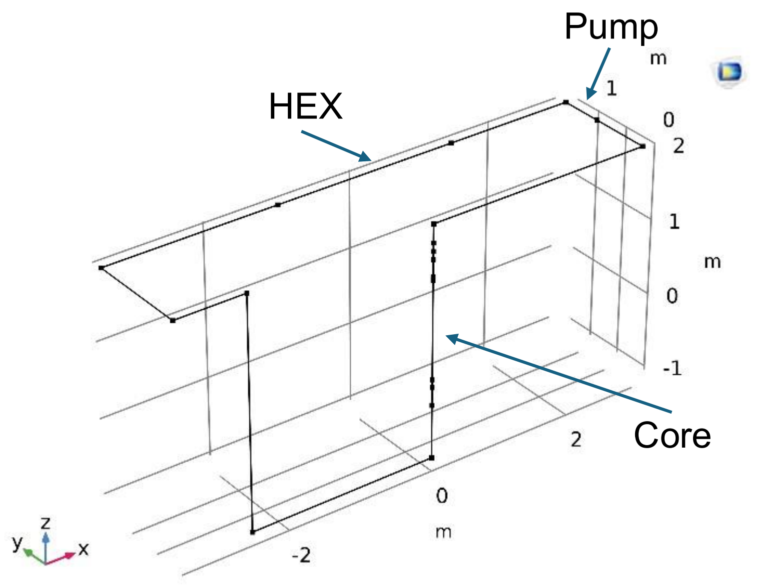
$$\frac{1}{v_g}\frac{\partial \varphi_g}{\partial t} - \nabla \cdot D_g \nabla \varphi_g + \Sigma_{r,g}\varphi_g = \frac{\chi_{pg}(1-\beta)}{k_{eff}}\sum_{g'=1}^{G} \nu_{g'}\Sigma_{f,g'}\varphi_{g'} + \sum_{g'\neq g}^{G}\Sigma_{s,g'\to g}\varphi_{g'} + \sum_{i=1}^{I}\chi_{dg,i}\lambda_i C_i$$

- **A fully coupled fluid flow-species transport is used to track the DNPs**

$$A\frac{\partial C_i}{\partial t} + \nabla \cdot [AuC_i] = \nabla \cdot (D_i \nabla A C_i) + \frac{A\beta_i}{k_{eff}}\sum_{g'=1}^{G}\nu_{g'}\Sigma_{f,g'}\varphi_{g'} - A\lambda_i C_i$$

- **A quasi-static method is used to calculate the reactivity response**

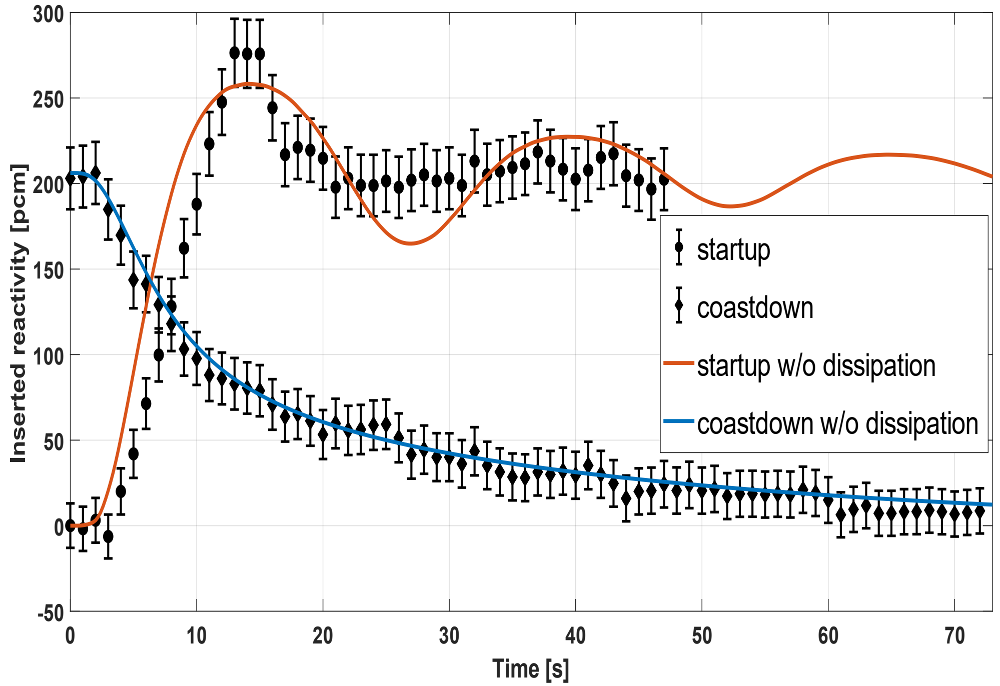
$$k_{eff}(t) = k_{eff}^0 \frac{\int_V \sum_{g'=1}^{G} \nu_{g'}\Sigma_{f,g'}\varphi_{g'}(t)}{\int_V \sum_{g'=1}^{G} \nu_{g'}\Sigma_{f,g'}\varphi_{g'}(t)} \qquad \rho_{in}(t_i) = -\Delta\rho = \frac{k_{eff}(t) - k_{eff}^0}{k_{eff}(t)\times k_{eff}^0}$$



Geometry of the 1D model for the MSRE fuel circulation loop.

Results and Discussion (1/3)

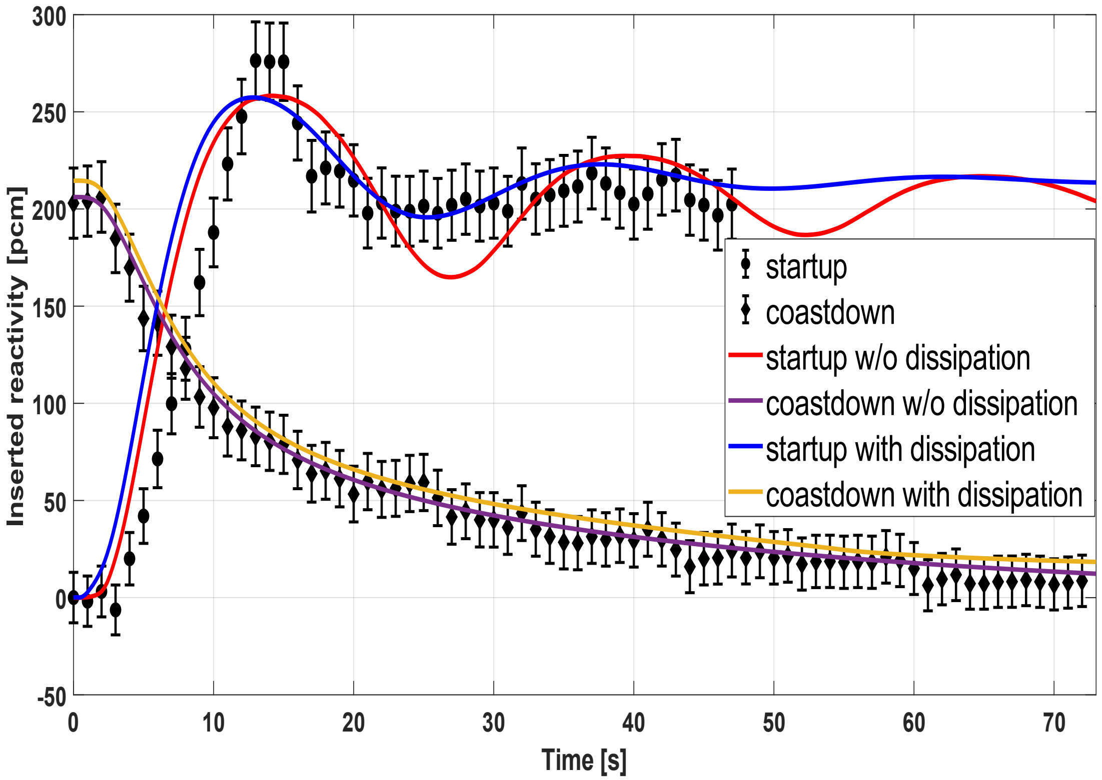
- **First, the reactivity response is obtained without taking the dispersion into account.**
- **For the startup test, the reactivity response has oscillations with a larger magnitude compared to experimental data.**
- **This is not observed in the countdown test**



Reactivity response during the pump transient test without considering turbulent diffusion.

Results and Discussion (2/3)

- **Taylor diffusion coefficient is added to correct for the use of a 1D velocity.**
- **Dissipation has a damping effect on the reactivity oscillations for the startup test.**
- **The results are in better agreement with the experimental data.**
- **The dissipation has a minimal impact on the coastdown test because the salt was thoroughly mixed at the beginning of the test.**



Reactivity response during the pump transient test with and without considering the turbulent diffusion.

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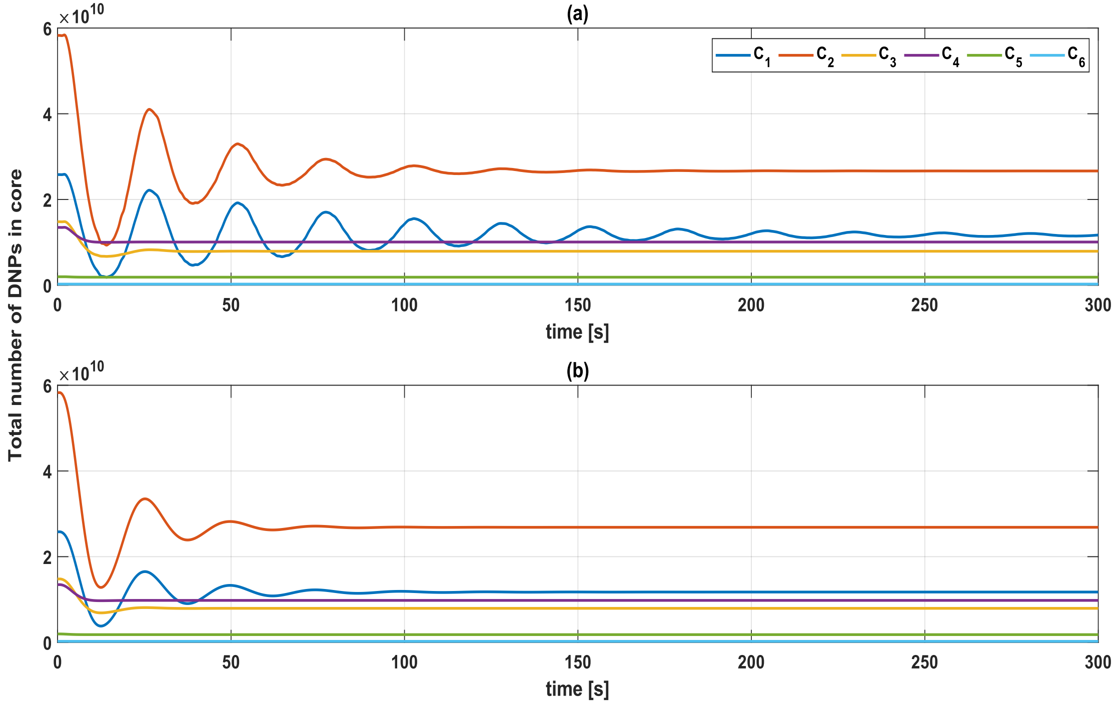
Results and Discussion (3/3)

- The reactivity oscillations are associated with oscillations in the total number of DNP in the core at any given time.

- DNP dispersion facilitates quicker homogenization of the initial concentration, resulting in reduced oscillations in reactivity.



The total number of DNPs during the pump startup test: (a) with no turbulent diffusion, and (b) with turbulent diffusion considered by the Taylor correlation.

Conclusions and Future Work

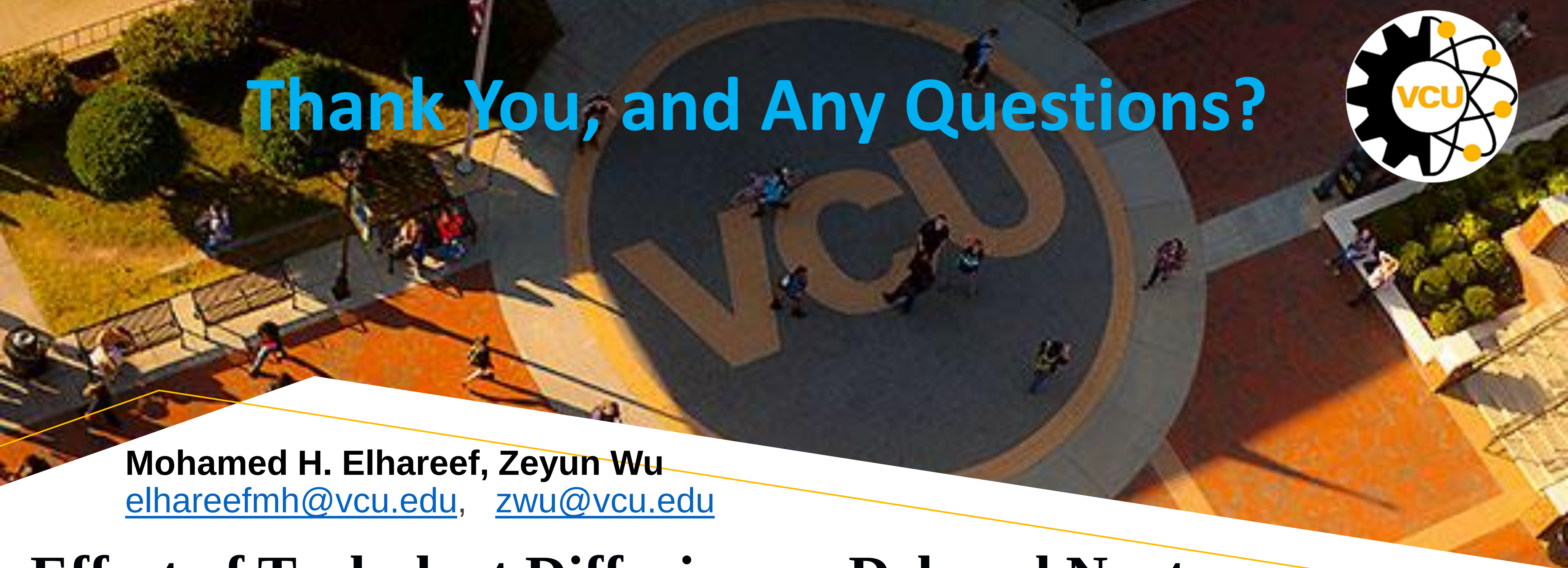
- The studies show that the adoption of Taylor correlation for turbulent diffusion in pipes improved the accuracy of predicting the reactivity response except in the initial phase of the startup test when the flow rate is sufficiently low, and the flow is in the laminar regime.
- More studies are needed to address the suitable correlations for both the molecular and turbulent diffusion on the response on of MSRs.
- Also, higher level models (2D/3D) are needed to study the effects of the MSRE geometrical characteristics (especially in the downcomer and lower plenum) on the DNPs mixing.

Acknowledgments

“Regenerate Undocumented Data in Historical Experiments for MSRE Transient Benchmark Development”

Award No. DE-NE0009162

Thank You, and Any Questions?



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Backup Slides

MSRE Pump Transient Tests

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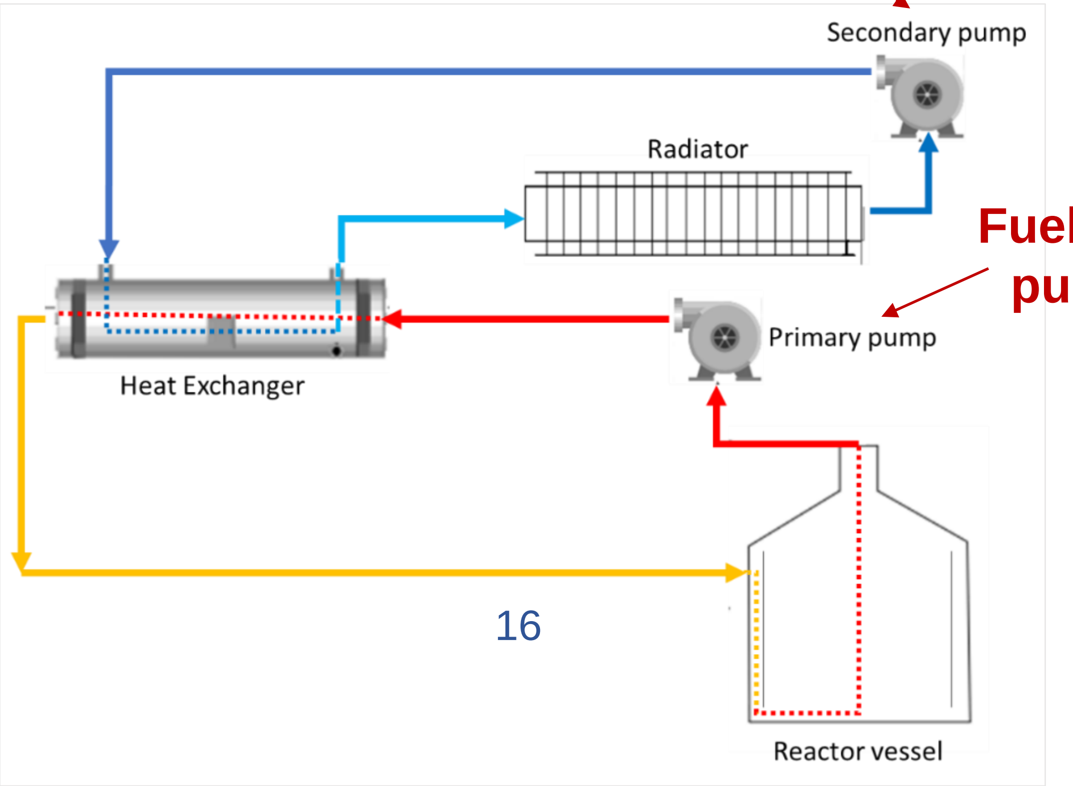
Coolant salt pump

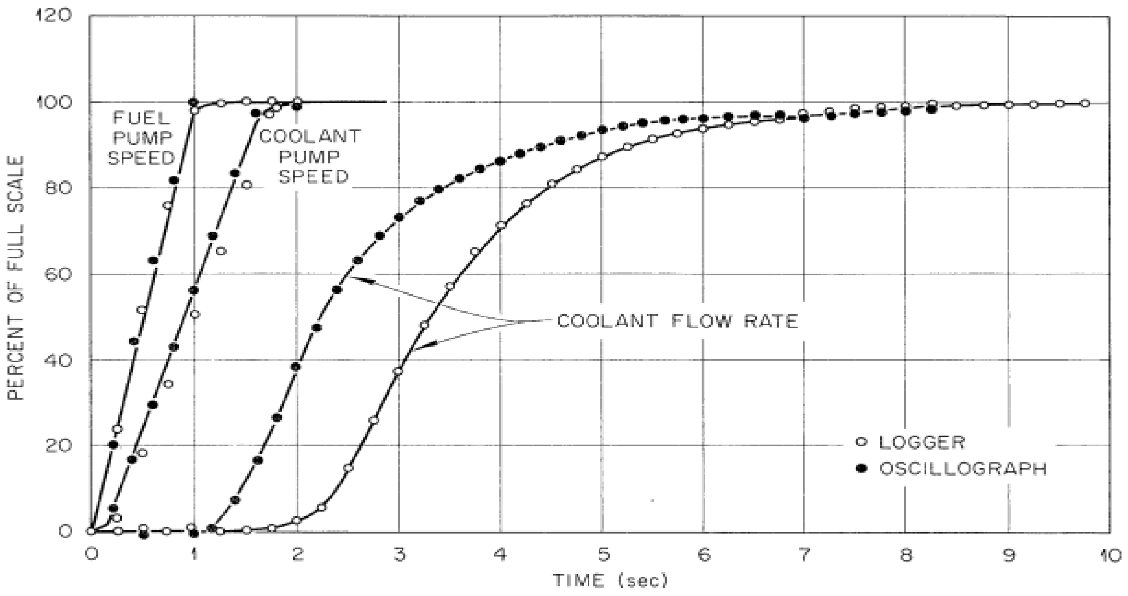
Fuel salt pump

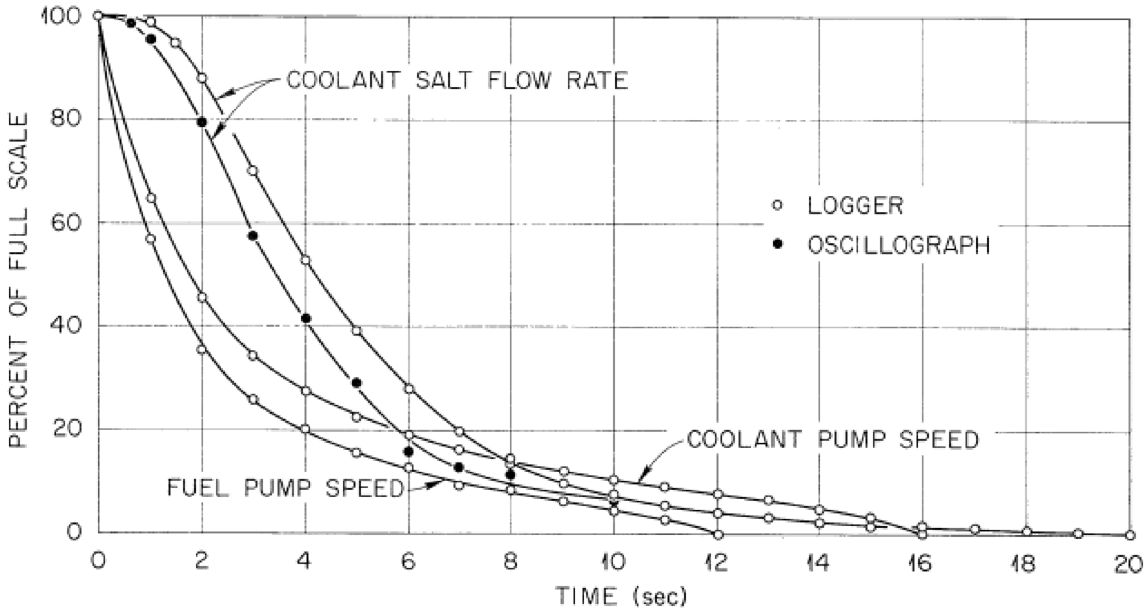


Schematics of the MSRE salt circulation loops.

Pump Transient Test Data (1/2)

- **Pump <u>startup</u> test**
- **Pump <u>coastdown</u> 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).

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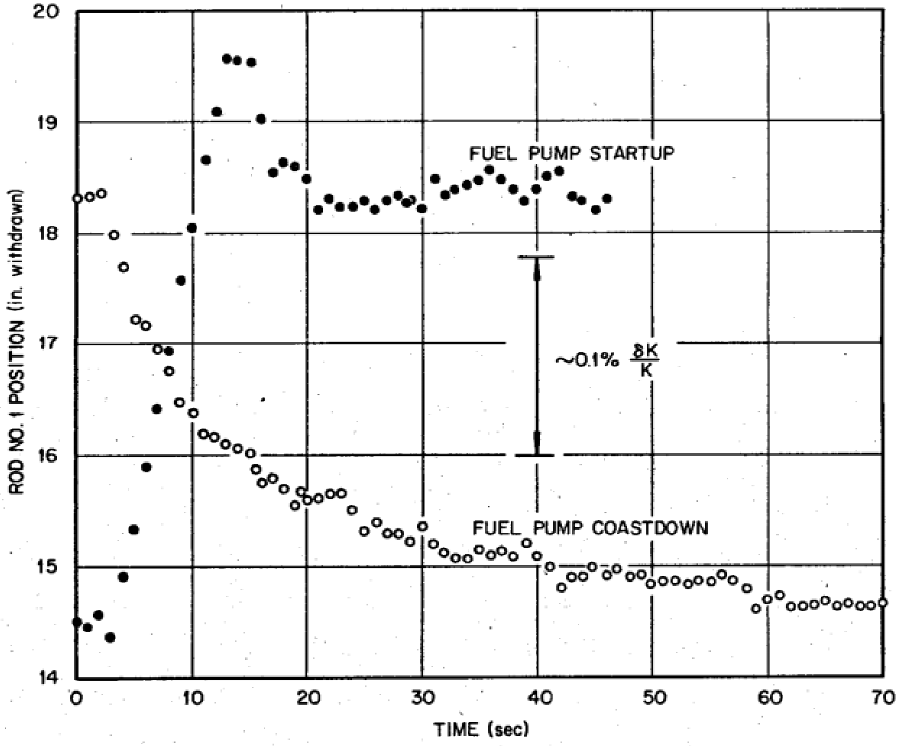
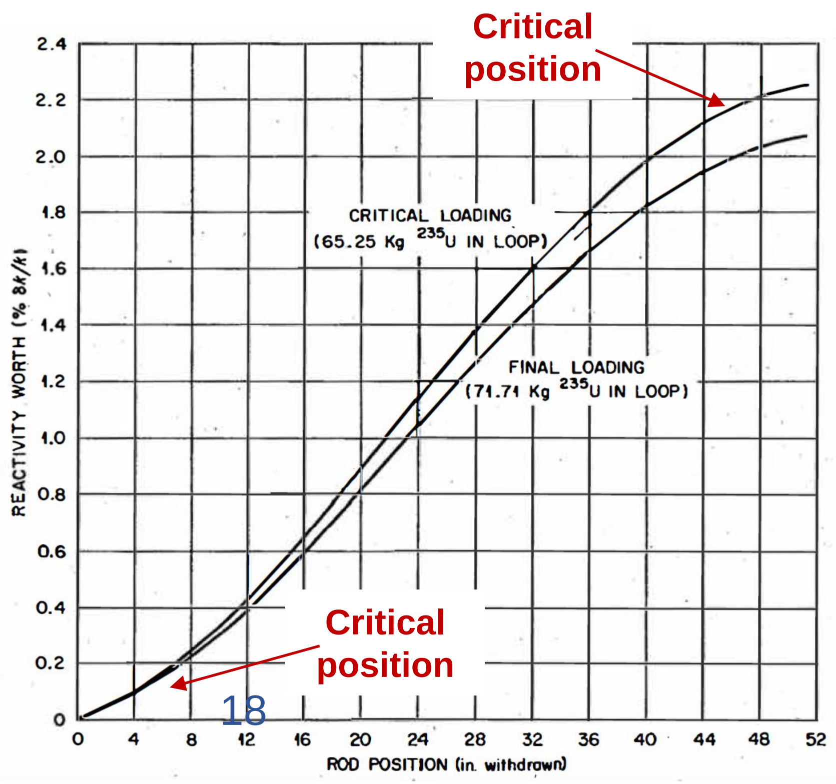
Pump Transient Test Data (2/2)

- 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