2022 MSR Workshop

SAM FOR MSR SYSTEM ANALYSIS

RUI HU
Argonne National Laboratory

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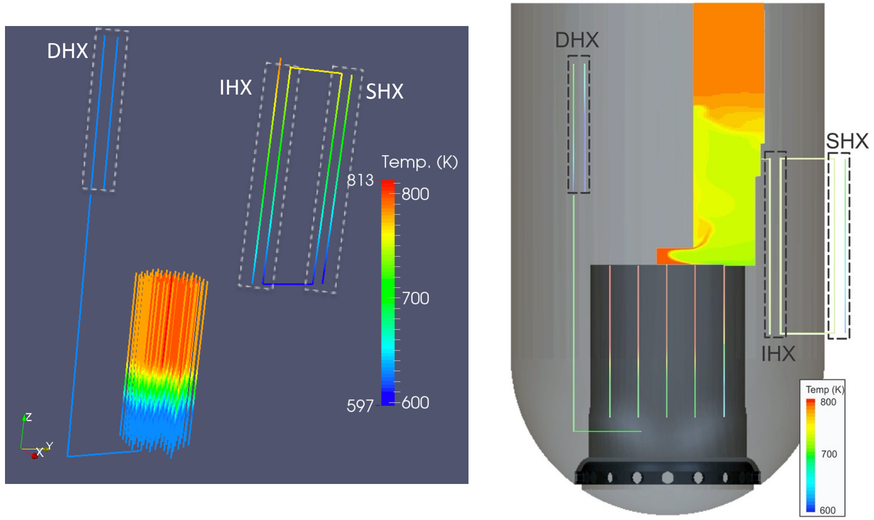
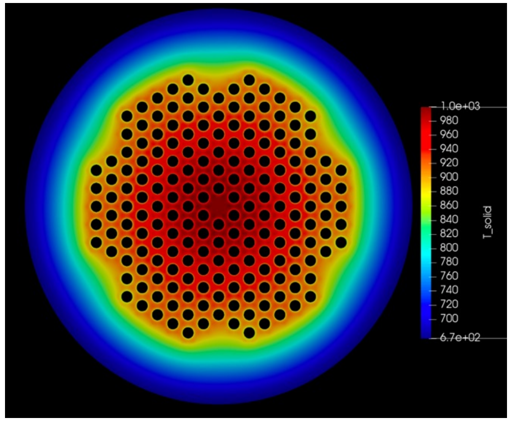
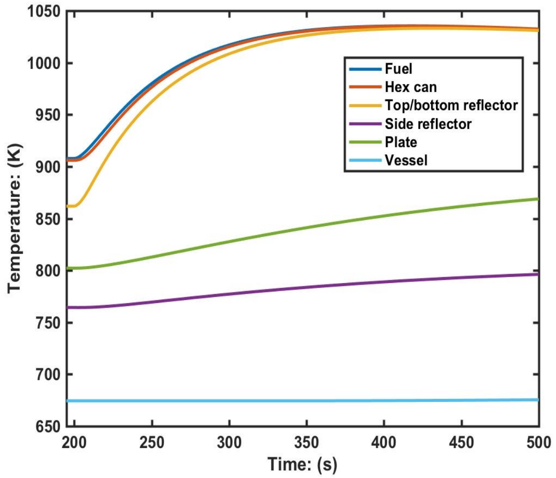
SAM OVERVIEW

- A modern system analysis code for advanced non-LWR safety analysis.
  - Cover almost all non-LWR concepts.
- Advances in software engineering, numerical methods, and physical models (built-on MOOSE framework and its libraries);
- Advancements in loop system, core, and large volume modeling;
- Flexible multi-scale multi-physics integration with other MOOSE- or non-MOOSE-based tools.
- Part of BlueCRAB for confirmatory calculations of licensing applications at USNRC.
- 2019 R&D 100 Award.



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





Transient multi-physics simulation of heat-pipe-cooled micro-reactor

What Are in Included SAM?

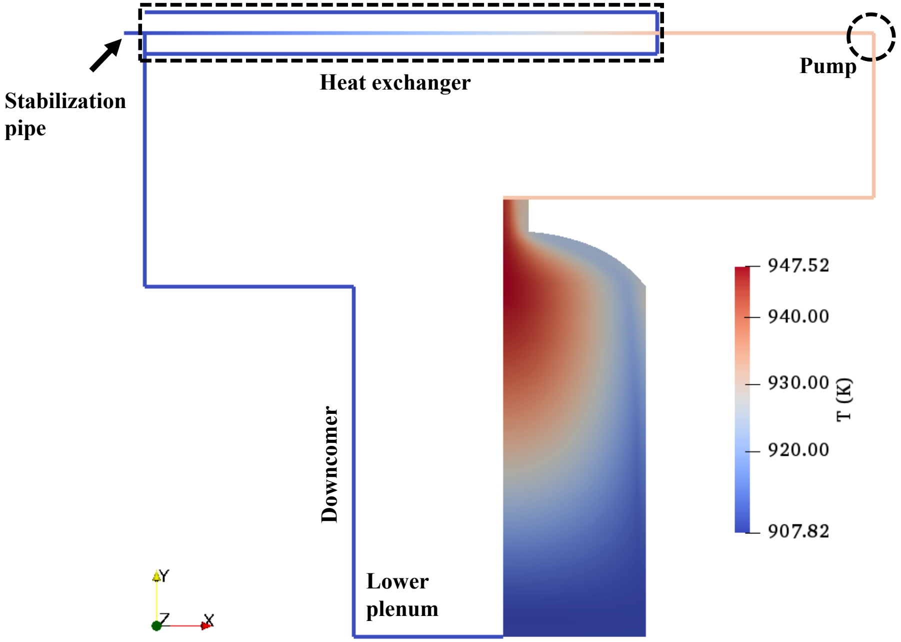
- Closely related to what it does

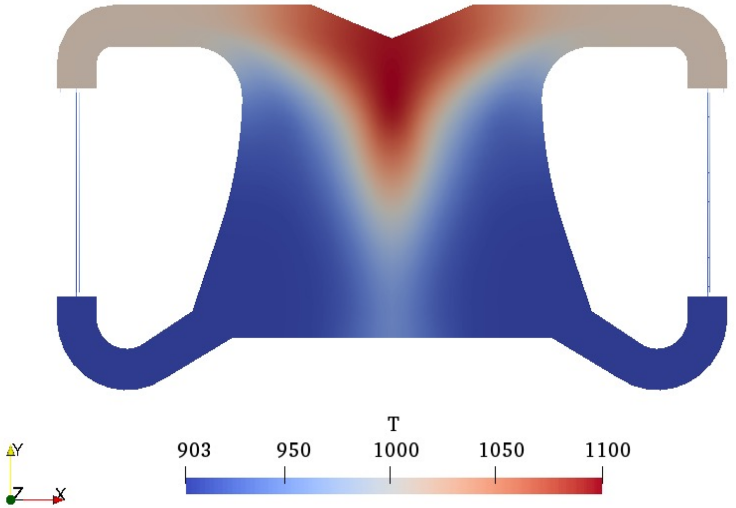
- "System computer codes must be able not only to simulate several subsystems, many components and their couplings, but also the simultaneous occurrence of various phenomena and processes." – Salomon Levy

– Flow models (single-phase, 1-D, multi-D, …)
– Heat transfer (convective, conduction, thermal radiation, …)
– Reactor kinetics (point kinetics, decay heat, reactivity feedbacks)
– Special components (pump, heat exchanger, valves, heat pipes, fluid diode, liquid volume, …)
– Special processes (mixing, thermal stratification, …)
– Special models (fluid solidification, species transport, structure expansion, …)
– Control & trip systems
– UQ integration
– Multi-scale multi-physics coupling

SAM CODE CAPABILITIES FOR MSR

- Relevant/Specific MSR capabilities:
  - Flexible input of fluid properties – include user defined ones.
  - General heat transfer correlations, applicable to molten salts, and allow user defined ones.
  - Flexible heat transfer modeling with multi-scale approach.
  - Reactor kinetics model for circulating fuel.
  - Flexible reactivity feedbacks.
  - Fission product (including delayed neutron precursor) transport models, including interaction with graphite, bubbles.
  - Tritium transport model.
  - Fluid solidification.





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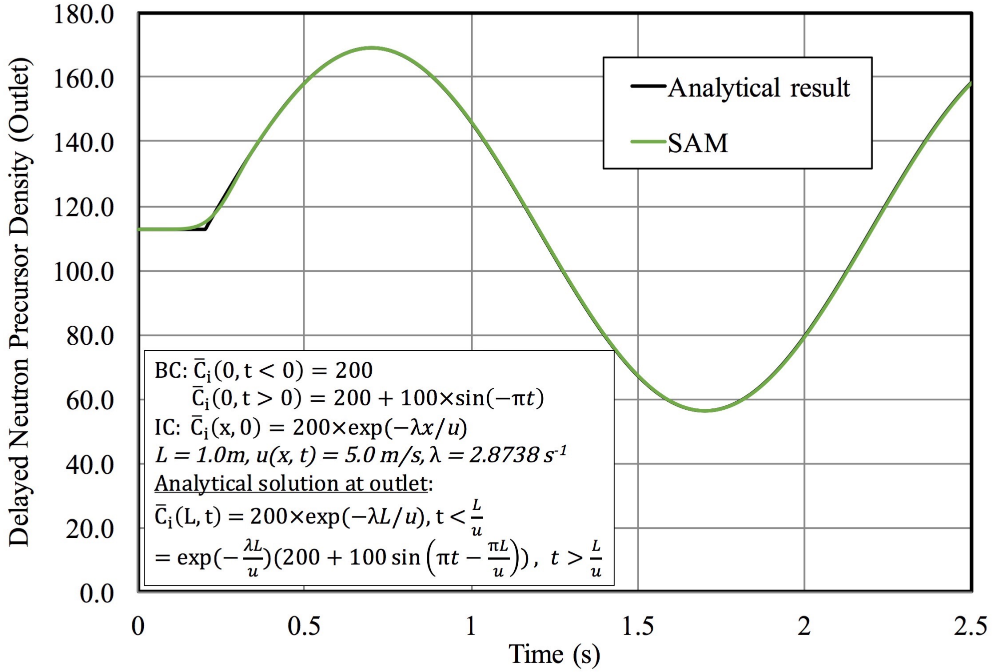
MSR TRANSIENT MODELING – SPECIES TRANSPORT

- A passive scalar particle transport model was developed to track the distributions of particles in the fluid
  - Delayed neutron precursors
  - Decay heat precursors
  - Tritium
  - Fissile fuel particles

$$\frac{\partial \rho c_i}{\partial t} + \nabla(\rho u c_i) - \nabla(D_i \nabla \rho c_i) + \lambda_i \rho c_i = S_i$$

- Species Transport in Solid
  - Diffusion,
  - trapping, detrapping in tritium transport

- Species Transport at Fluid-Solid interface
  - Convective mass transfer
  - Solubility constraints: Henry's law, Sievert's law



Delayed-Neutron Precursor Density at 1-D Pipe Outlet
(Analytical Solutions vs. SAM Simulation)

MSR TRANSIENT MODELING – REACTOR KINETICS

Point-Kinetic model with delayed neutron precursor drifting

- In addition to the regular Point-Kinetic model, delayed neutron precursor drifting in the MSR system is considered.

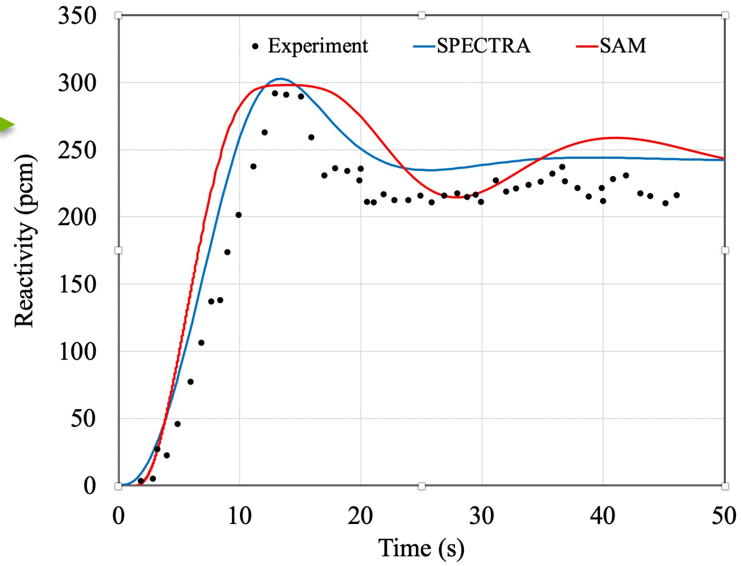
$$\frac{dn(t)}{dt} = \frac{\rho - \beta - \sum_i \left(\dot{c}_{in,i}(0) - \dot{c}_{out,i}(0)\right) \Lambda}{\Lambda} n(t) + \sum_i \lambda_i C_i$$

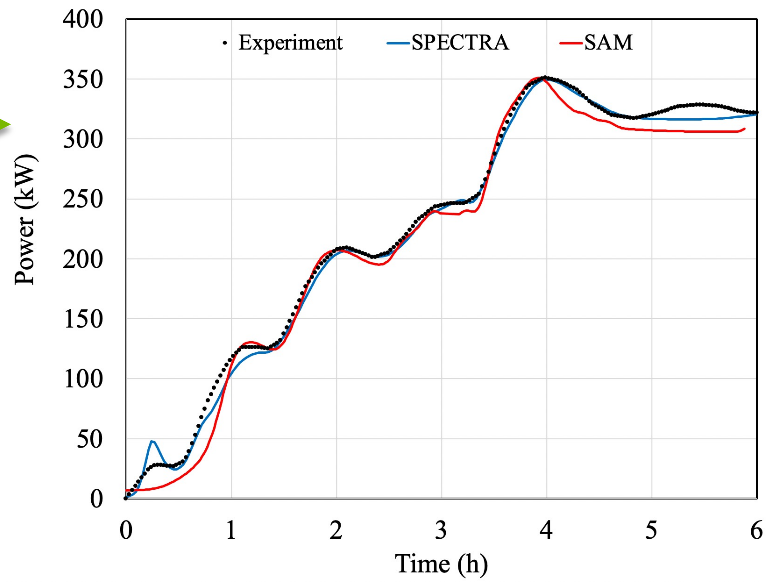
$$\frac{dC_i}{dt} = \frac{\beta_i}{\Lambda} n - \lambda_i C_i + \left(\dot{c}_{in,i} - \dot{c}_{out,i}\right)$$

- Flexible reactivity feedback modeling
  - Coolant reactivity feedback
  - Radial expansion feedback
  - Axial expansion feedback
  - Fuel Doppler feedback
  - Structure temperature reactivity feedback

MSRE TRANSIENT BENCHMARK

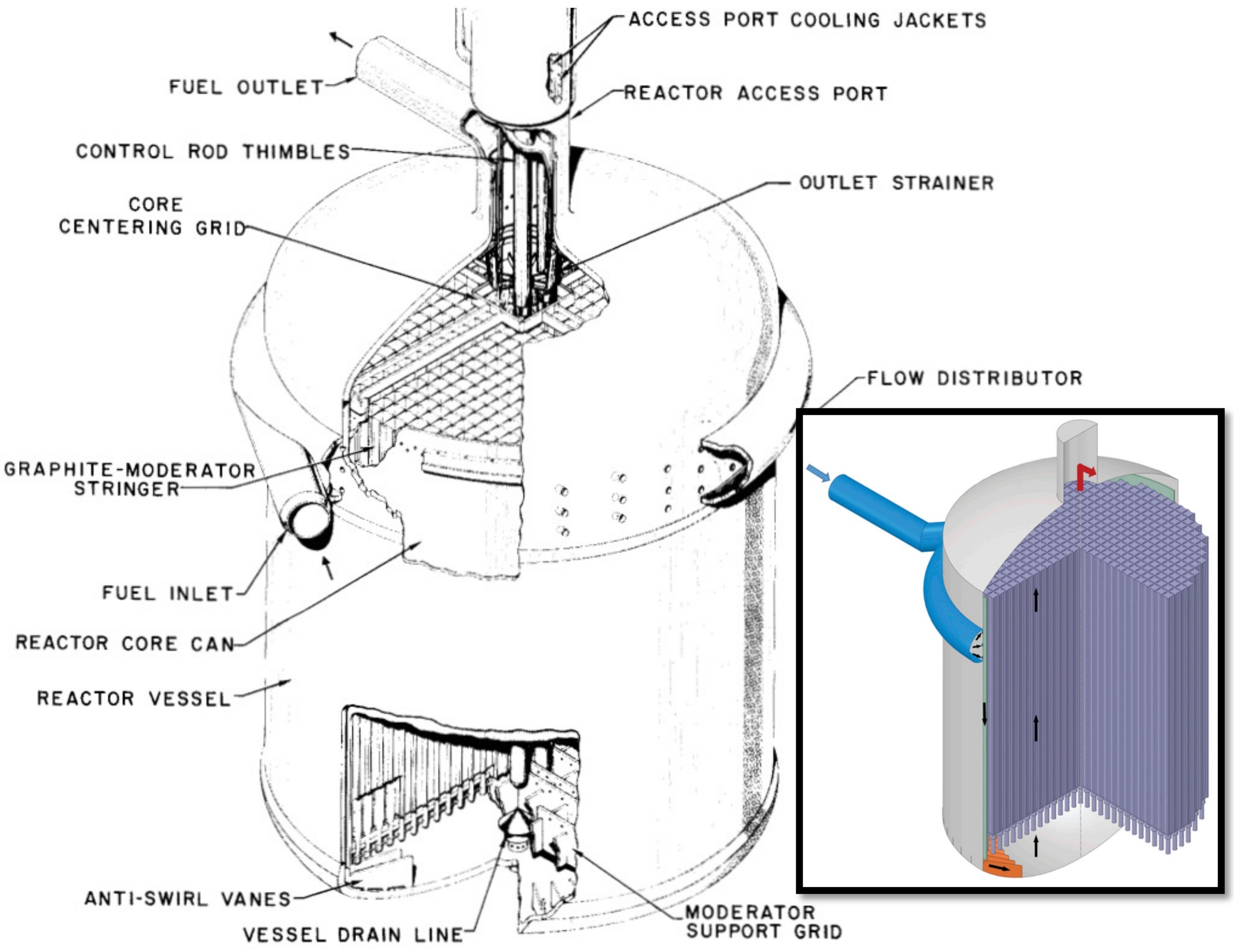
- Activity supported under NEAMS MSR Application Drivers; ORNL provided significant amounts of newly recovered MSRE data.
- Use the valuable MSRE data to enhance and validate SAM for MSR (flowing fuel salt) transient modeling and simulation
  - Pump startup tests
  - Pump shutdown tests
  - Natural convection tests
  - Reactivity insertion tests
  - *Frequency domain tests*

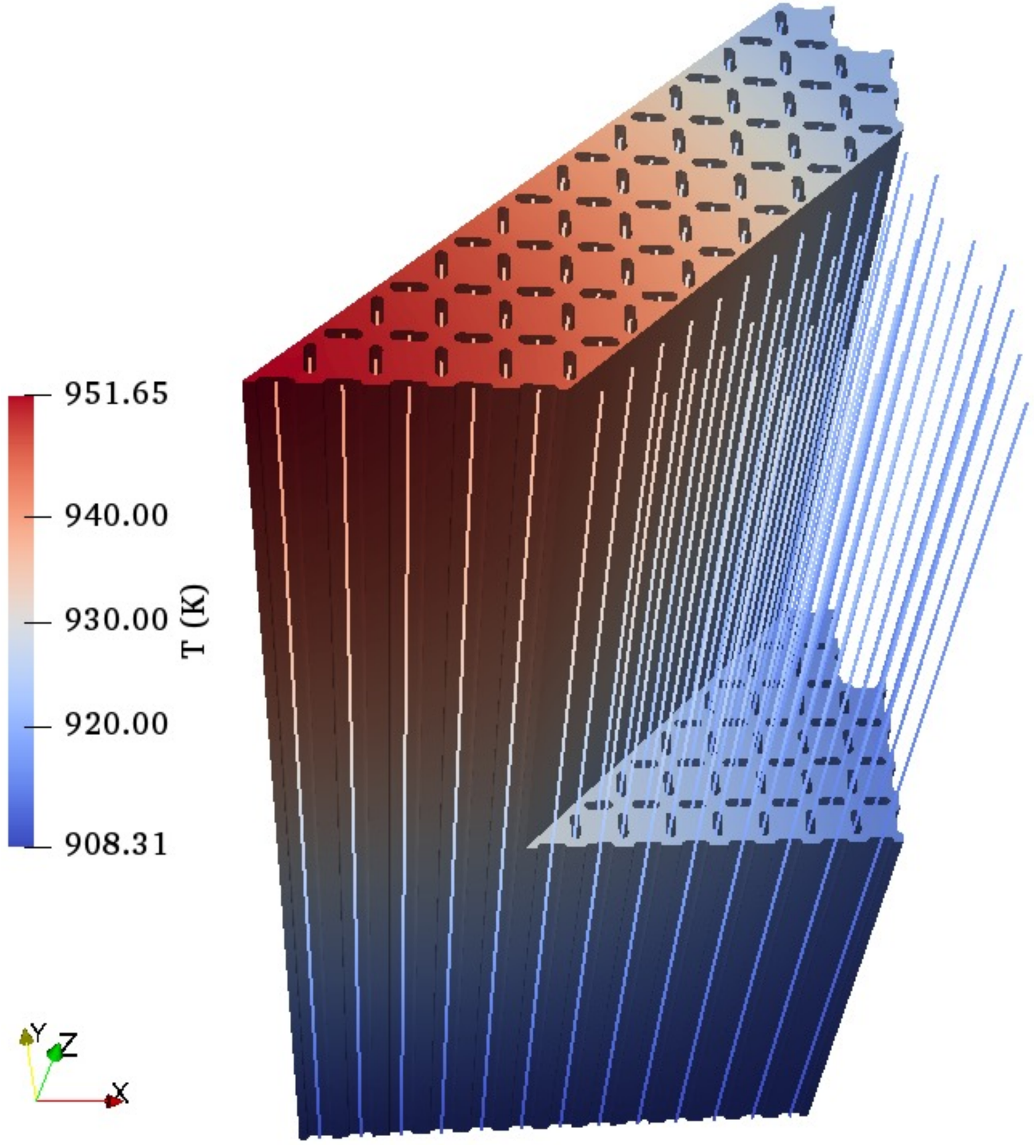




(T. Hua, T. Fei, B. Feng, R. Hu, M.M. Stempniewicz, F. Roelofs, NURETH-19, 2022.)

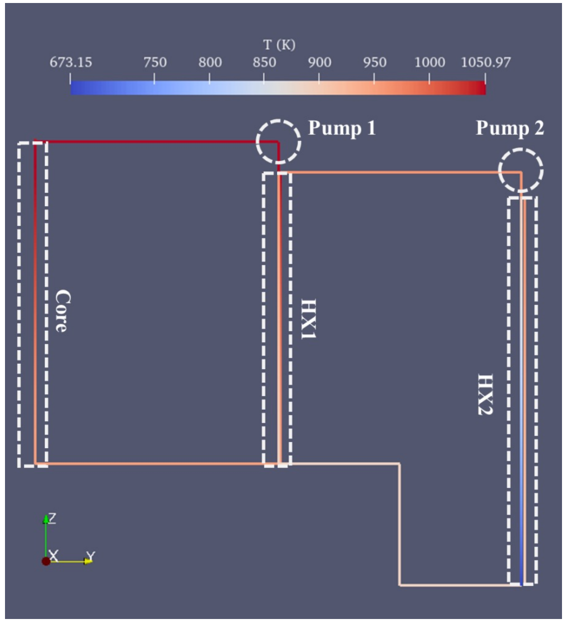
MSRE MODELING WITH COUPLED 3-D HEAT STRUCTURE AND 1-D CHANNELS



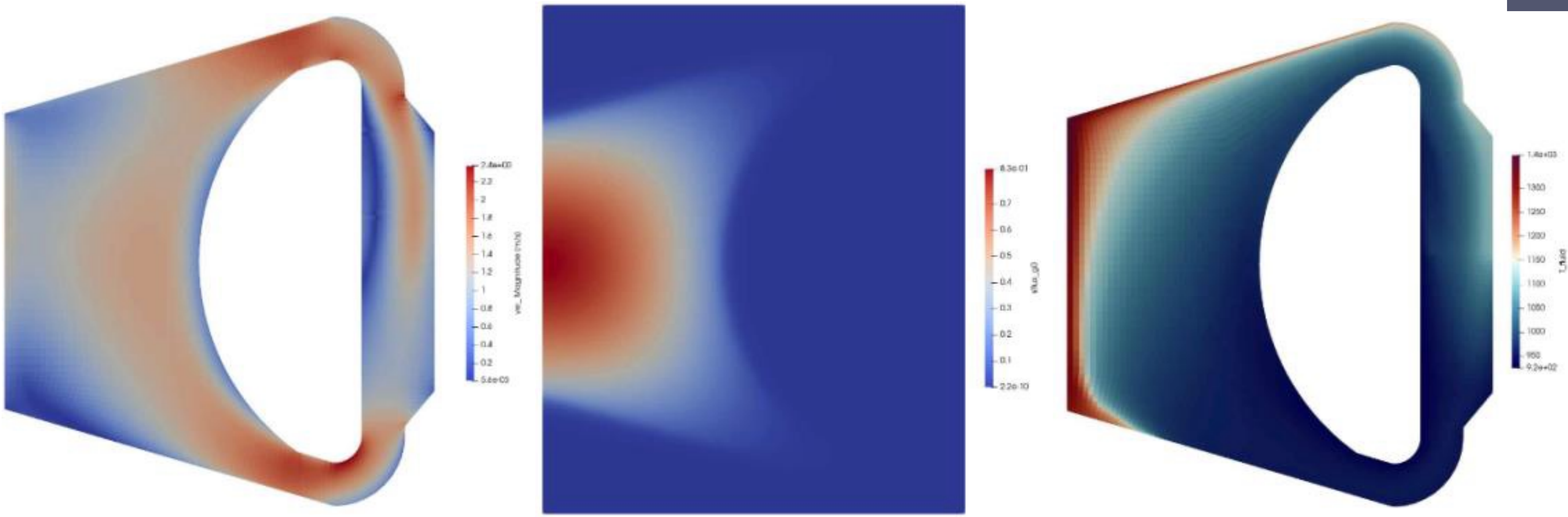


INTEGRATED MSFR DEMO

- Joint Argonne-INL efforts under NEAMS in FY22.
- Demonstration of a coupled SAM-Pronghorn-Griffin transient simulation of the MSFR
  - SAM: ex-core and the whole system; Pronghorn: core or primary loop
  - Griffin: core reactor physics
- Transient Modeled: MSFR primary loop pump coast down
  - 50% pump head drop, full pump trip



1D MSFR loop model



(R. Hu, J. Fang, D. Nunez, M. Tano, G. Giudicelli, R. Salko, ANL/NSE-22/56, 2022)

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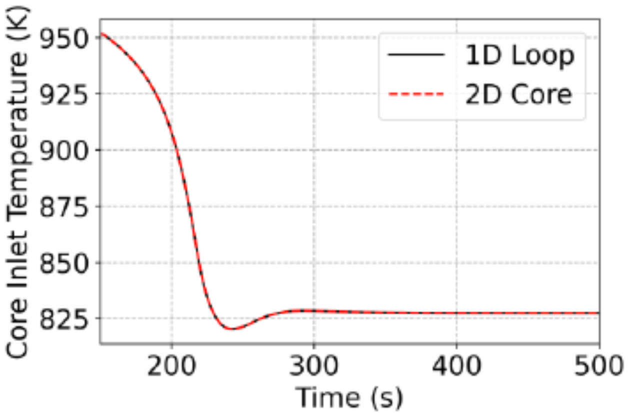
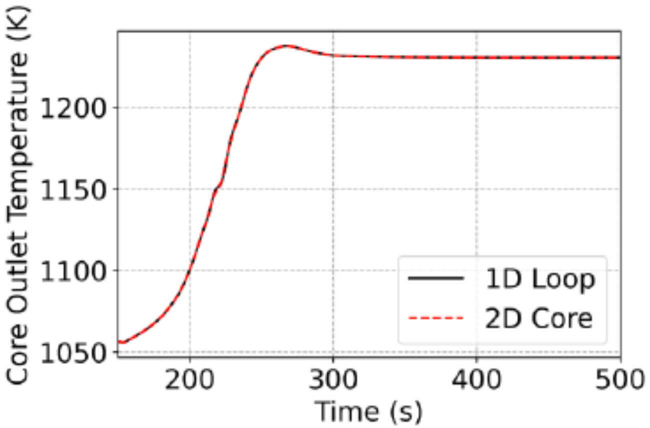
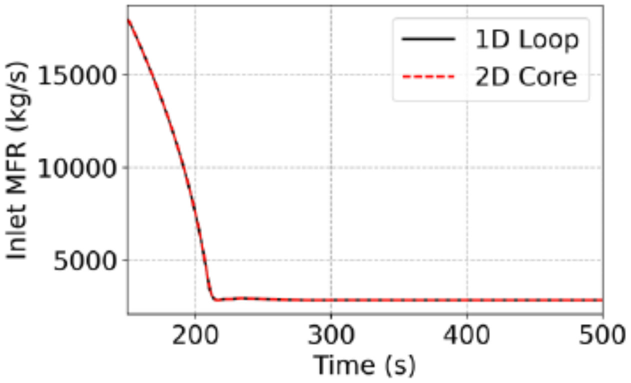
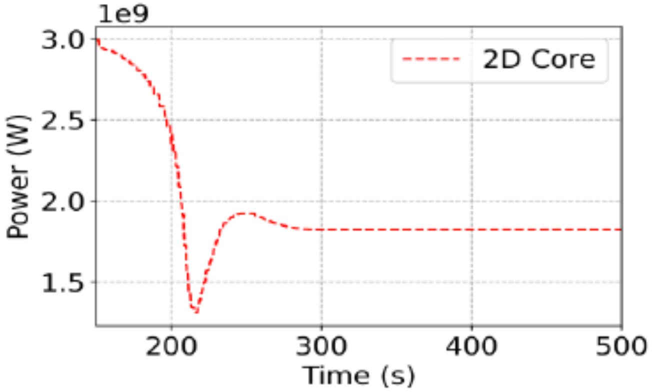
TRANSIENT SIMULATION RESULTS – PUMP TRIP

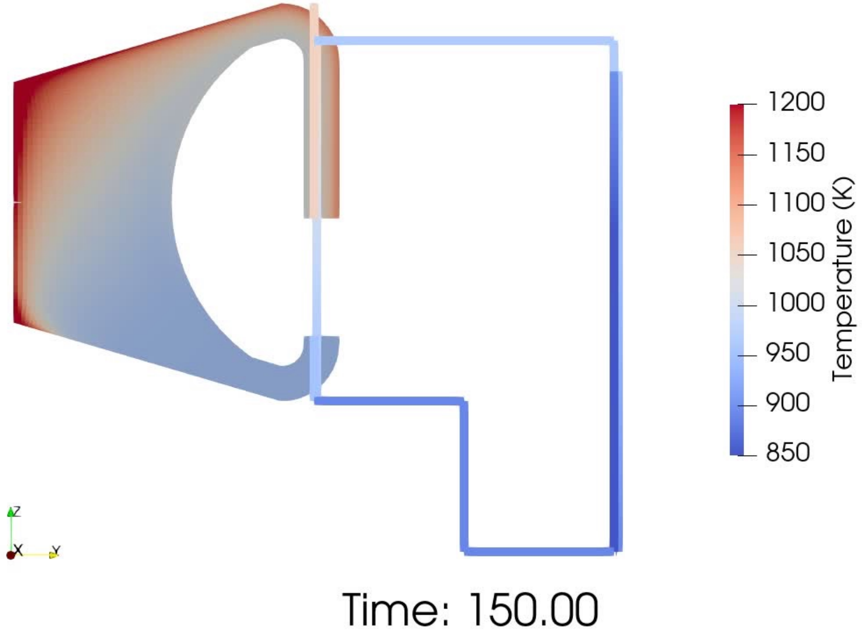
- Primary loop pump tripped, but the intermediate loop remains working.





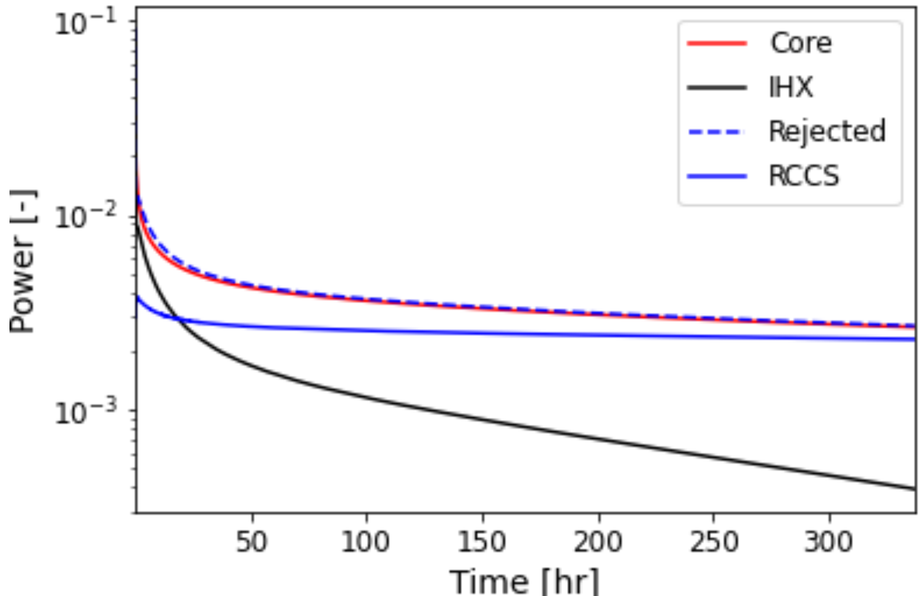


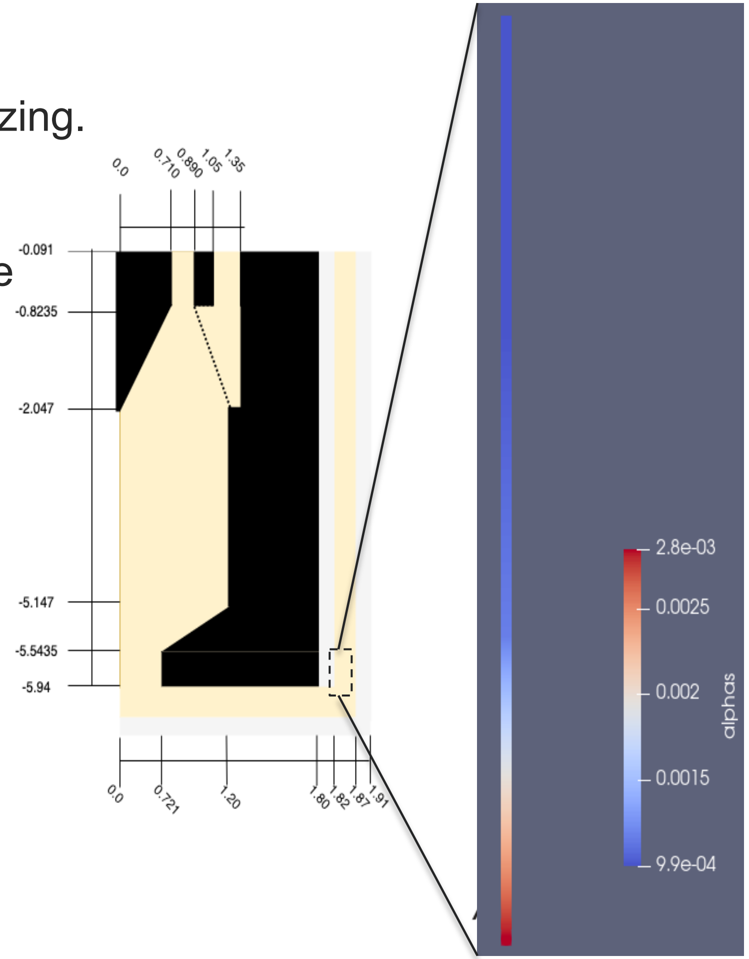




SALT FREEZING MODEL

- Salt freezing may block key flow passages during overcooling transients.
- Initial model developed by an NEUP award;
- Further development in collaboration with Kairos Power
  - Typical geometries: plate, tube, annulus
  - Liquid-phase equations consider area varying effect
  - Solid-phase equations consider heat and mass balances associated with salt freezing.
- PBFHR overcooling simulation
  - PCP is lost, IHX remains operating, reactor protection system shuts down the core
  - System operates for ~14 days under natural circulation

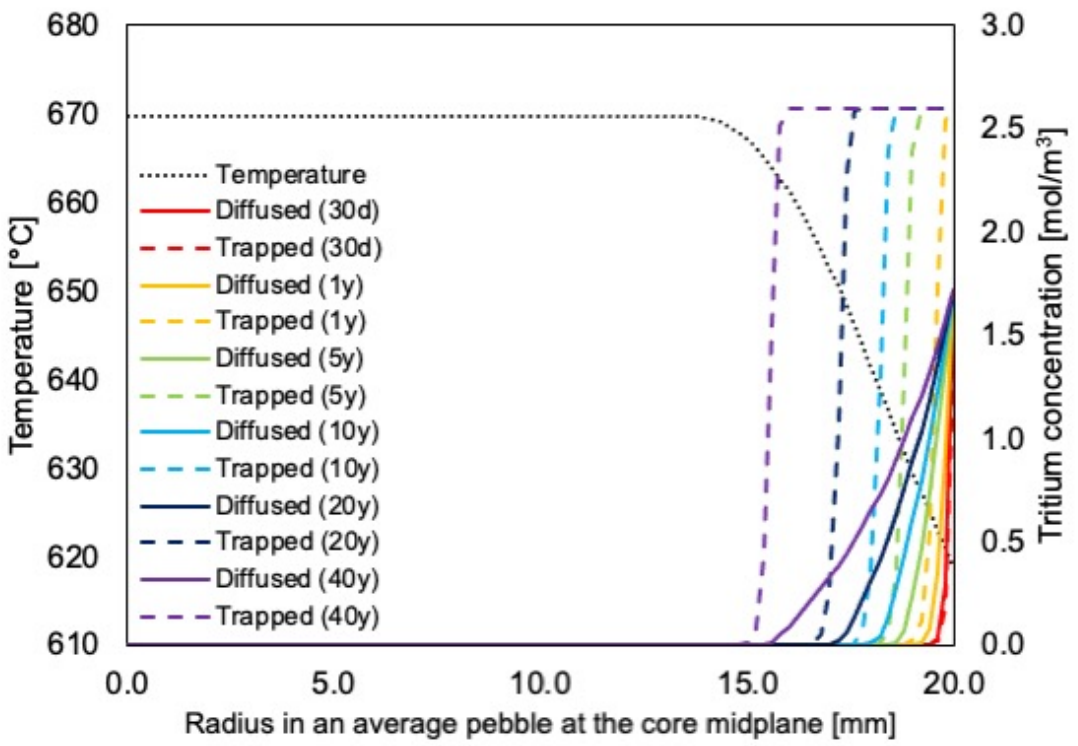




TRITIUM TRANSPORT MODEL

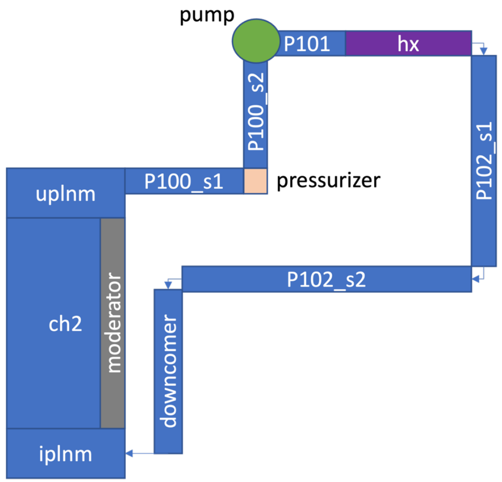
- System-level source term modeling is needed to capture a range of tritium transport phenomena:
  - Species generation and transport in fluid system
  - Uptake in graphite fuel pebbles and reflector
  - Permeation through pipe and vessel walls
- Species transport capability tightly coupled with thermal hydraulics:
  - Passive transport in 1D fluid components
  - Migration to fluid-solid interface via convection
  - Bulk diffusion through 2D solid components
  - Trapping & de-trapping within solid
  - Power-dependent generation rate in core
  - Models to capture evolution to cover gas
- Validation using Causey (1968) experiment

Tritium build-up in a reference FHR

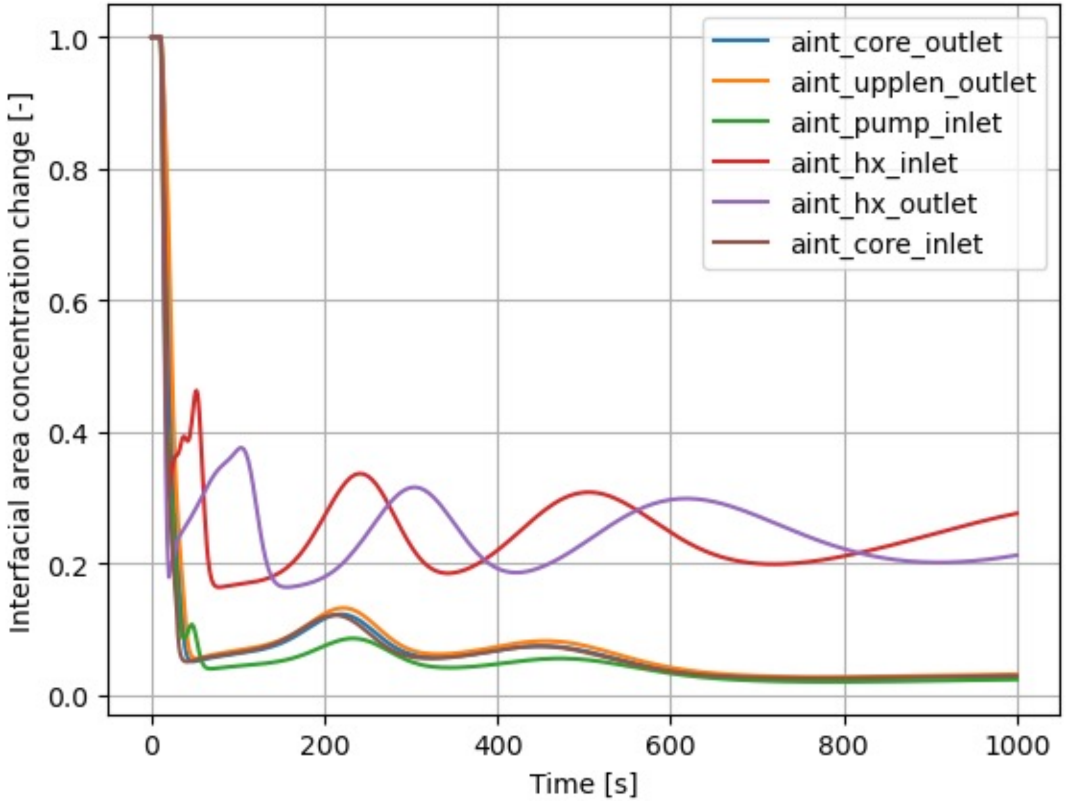


(Acknowledgements: Kairos iFOA support)

GAS TRANSPORT MODEL



- Implementation of gas transport model into SAM
  - Focusing on bubble advection
- Includes modeling of drift velocity, calculation of volume fraction, bubble radius, and interfacial area
- Testing for unit verification and simple loop problems
- MSRE primary loop demonstration simulations
- Validation with Chavez (2021) experiment.



(Acknowledgements: R. Salko, ORNL)

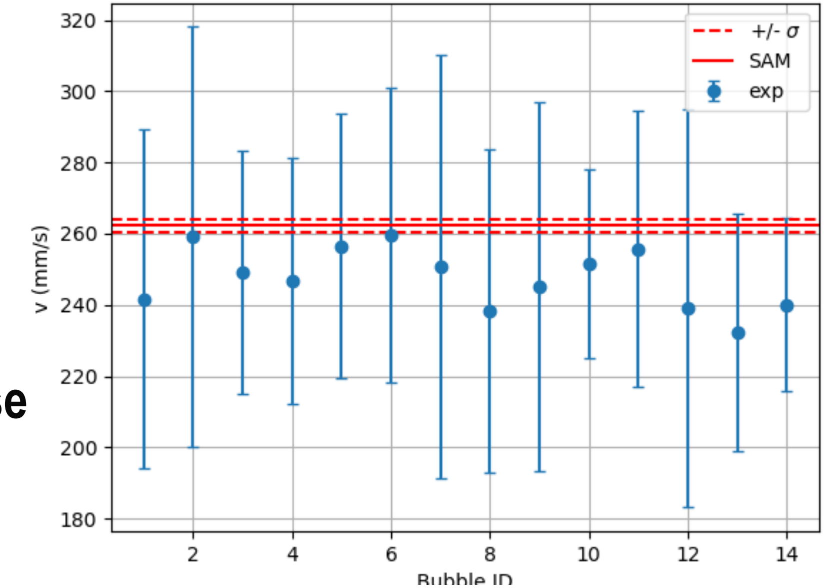
(R. Hu, J. Fang, D. Nunez, M. Tano, G. Giudicelli, R. Salko, ANL/NSE-22/56, 2022)

GAS MODEL VALIDATION

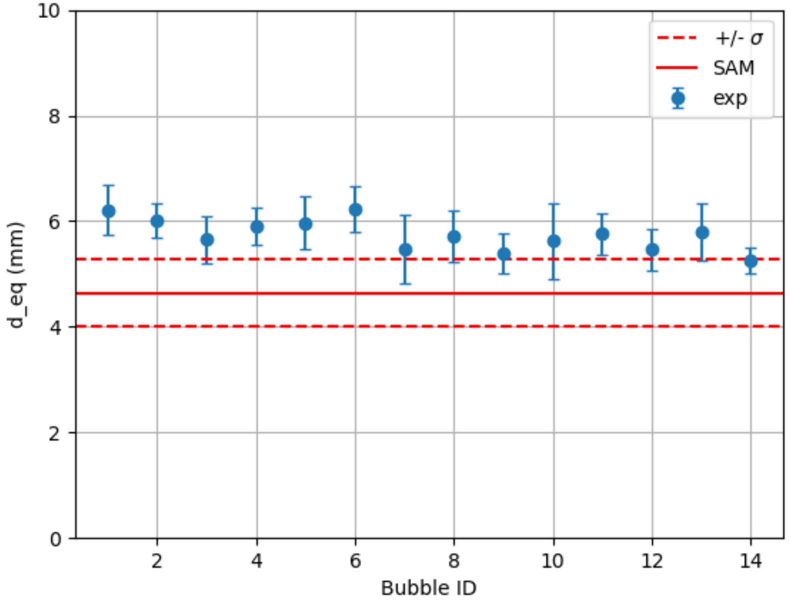
Denise E. Chavez, Se Ro Yang, Rodolfo Vaghetto, and Yassin Hassan. Experimental investigation of single helium bubbles rising in flinak molten salt. *International Journal of Heat and Fluid Flow*, 92, 2021. doi: 10.1016/j.ijheatfluidflow.2021.108875.

- Chavez tests measure helium bubbles rising in stagnant molten salt
- Dakota used to propagate measurement and fluid property uncertainty in SAM
- Overprediction of diameter likely related to wall effects in facility

Bubble rise velocity



Bubble diameter



(R. Hu, J. Fang, D. Nunez, M. Tano, G. Giudicelli, R. Salko, ANL/NSE-22/56, 2022)

CONCLUSION REMARKS

- SAM is a modern system-level analysis code for advanced non-LWR safety analysis, utilizing modern programming architecture, advanced numerical methods, and improved physical models.
- Complex and integrated code built upon simplest models aiming for simulating whole system behavior under simultaneous occurrence of various phenomena and processes.
- Preliminary MSR modeling capabilities assessed with code validations and demonstrations
  - System thermal fluids + PKE, including salt freezing
  - Species transport model, DNP, tritium, bubble transport

- Ongoing work
  - Continued physical model developments and usability improvements
    - RPI NEUP on mass transport; interface Saline for MSTDB-TB;
  - Continued V&V efforts, benchmark with MSRE and other IET tests
    - MSTTE at INL
  - Multi-scale multi-physics simulation of reference advanced reactor designs
    - Integrated simulations, as necessary, with Griffin, Mole, Nek/Pronghorn, Thermochimical, MSTDB

ACKNOWLEDGEMENTS

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INL: M. Tano, G. Giudicelli
ORNL: R. Salko
Kairos: Q. Zhou
NRG: M. Stempniewicz

THANK YOU!

QUESTIONS?

Presenter email:
rhu@anl.gov

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