Multiphysics Analyses of MSR Transients and Validation Using MSRE

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NEAMS MSR Applications Team

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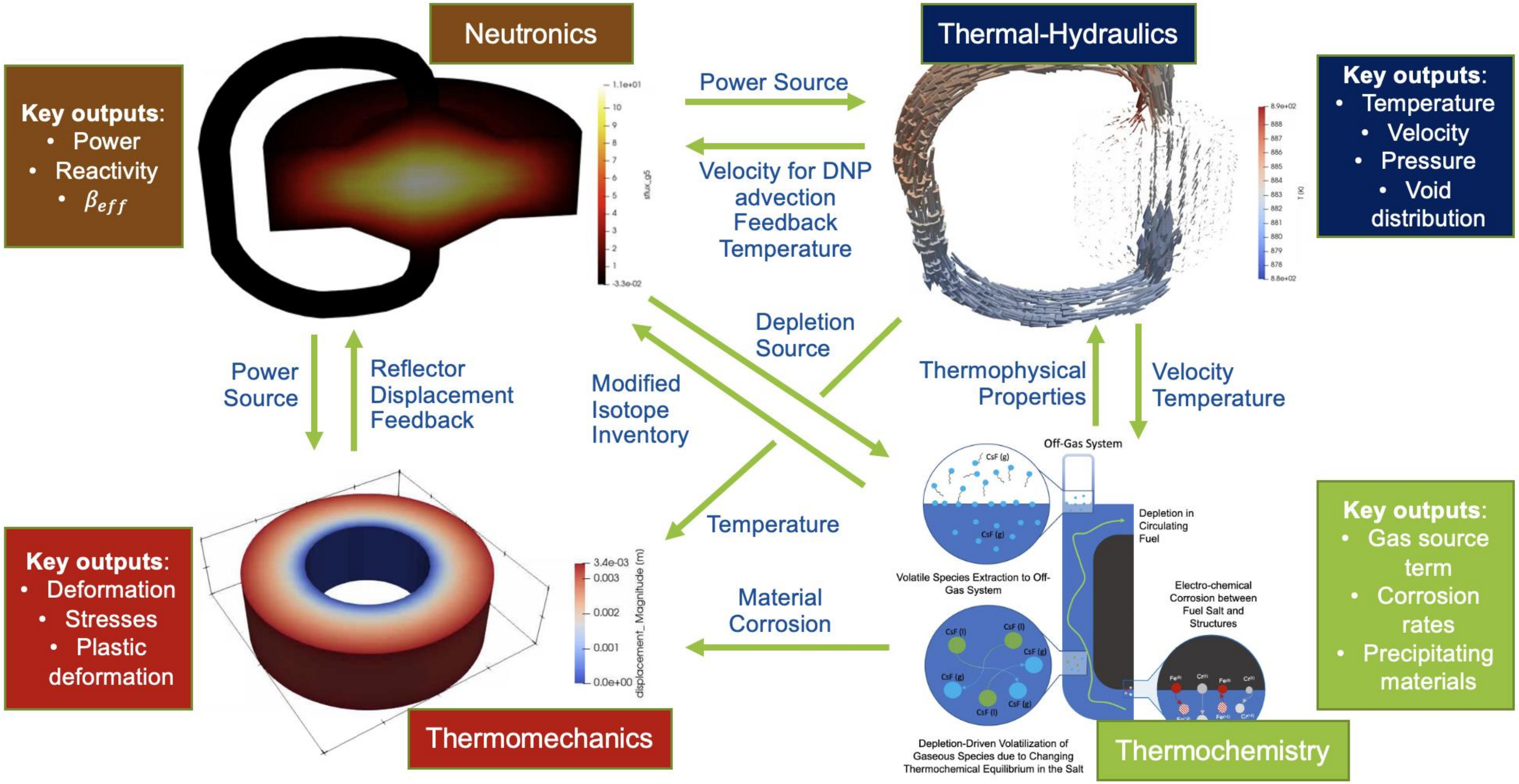
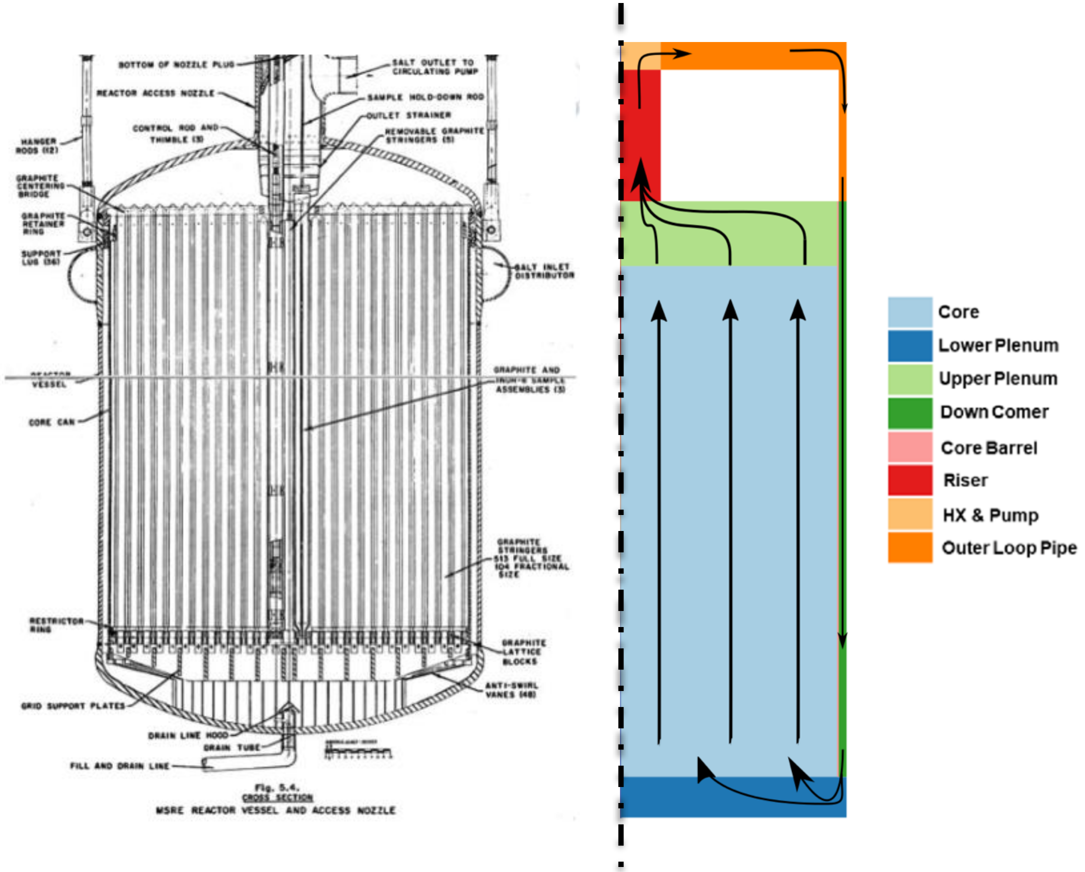
Why Multiphysics for MSRs?

- **Physics Coupling**: Multiphysics modeling captures the interactions between thermal, fluid, and neutron behavior in MSRs, which are needed for accurate simulations.
- **Enhanced Safety Analysis**: Multiphysics modeling helps in assessing safety scenarios by simulating the coupled effects of different physical processes, such as thermal expansion, fluid dynamics, and chemical reactions.
- **Design Optimization**: Multiphysics modeling enables optimization of reactor design and operation by providing detailed insights into the behavior of the reactor under various conditions.
- **Predictive Capability**: Multiphysics modeling enhances predictive capabilities for reactor performance and potential failure modes, improving reliability and efficiency.
- **Regulatory Compliance**: Multiphysics modeling can assist in meeting regulatory requirements by providing comprehensive data and validated models for safety and performance evaluations.

MSR Multiphysics



Multiphysics Validation for MSRE



MSRE core (left) [Robertson, 1965] and 2-D R-Z model (right)

Isotope	^{235}U Fuel Loading	^{233}U Fuel Loading
Li-7	2.634E-01	2.618E-01
F-19	5.948E-01	5.936E-01
Be-9	1.179E-01	1.229E-01
U-233	–	4.977E-04
U-234	–	3.118E-05
U-235	1.203E-03	3.778E-06
U-238	2.443E-03	1.069E-06
Zr-90	1.042E-02	1.085E-02
Zr-91	2.273E-03	2.366E-03
Zr-92	3.474E-03	3.616E-03
Zr-94	3.521E-03	3.665E-03
Zr-96	5.673E-04	5.904E-04

Relative isotopic atomic fractions during the ^{233}U and ^{235}U loads of MSRE

Parameter [Units]	Fuel Salt	Graphite
Density [kg/m^3]	2,263 – 0.478 (T[K] – 923.0)	1,860.0
Thermal Conductivity [W/(m.K)]	1.4	40.1
Specific Heat [J/(kg.K)]	1868.0	1757.3
Dynamic Viscosity [Pa.s]	0.008268	-

Thermophysical properties of the fuel salt and the moderator

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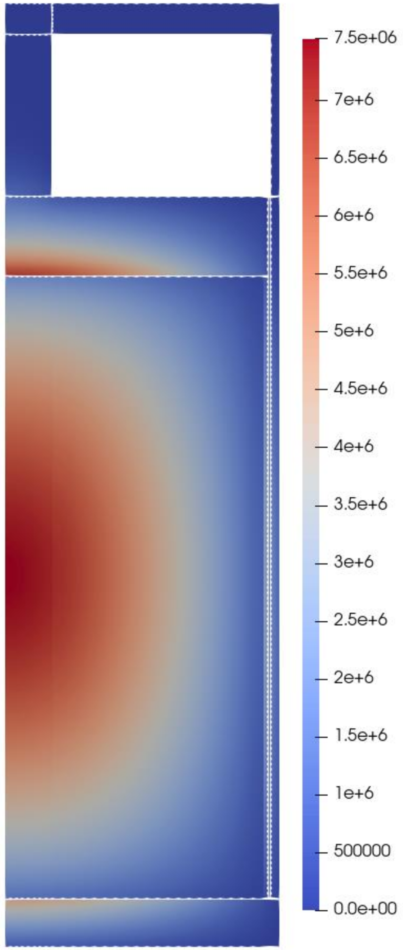
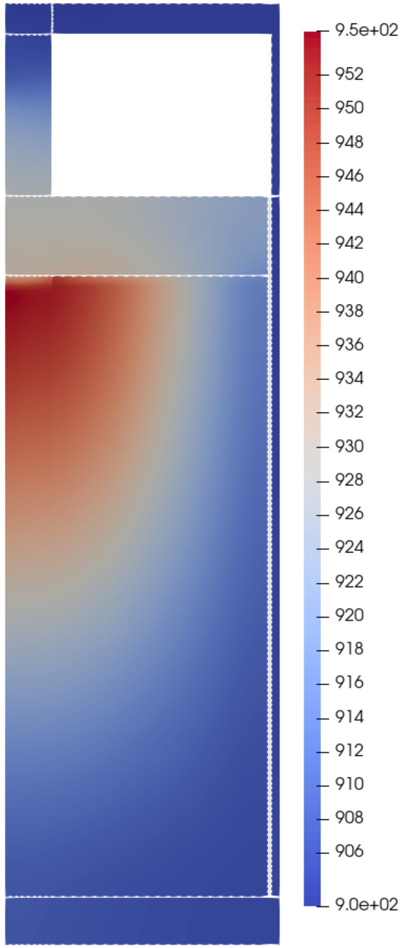
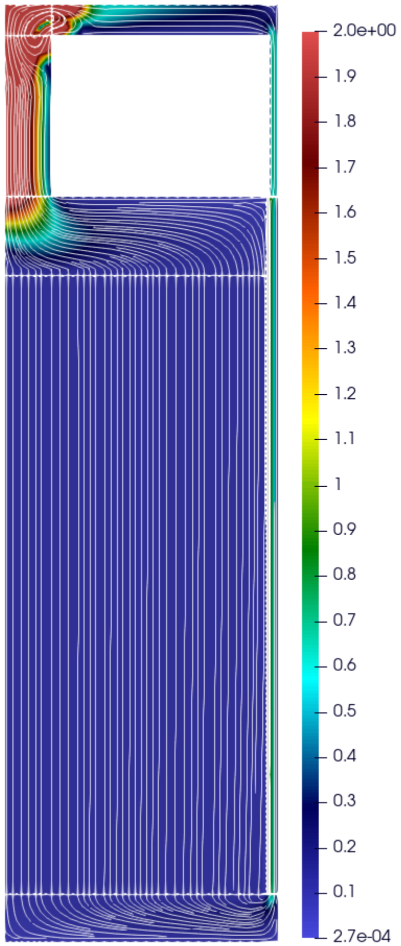
Steady-State Fields



Power density [W/m3]



Temperature [K]



Salt Velocity [m/s]

Takeaway: reasonable fields obtained for steady-state operation in Griffin-Pronghorn MSRE model

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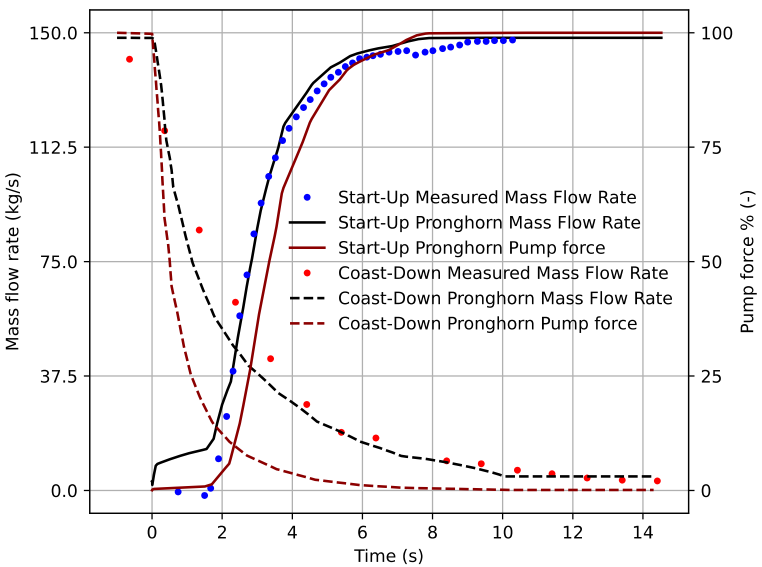
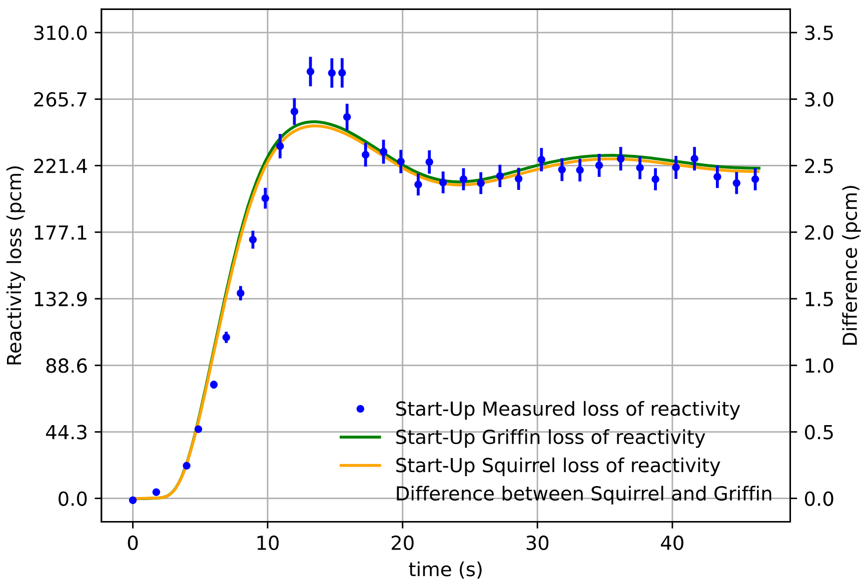
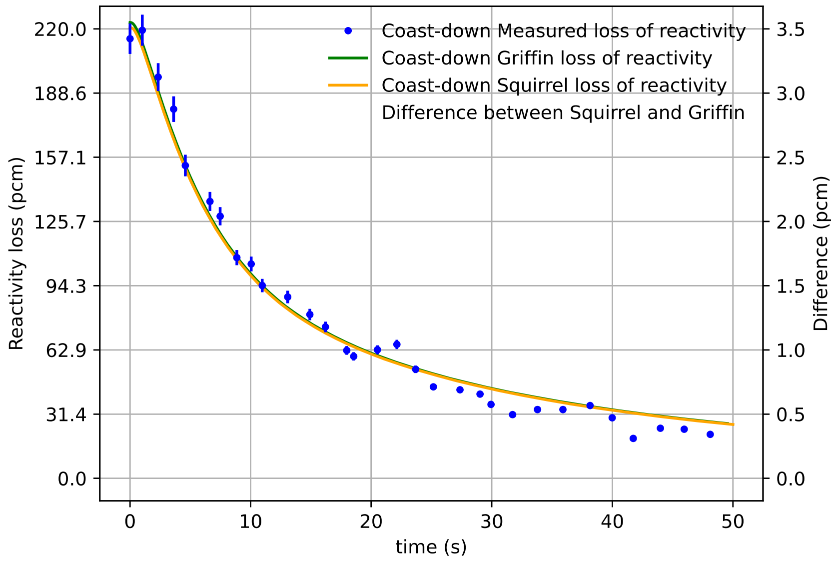
Pump Startup and Coast-Down Transients



Mass flow rate comparison during pump startup and coast-down [Prince et al., 1968]



Comparison of **reactivity loss** during pump **start-up** transient [Prince et al., 1968]



Comparison of **reactivity loss** during pump **coast-down** transient [Prince et al., 1968]

Takeaway: Griffin-Pronghorn MSRE multiphysics model validated for transient flow rate and zero-power pump start-up and shutdown

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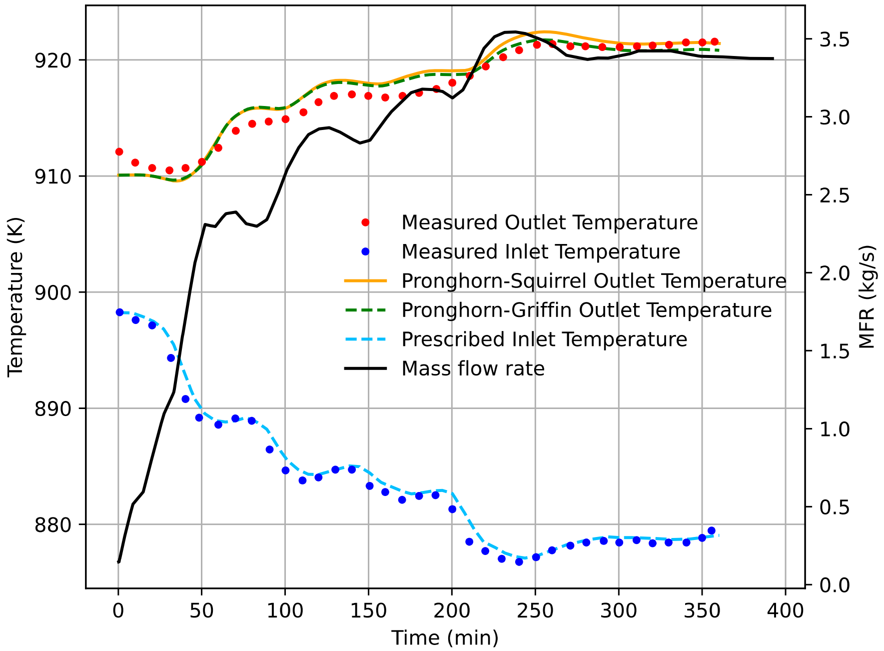
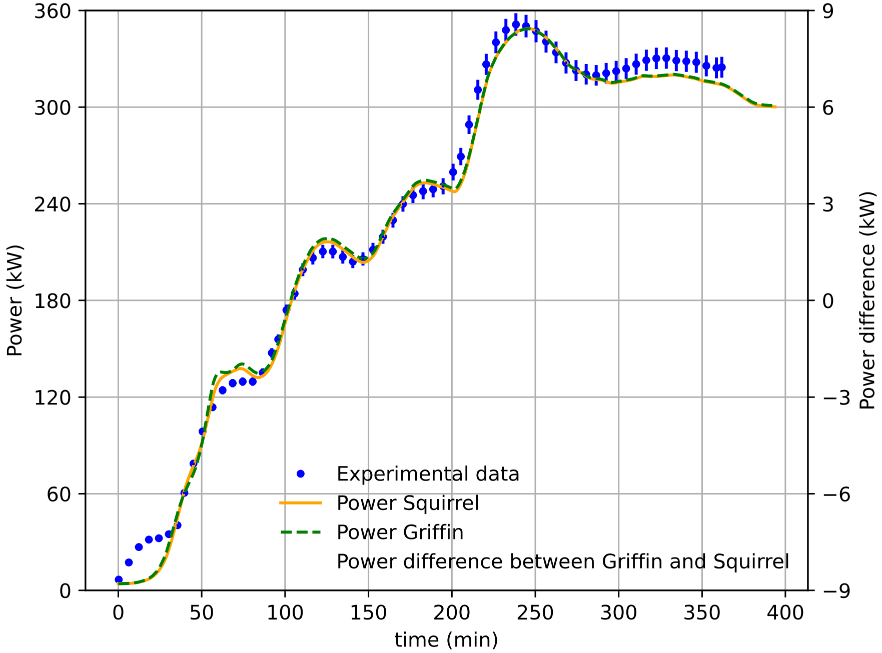
Natural Convection Transient



Mass flow rate and **temperature** evolution during the natural circulation test [Prince et al., 1968]



Reactor **power** evolution during the natural circulation test [Prince et al., 1968]

Takeaway: Griffin-Pronghorn MSRE multiphysics model validated for temperature and power evolution in transition to natural convection transient

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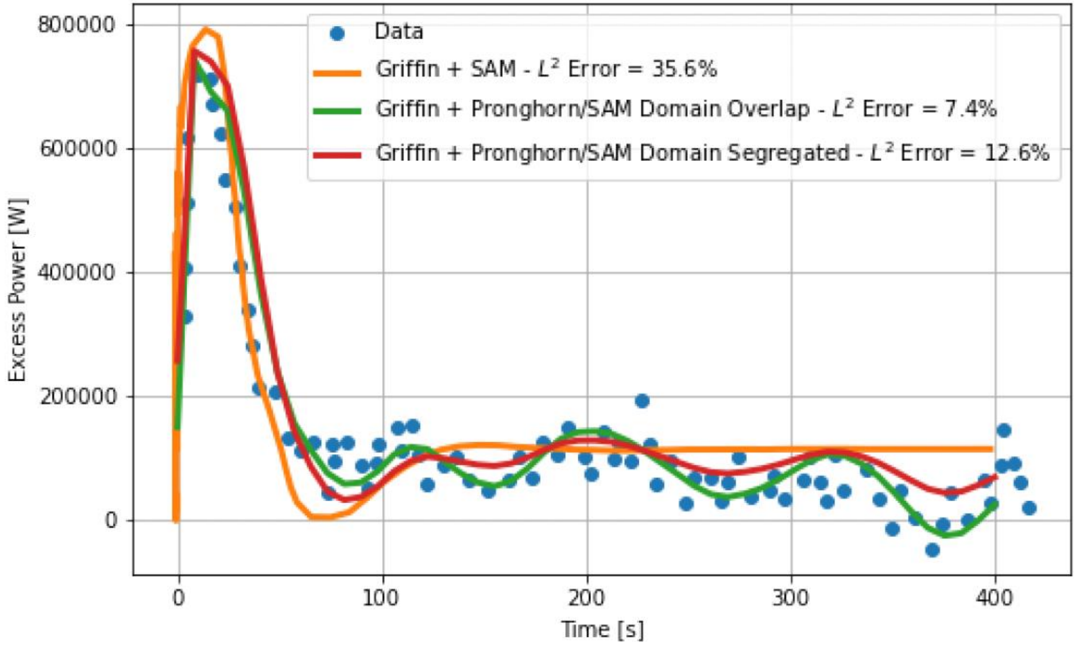
Reactivity Insertion Transient



Reactivity Insertion Transient at 5MW of thermal power

- A key limitation is the 1D to multiD boundary condition in Pronghorn, which requires careful selection to avoid boundary effects.
- The transient model has been validated for reactivity insertion transients, showing improved performance with Pronghorn's higher fidelity and lower numerical diffusivity

Takeaway: Griffin-Pronghorn-SAM MSRE multiphysics model validated for reactivity insertion transient at 5MW

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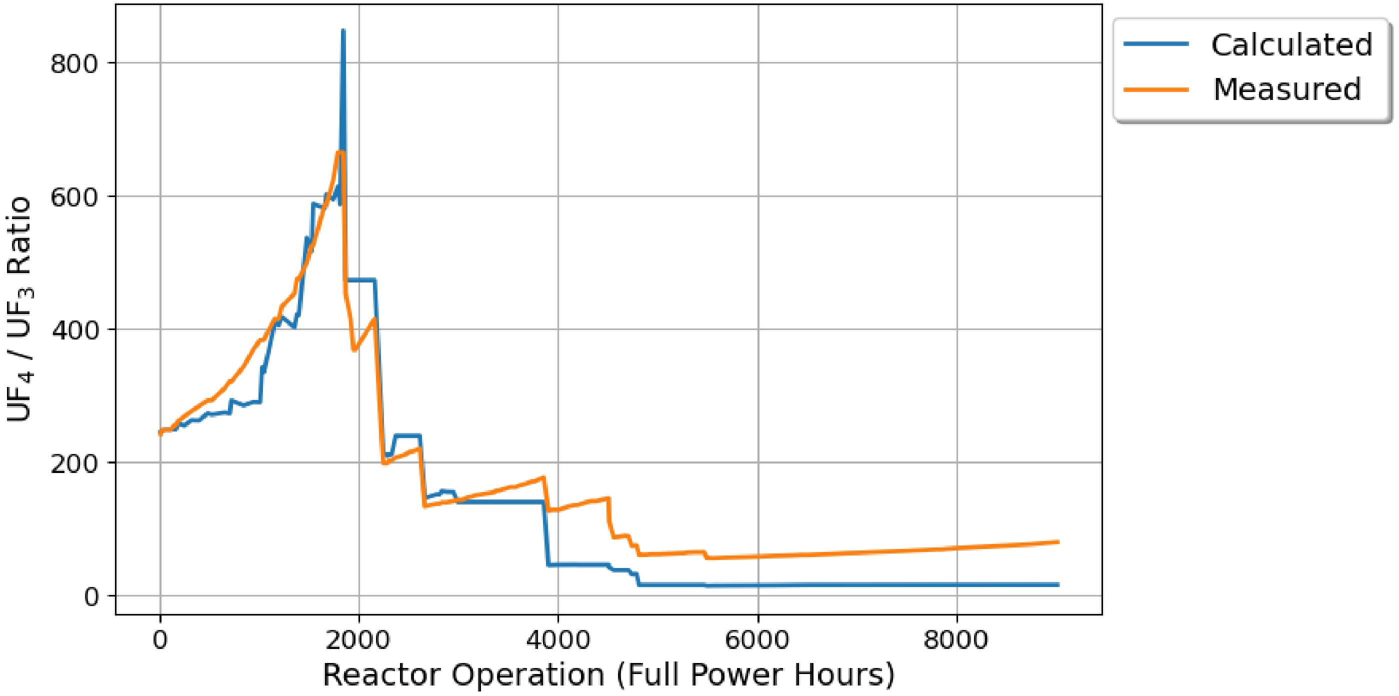
Redox Potential Evolution



UF_4 to UF_3 ratio in the MSRE during ^{235}U runs for fuel-salt depletion and reducing material additions, measurements from Thoma (1971) report

- The redox potential of the MSRE fuel salt was monitored by measuring the UF3 percentage relative to total UF(x) during ^{235}U runs, initially at ~0.41% and increasing to a maximum of ~1.74% with reducing metal additions.
- Without active chemistry control, UF_3 naturally converts to UF_4 due to depletion-driven oxidation, decreasing UF_3 levels as noble fission products fail to replace cationic charge.
- The Griffin-depletion model captures the thermochemistry changes well, though it shows bias in the latter reactor operation stages due to over-reduction from incorrect beryllium additions.

Takeaway: Griffin-Pronghorn-Thermochimica MSRE multiphysics model partially validated for redox potential evolution

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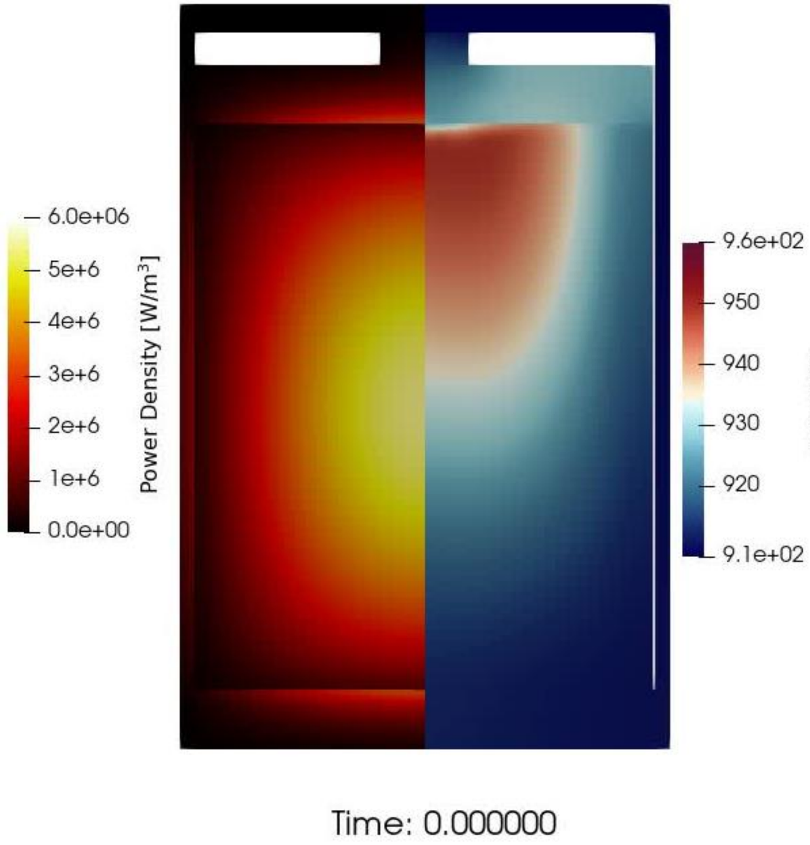
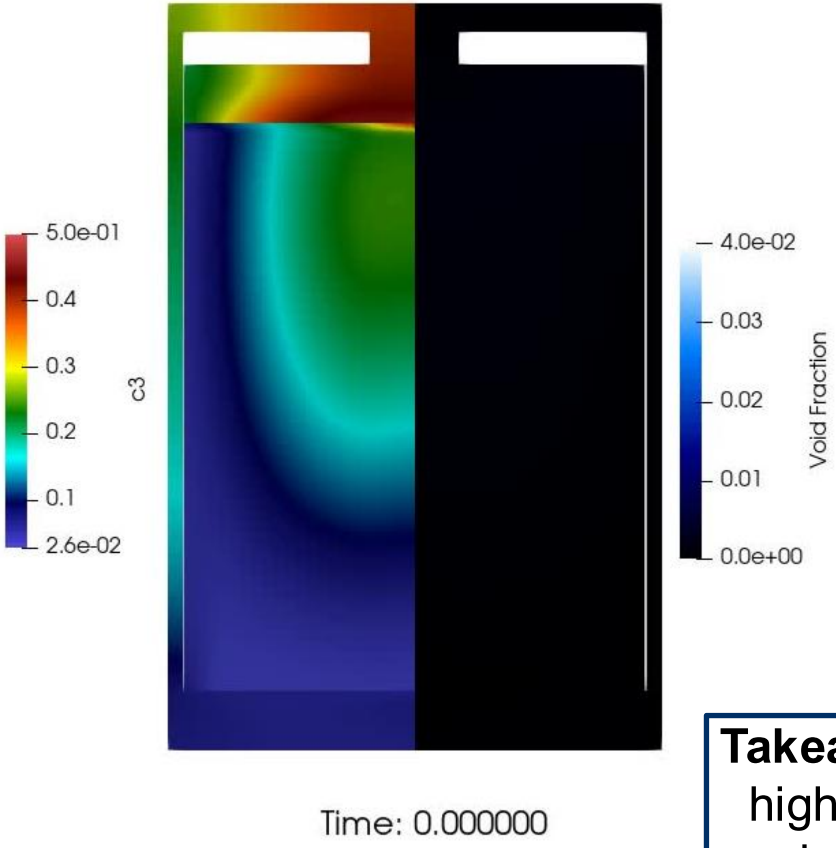
Coupling Demonstration 1: Large Reactivity Insertion Transient in MSRE





- 100 pcms are injected in the reactor core at the initial time
- During a reactor transient, the distribution of void plays a fundamental role in power attenuation
- Additionally, the distribution of void is important in the reactor setpoint after the transient

Takeaway: Reactivity insertion transients at high power require capturing the detailed interaction between multiple physics

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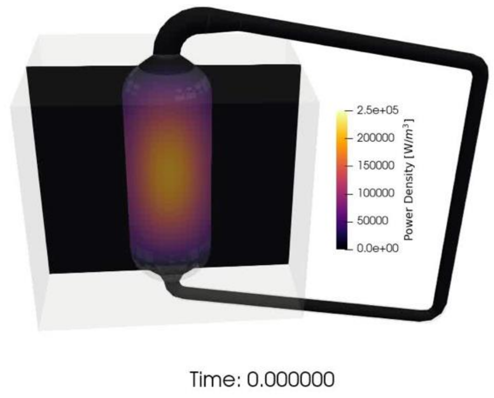
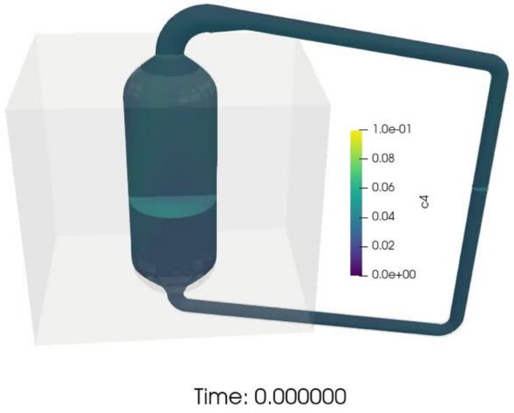
Coupling Demonstration 2: Station Blackout in L-MSR

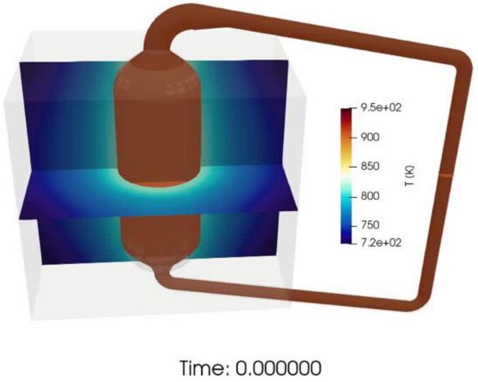
Power Density



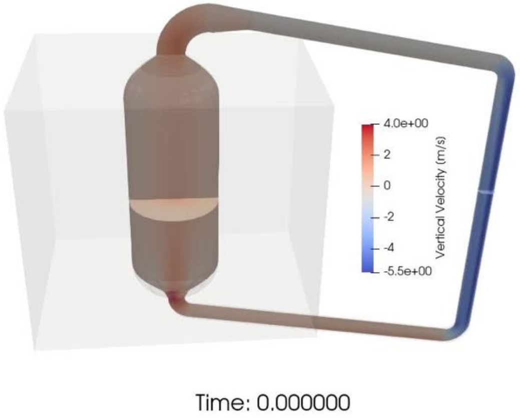
Delayed Neutron Precursor Concentration for Group 4



Temperature



Fuel Salt Velocity



- Reactor initially operates at nominal steady-state conditions
- All electrical power is lost at t=0s. This causes a LOFA as the pump stops and the loss of thermal insulation provided by the electric blankets and tracers.
- The evolution of the reactor is quite complex as it involves the interplay between
    - Delay of the neutron precursor circulation during the shutdown and transition to natural convection operation
    - Reactor fuel heating by prompt and delayed nuclear power
    - Transient cooling of the reactor and reflector due to loss of thermal insulation.
- Eventually, the reactor reaches a higher power operation where the heat generated is offset by heat losses to the environment.

Takeaway: NEAMS tools can simulate long-term transients in pool-type MSRs

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Summary and Conclusions

Coupling	Rationale	Demonstrated	Validation
Neutronics Thermal-Hydraulics	Needed to model low and nominal operating transients in MSRs	Thermal MSRs: Yes Fast MSRs: Yes	Thermal MSRs: Yes (MSRE) Fast MSRs: No
Neutronics Thermochemistry	Needed to model speciation and species tracking	Thermal MSRs: Yes Fast MSRs: Yes	Thermal MSRs: Partial (MSRE) + In Progress Fast MSRs: No
Thermal-Hydraulics Thermochemistry	Needed for accurate computation of the flow field	Thermal MSRs: Yes Fast MSRs: Yes	Thermal MSRs: In Progress Fast MSRs: No
Neutronics Thermal-Hydraulics Thermochemistry	Needed for computing long-term steady-state operation of MSRs	Thermal MSRs: In progress Fast MSRs: In progress	Thermal MSRs: In Progress Fast MSRs: No
Neutronics Thermal-Hydraulics Thermochemistry Thermomechanics	Needed for adding accurate structural performance models for MSRs	Thermal MSRs: No Fast MSRs: Partial (MCRE)	Thermal MSRs: No Fast MSRs: No

Completed In progress Not completed or panned

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