SAM enhancements for MSR applications

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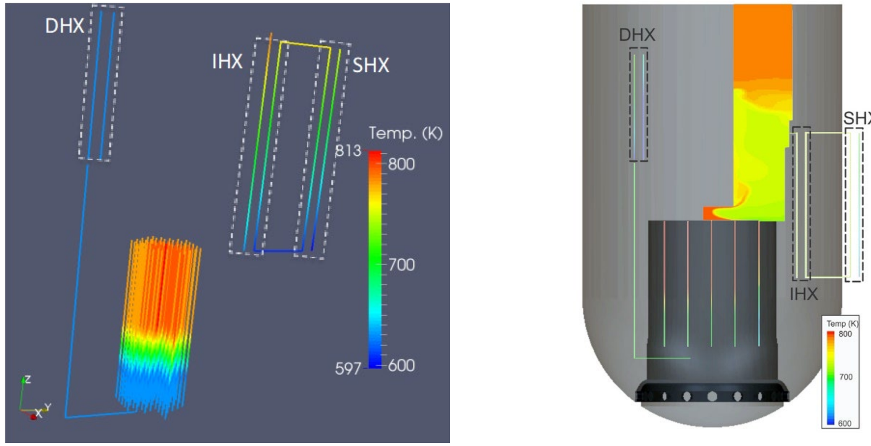
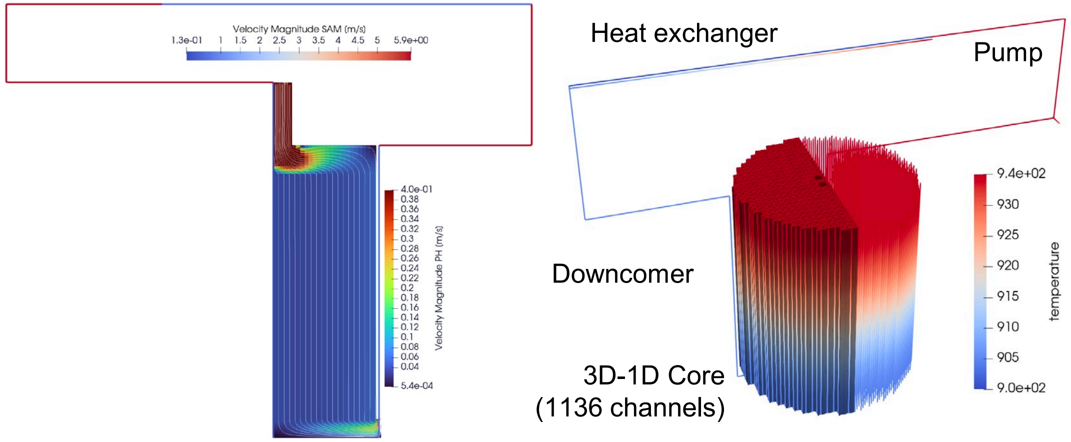
SAM Overview

SAM Code Special Issue
in *Nuclear Technology*

- **A modern system analysis code that provides fast-running, modest-fidelity, whole-plant transient analysis capabilities for non-LWR concepts**
  - Best-estimate, integrated plant response modeling across fuel/assembly/core, primary & intermediate heat transport, balance of plant, decay heat removal, and I&C / protection system response
- Built on the **MOOSE framework**, leveraging advances in software engineering, numerical methods, and native multi-physics / multi-scale coupling integration
- Conformal to ASME NQA-1
- One of several NEAMS tools within BlueCRAB for confirmatory calculations of licensing applications at U.S. Nuclear Regulatory Commission



Stand-alone and Coupled SAM and CFD code simulations of SFR



MSRE primary system models with 2D Pronghorn core (left) and 3D graphite with 1D salt channel core (right)

R. Hu et al. "SAM: A Modern System Code for Advanced Non-LWR Safety Analysis", *Nuclear Technology*, *211*(9), 1883–1902, 2025.

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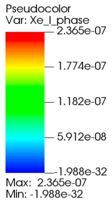
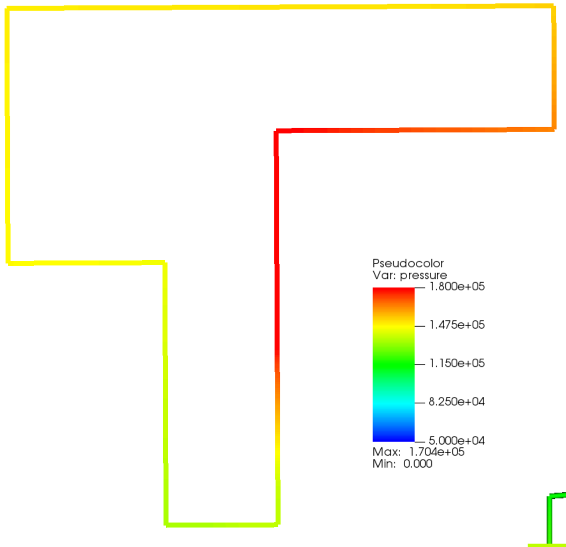
MSR modeling capabilities in SAM

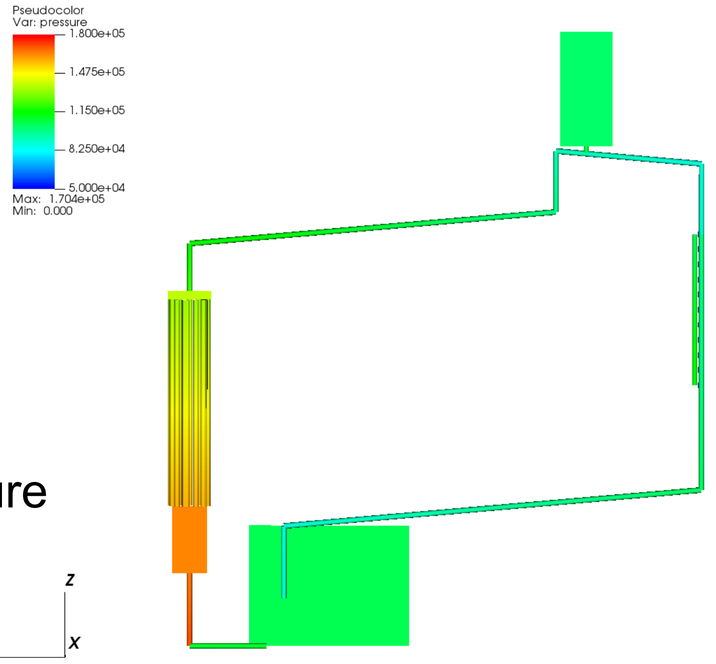
FY25 Report on OSTI

- **Ongoing efforts to develop SAM for MSR:**
  - Salt thermophysical properties (+ *Saline*)
  - Salt freezing
  - Species tracking for delayed neutron precursors and fission products in both salt and sparge gas
  - Species decay and decay heat
  - Species phase transfer
  - Modeling of non-condensable gas transport
- **Recent code enhancements:**
  - Completion of noble gas transport model with migration in graphite and PKE reactivity feedback
  - Updates to non-condensable gas model for gas removal
  - Multi-scale/multi-phase *Sh* closures from MOSCATO
  - Integration of redox corrosion model from NEUP with Rensselaer Polytechnic (RPI)





Prediction of salt ^{135}Xe distribution in MSRE

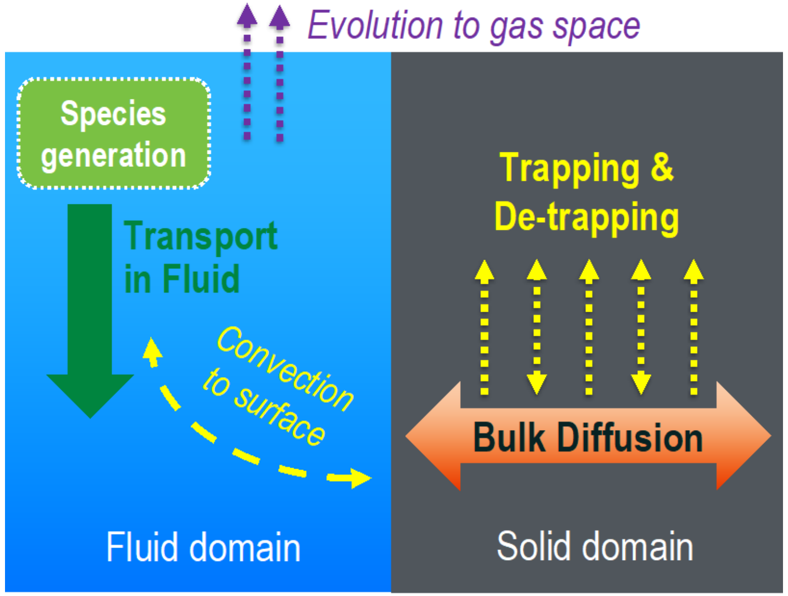


Prediction of pressure distribution in LSTL

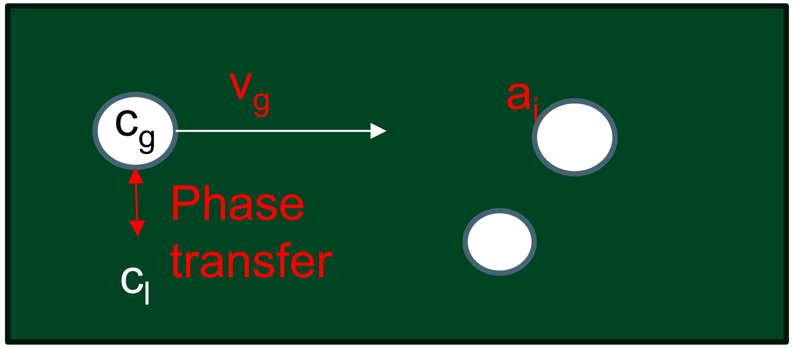
T. Mui et al. “Integrated Molten Salt Reactor Modeling Capabilities in NEAMS Thermal Hydraulics Tools”, ANL/NSE-25/71, 2025. https://www.osti.gov/biblio/2998579

Species and gas transport framework

- **Species transport** (passive scalar) capability was initially developed to track the distributions of particles transported in the fluid system
  - Accounts for local decay, generation, transfer between fluid/solid domains, and trapping behavior in solid structures
  - Also incorporated into point kinetics and reactor power models for delayed neutron/decay heat precursor tracking
- **Gas transport** model later added to capture distribution and local behavior, assuming the gas is non-condensable and uniform pressure with liquid
  - Prediction of gas void distribution and bubble diameter / interfacial area calculated from Weber number
  - Drift flux model implemented to predict bubble velocity



Species transport pathways modeled in SAM



Gas (bubble) drift flux model with inter-phase species transfer

T. Mui et al. "Species Transport Framework Development in SAM for System-Level Tritium Source Term Analysis" and R. K. Salko et al. "Implementation of a Drift Flux Model into SAM with Development of a Verification and Validation Test Suite for Modeling of Noncondensable Gas Mixtures", *Nuclear Technology*, 211(9), 2025.

Noble gas transport and reactivity feedback

- **System-level noble gas transport model accounts for interphase transfer between liquid-gas (bubbles) and now liquid-solid (porous/graphite)**
  - Noble gas dissolved in liquid transfers to graphite pores through a two-film model
  - Knudsen diffusion within pore gas space
- **Species reactivity feedback added to PKE model to account for evolution of ^{135}Xe concentration**
  - Reactivity feedback will integrate provided reactivity coefficients with species concentrations and volume over axial length for gas/liq/solid phase
  - Integrated into SAM Point Kinetics model, demonstrated using MSRE

Species fluid/gas transport and interphase transfer

$$\frac{\partial c_l}{\partial t} + \frac{\partial (v_l c_l)}{\partial x} + \lambda_{Xe} c_l + \phi \sigma_a c_s + k_m a_i \left(c_g HRT - c_l \right) - \lambda_{I^{135}} c_{I^{135}} = 0$$

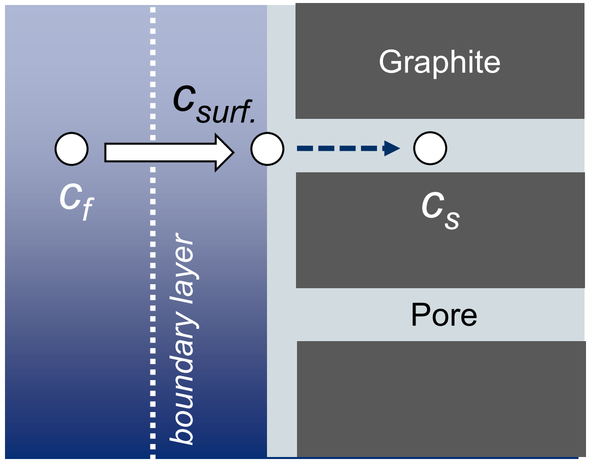
Species porous diffusion in solids (Xenon in graphite)

$$\frac{\partial c_s}{\partial t} - \frac{D_{Xe,s}}{\varepsilon} (\nabla^2 c_s) + \lambda_{Xe} c_s + \phi \sigma_a c_s = 0$$

Fluid-solid interface species flux

$$J_{xe} = k_m \left(c_f - HRT \varepsilon^{-1} c_{s,surf.} \right)$$

c: Species concentration (#/m^3)
λ: Species decay coefficient (1/s)
$\phi \sigma_a$: Species burnup rate (1/s)
D: Effective diffusivity (m^2/s)
ε: Porosity
k_m: Mass transfer coefficient (m/s)
H: Henry's law solubility (mol/m^{3}Pa)



Species convection and diffusion in porous structures

Species reactivity feedback

$$\rho_{species} = \sum_{n}^{N} \alpha_n c_{phase}(t) V_{phase}$$

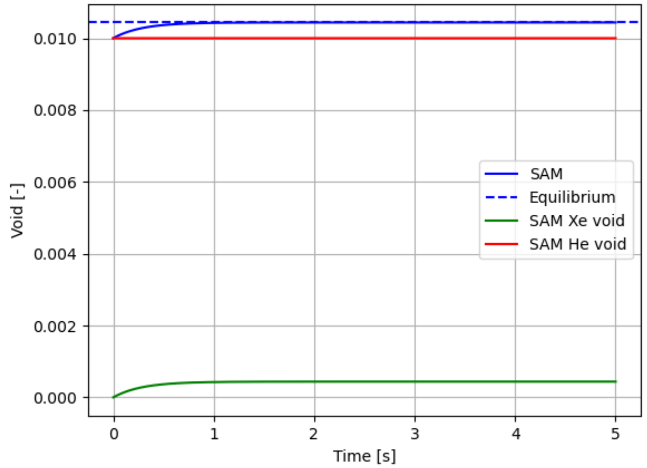
ρ: Reactivity (Δk/k)
α: Species reactivity coefficient (Δk/k per #)
c: Species concentration (#/m^3)
V: Volume of phase (m^3)

Updates to gas (bubble) transport model

- Updates to extend interphase species-gas transport model (FY24) based on stakeholder needs
- Non-condensable gas can be **modeled as a mixture**, needed when fission gas products are the dominant source of void
- Added option to model **'passive' drift flux transport of an arbitrary gas mixture**, suitable for small void (< 1%)
- **Bubble efflux model** to capture removal of gases from liquid volume/tank components
- **Low volatile option** for phase transfer for species which have low transfer rates but must be quantified in the cover gas

Table. List of added regression verification tests

Off-gas test (pipe to liquid tank)	Tank with decaying species
Bubble constant diameter	Tank with a system of species
Pipe with fixed density	Tank with sparging gas (*bottom left fig*)
Branch tee (one-to-two)	Liquid/gas species injection into a pipe
Flow loop with gas transport	Liquid/gas species injection specific mass BC
Flow loop with gas transport and efflux	Liquid/gas inj. phase change (*bottom right fig*)



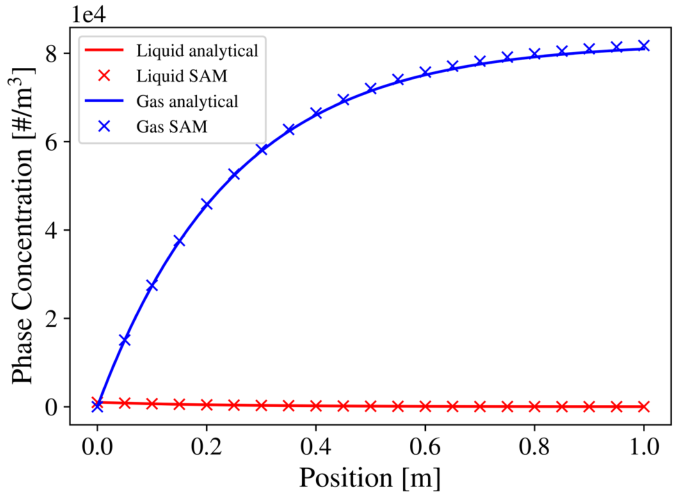


Fig. Analytical verification of gas sparging in tank (left) and pipe (right)

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Sherwood correlations from MOSCATO/NekRS

- Sherwood (Sh) number correlations are adopted as **closure models** for convective liquid-solid and liquid-gas mass transfer
- Previous modeling in SAM relied on **Chilton-Colburn analogy** based on local heat transfer coefficient, but only valid for pipe turbulent flow
- Improved Sh correlations derived from **high-fidelity CFD modeling in MOSCATO/NekRS**[1,2] for various flow geometries and Sc/Re ranges added to SAM
- Using meshes with high degree of near-wall refinement (10^5-10^6 elements and 10^6-10^7 DOFs), fitted correlations **reduce error as much as 10x compared to analogous literature Sh**
- **Calderbank-Moo-Young (1961) and Kress (1972)** correlations added for liquid-gas bubble transfer

$$\mathbf{Sh}_{\boldsymbol{Pipe}} = \mathbf{0.00308\ Re^{1.045}Sc^{0.327}}$$

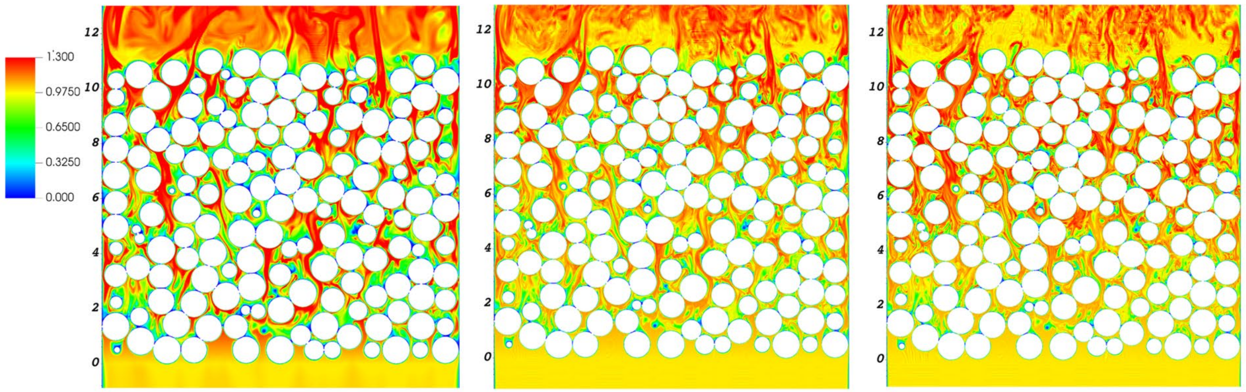
Re: [3000,10^4], Sc: [10,100], RME: $\pm 9.5\%$

$$\mathbf{Sh}_{\boldsymbol{Rod\ Bundle}} = \mathbf{0.023}\left(\frac{\boldsymbol{P}}{\boldsymbol{D}}\right)\mathbf{Re^{1.10}Sc^{0.36}}$$

Re: [3750,12500], Sc: [10,100], RME: $\pm 3\%$

$$\mathbf{Sh}_{\boldsymbol{Pebble\ Bed}} = \mathbf{2.0 + 0.50275\ Re_{\boldsymbol{p}}^{0.64123}Sc^{1/3}}$$

Re_p: [100,1000], Sc: [10,100], RME: $\pm 20\%$



Re=100, Sc=10   Re=100, Sc=50   Re=100, Sc=100

1. H. Yuan and N. Hoyt. “MOSCATO Solver Development and Integration Plan”, ANL/NSE-21/66.
2. H. Yuan and N. Hoyt. “MOSCATO Development and Integration in FY2023”, ANL/NSE-23/50.

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System-level redox corrosion model

- **Redox corrosion model is needed for modeling long term operation of MSRs**, such as depletion of Cr from Fe-Cr-Ni-based alloys
- Framework developed under a **NEUP with Rensselaer Polytechnic Institute (RPI)** in FY23-24 has been incorporated into SAM
- **System-level redox corrosion model** combines species transport framework with redox reaction kinetics model
- **Several modeling assumptions that will be revisited in FY25**:
  - Local vs global net conservation of charge
  - Diffusion kinetics of constituents within the alloy
  - User-friendly input syntax

Bulter-Volmer: $j_k = j_0 \left[\exp\left(\frac{(1-\alpha)nF}{RT} \eta \right) - \exp\left(\frac{-\alpha nF}{RT} \eta \right) \right]$

Nernst: $E_{eq} = E^0 + \frac{RT}{nF} \ln\left(\frac{c_{oxidized}}{c_{reduced}} \right)$

Corrosion source term: $j_k = nFK_d \left(c_{o/r,int.} - c_{o/r,bulk.} \right)$

Fig. Code-to-code verification of postulated Be rod in MSRE pump bowl

W. Ji, H. Yang, Q. Cheng, M. H. Sahadath, S. Walker, L. Zou, T. Mui, and R. Hu, “NEUP Final Report: Material transport model development and integration in the SAM code,” Tech. Rep. 21-24078, Rensselaer Polytechnic Institute, 2024.

Integrated demonstration of ^{135}Xe reactivity in MSRE (1/3)

- **Noble gas migration demonstrated using MSRE primary loop model** with average fuel salt / graphite moderator core channel
- Noble gas system of **^{135}I (liq) and ^{135}Xe (liq/gas)** modeled, including generation, decay, burnup, and interphase transfer
- **Equilibrium distribution after 72 hours** modeled, assuming 1.0% pump stripping

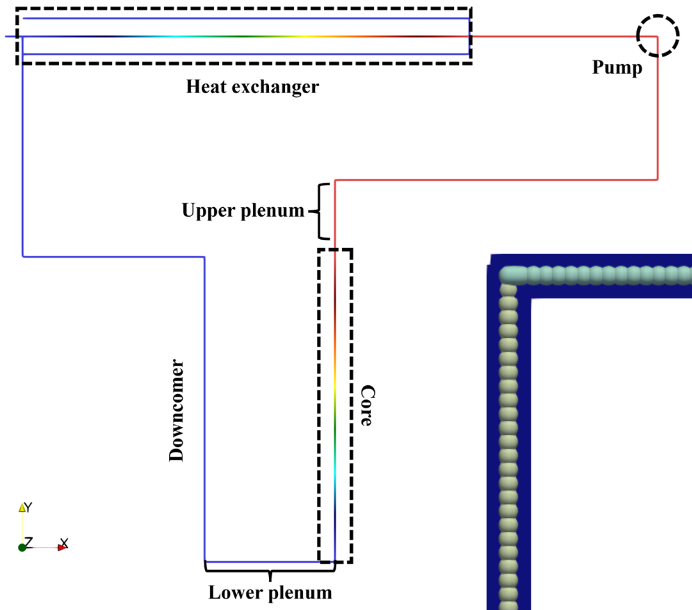
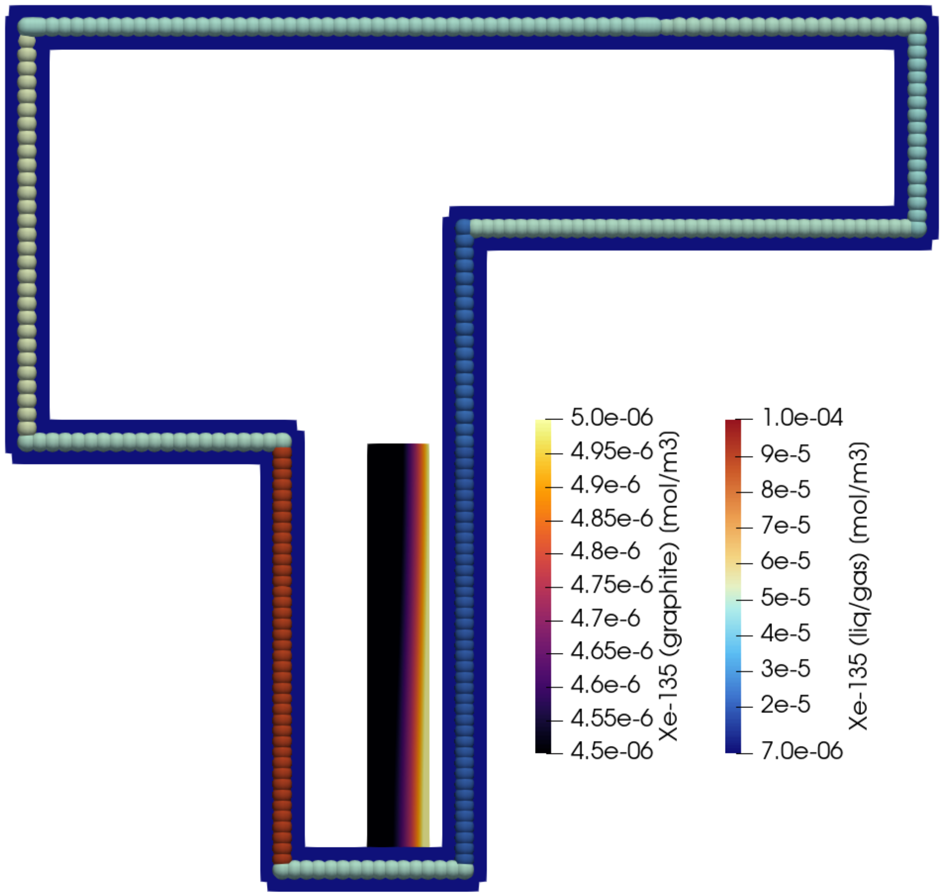


Fig. SAM MSRE model diagram (left) and ^{135}Xe distribution throughout primary fuel salt, He bubbles, and moderator graphite (below).



MSRE Core Model Parameters	Unit	Value
Total Power	MW	7.4
Total Flow	kg/s	169
Average Temperature	K	893
Average void	%	0.2
Avg. Liquid-Wall K_m	m/s	8.3×10^{-6}
Avg. Liquid-Bubble K_m	m/s	3.4×10^{-4}
Avg. Graphite Diffusivity D_{eff}	m^2/s	1.32×10^{-8}

Integrated demonstration of ^{135}Xe reactivity in MSRE (2/3)

- Due to low solubility of Xe in FLiBe, **most of the ^{135}Xe ends up in He bubbles (50%),** with accumulation in the graphite (30%) and the remainder dissolved in salt (20%)
- A **"shutdown" scenario** was modeled by dropping the power to 0 MW and reducing primary/secondary flow to 50% and observed over 40 hours.
- Primary loop reaches an equilibrium temperature, and with zero production or burnup, **^{135}I will decay to ^{135}Xe, which then decays out of the system**
- The initial pump coast down/flow reduction results in a **significant decrease in core void and ^{135}Xe bubble concentration**

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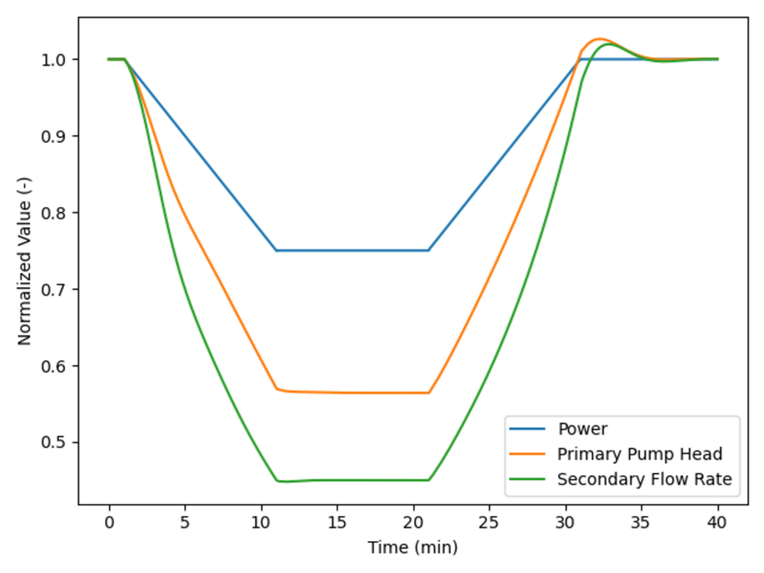
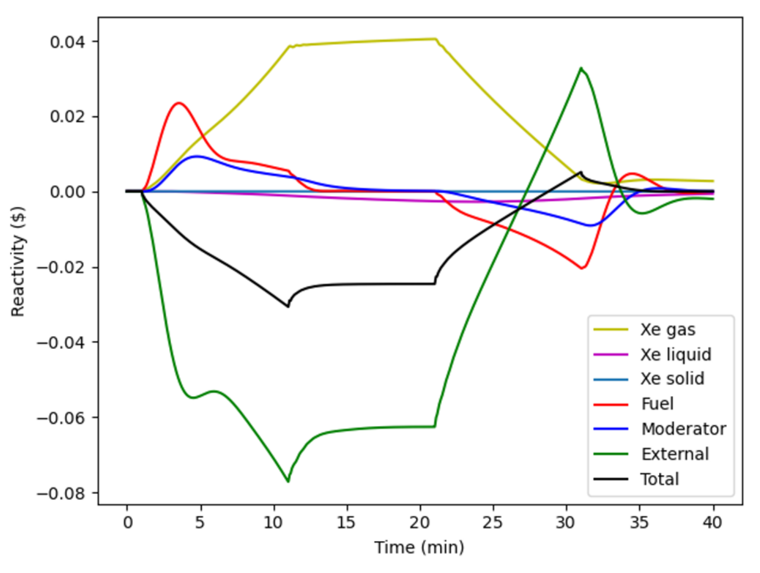
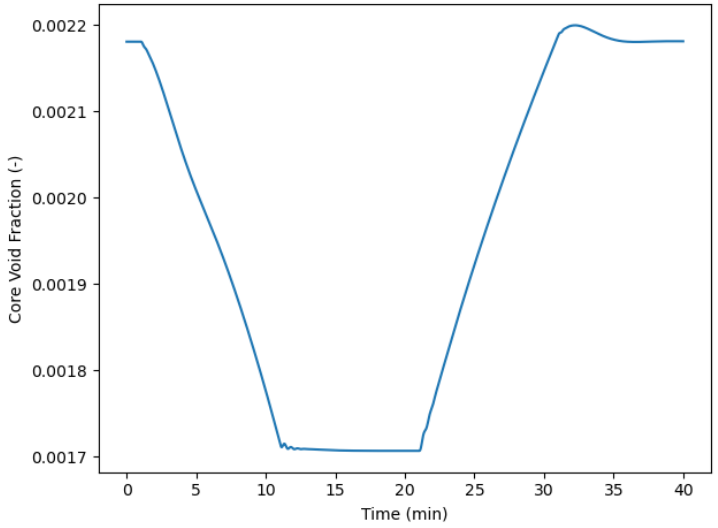
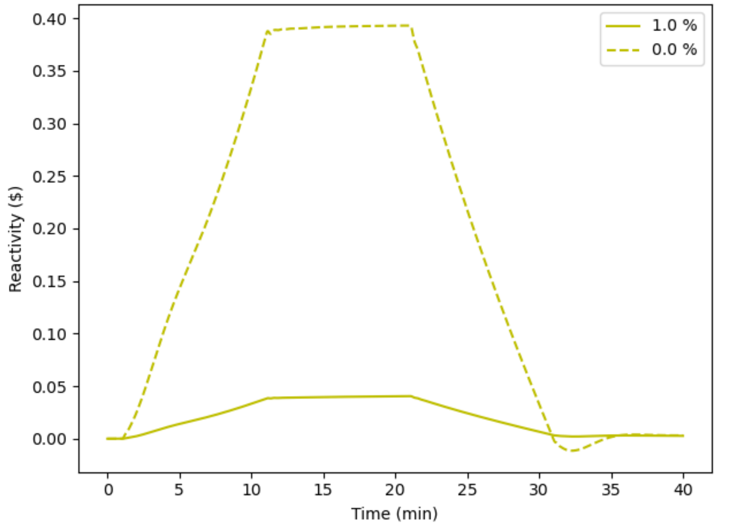
Integrated demonstration of ^{135}Xe reactivity in MSRE (3/3)

- Species (^{135}Xe) reactivity feedback demonstration with a **postulated power manipulation transient** using PKE
  - External reactivity (e.g. control rod) drops core power from 100% to target 75% for 10 mins, then returns power back to 100%
  - Control system maintains target inlet and outlet temperatures by changing primary pump head and secondary flow rate
- As observed previously, **core void is strongly impacted by flow rate**, which has a significant impact on the reactivity feedback due to ^{135}Xe concentration
- The **pump stripping efficiency** also has a significant impact on ^{135}Xe reactivity









Summary

- **Noble gas transport and reactivity model completed and demonstrated**
  - *Future work: Validation with MSRE ^{85}Kr experiment and ^{135}Xe poisoning data*
- **Improved multi-scale/phase *Sh* correlations and gas transport modeling**
  - *Next: Continuous integration of improved correlations & ML-driven methods*
- **Integrated system-level redox corrosion model**
  - *Next: Revisit modeling assumptions, i.e. global charge balance and alloy diffusion kinetics*
- **Ongoing work to expand MSR capabilities in SAM:**
  - System-level noble metal transport and heat deposition
  - User-friendly input syntax improvement for modeling complex systems of species/gas transport

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