LRS: INL/MIS-26-90665

Pronghorn enhancements for MSR applications

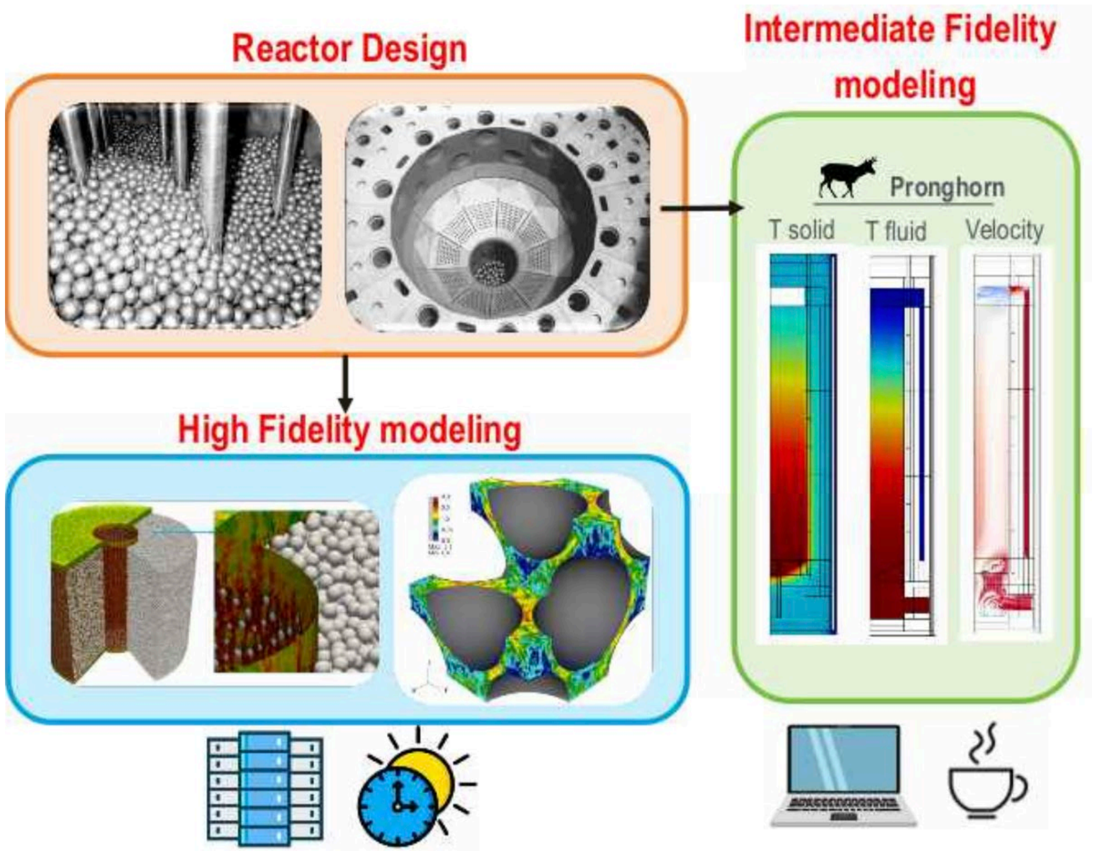
ART-MSR Review Meeting

April 22nd, 2026

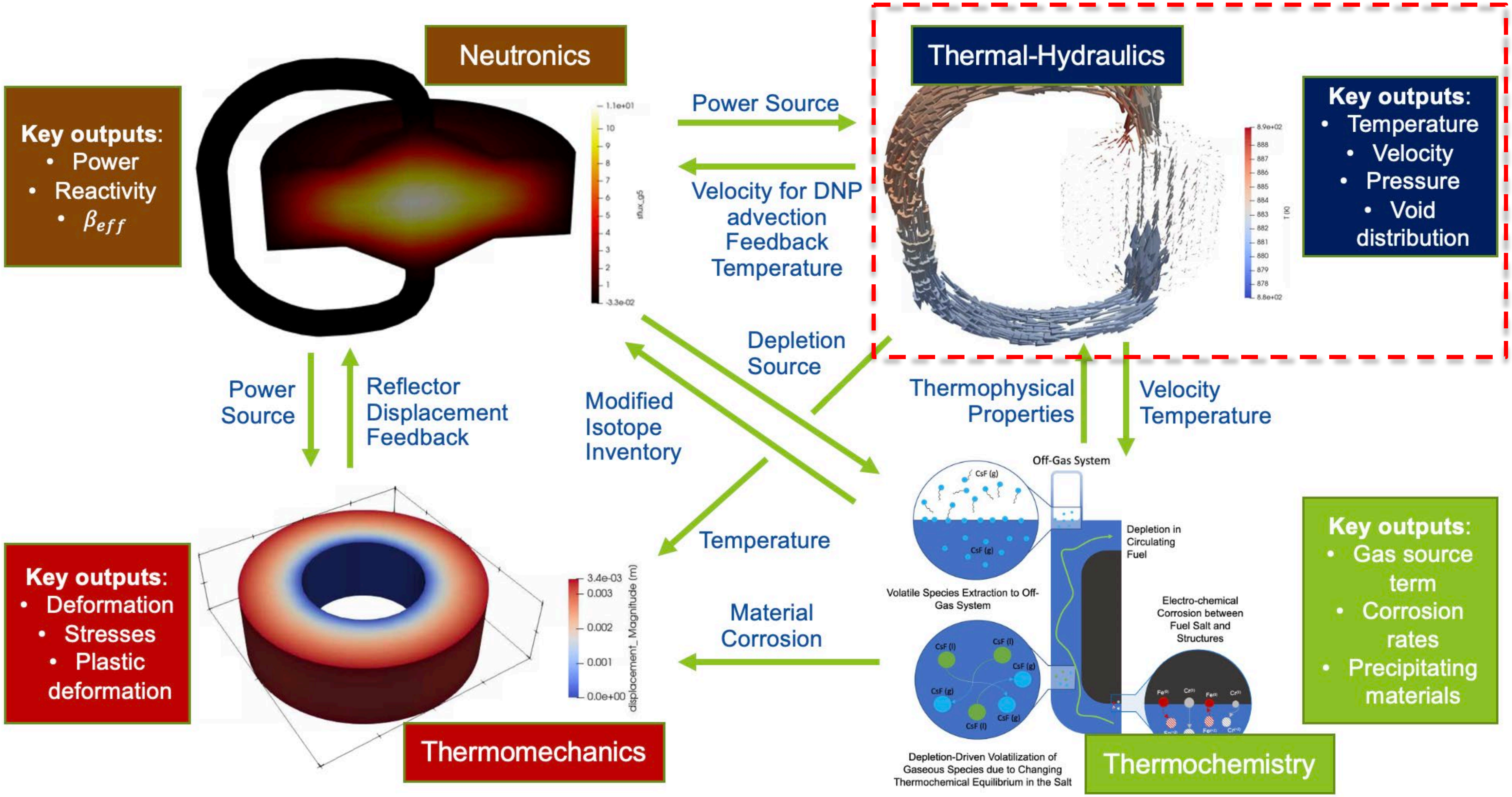
Mauricio Tano, Ramiro Freile, Mengnan Li, Victor Coppe Leite, Peter German, David Reger, Guillaume Guidicelli

Pronghorn

- **Pronghorn:** Intermediate-fidelity multidimensional coarse-mesh CFD code
- Capabilities:
  - Coarse-mesh CFD with finite volume discretization
  - Incompressible or weakly compressible flows
  - Porous flow modeling with a wide range of correlations
  - **RANS turbulence modeling with several turbulence models**
  - **Two-phase flow modeling**
  - Straightforward coupling to neutronics and other physics within the MOOSE framework
  - Level of resolution appropriate for full core modeling



Pronghorn's Role in MSR Multiphysics Framework



- **Pronghorn**
- SAM
- Nek5000/NekRS

Key TH Improvements in Pronghorn for MSR Modeling

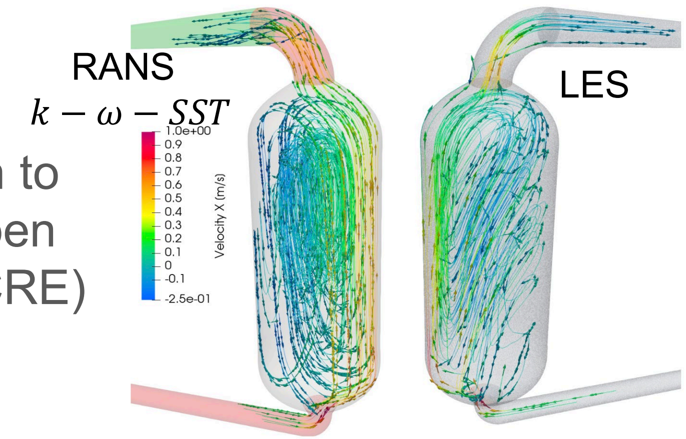
#	Issue Description	Solution
1	**Two-equation RANS Turbulence Modeling**: calibrating the mixing length model requires significant effort to reach high-accuracy solutions and is cumbersome for routine engineering applications	• State-of-the-art two-equation $k-\epsilon$ and $k-\omega-SST$ models with equilibrium and non-equilibrium wall treatment implemented and validated in MOOSE-NS • HOLO approach
2	**Near-Wall Turbulence Modeling**: inaccuracies are observed when comparing Pronghorn models with MCRE experiments due roughness and curvature in walls	• Wall functions with curvature and roughness corrections implemented and validated in MOOSE • Adapted wall functions for corrosion profiles
3	**Two-phase Flow Modeling**: the effect of void fraction during routine multiphysics transients and accidental void entrainment, which are part of MSR design and safety bases, cannot be modeled	• Multi-D generalization of mixture drift-flux model developed and validated in MOOSE • Working prototype of multiphase Euler-Euler mixture
4	**Pronghorn-SAM Coupling**: for extend MSR support, Pronghorn-SAM coupling needs to be demonstrated for transients with weak-compressibility effects and flow reversal	• Domain overlapping action in BlueCRAB extended to deal with compressibility and Pronghorn code extended to deal with flow reversal

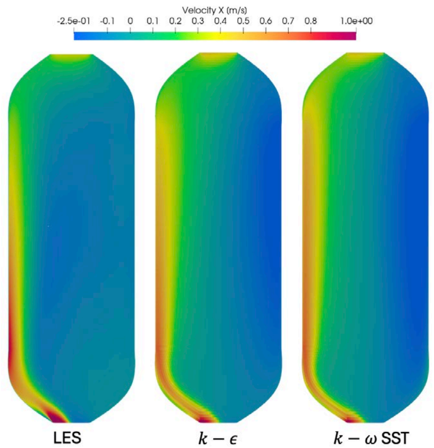
Two-equations RANS Turbulence Modeling

Model	Implementation	Near-wall Treatment	Corrections	Solvers Supported	Near-wall temperature modeling
$k-\epsilon$	Standard (Jones and Launder)	Two-layer stepwise treatment. Preferred high y^+	Durbin production limiting	Linear and Nonlinear	Yes
$k-\omega-SST$	Wilcox	. Two-layer blended. Supports both low and high y^+	Free-shear, vortex-stretching, and low-Reynolds number modifications	Linear	Yes

- Models validated for:
  - Turbulent channel [1] $Re_\tau = 395$ and $Re_\tau = 590$
  - Backward Facing Step [2] $Re_h = 36{,}000$
  - Swirling Flow in a Bent Pipe [3] $Re = 50{,}000$
- Near-wall corrections for roughness and transverse curvature

Application to L-MSR (open source MCRE)





	Number of elements	Pressure Drop [Pa]	
		$k-\epsilon$	$k-\omega$ SST
Coarse	~26K	3850	3950
Medium	~208K	3050	3100
Fine	~1664K	2815	2840

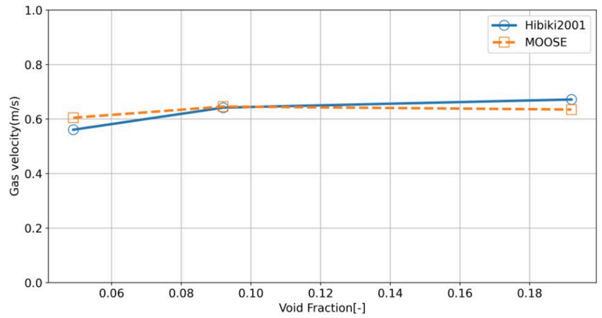
	LES	$k-\epsilon$	$k-\omega$ SST
Pressure Drop [Pa]	2780	2815 ± 135	2840 ± 136

1. Mansour, N.N., Kim, J., Moin, P. (1988). Reynolds-stress and dissipation-rate budgets in a turbulent channel flow. J. Fluid Mech., Vol. 194, pp. 15-44
2. Le, H., Moin, P., Kim, J. (1997). Direct numerical simulation of turbulent flow over a backward-facing step. J. Fluid Mech., Vol. 330, pp. 349-374.
3. So, R.M.C., Anwer, M. (1993). Swirling turbulent flow through a curved pipe. Part 2: Recovery from swirl and bend curvature. Exp. Fluids, Vol. 14, pp. 169-177.

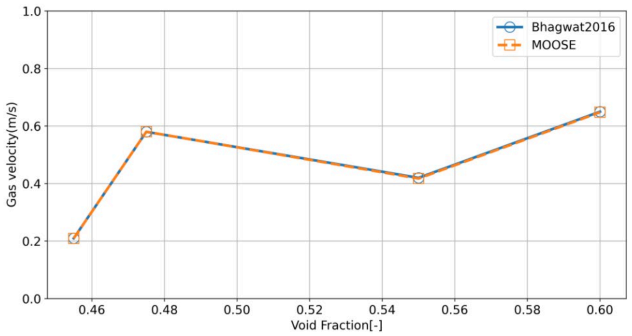
Two-Phase Flow Modeling

Model	Modifications	Solvers Supported	Compatible with wall functions
Drift flux model in porous media formulation	- Generalization to multi-D flows - Porous media support	Linear and Nonlinear	Yes

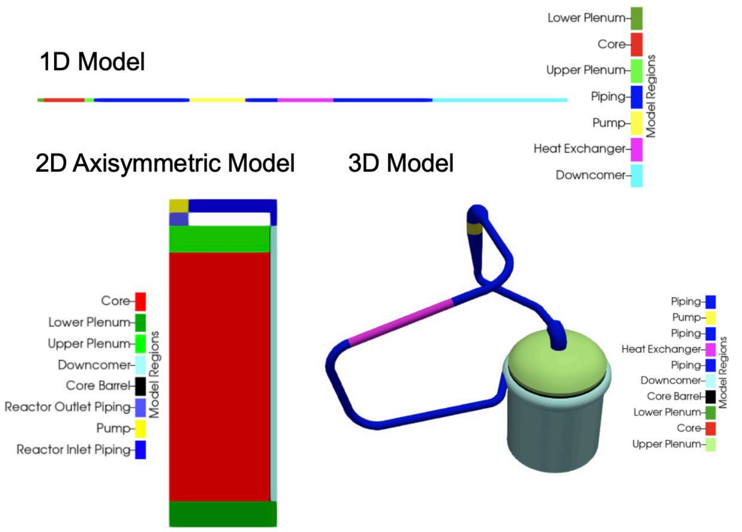
- Models validated for:
  - Vertical Air-Water Pipe [6] $\alpha \in [0.049, 0.192]$



  - Horizontal Air-Water Pipe [7] $\alpha \in [0.455\ 0.600]$

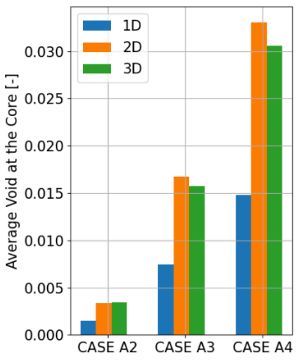


Application to MSRE



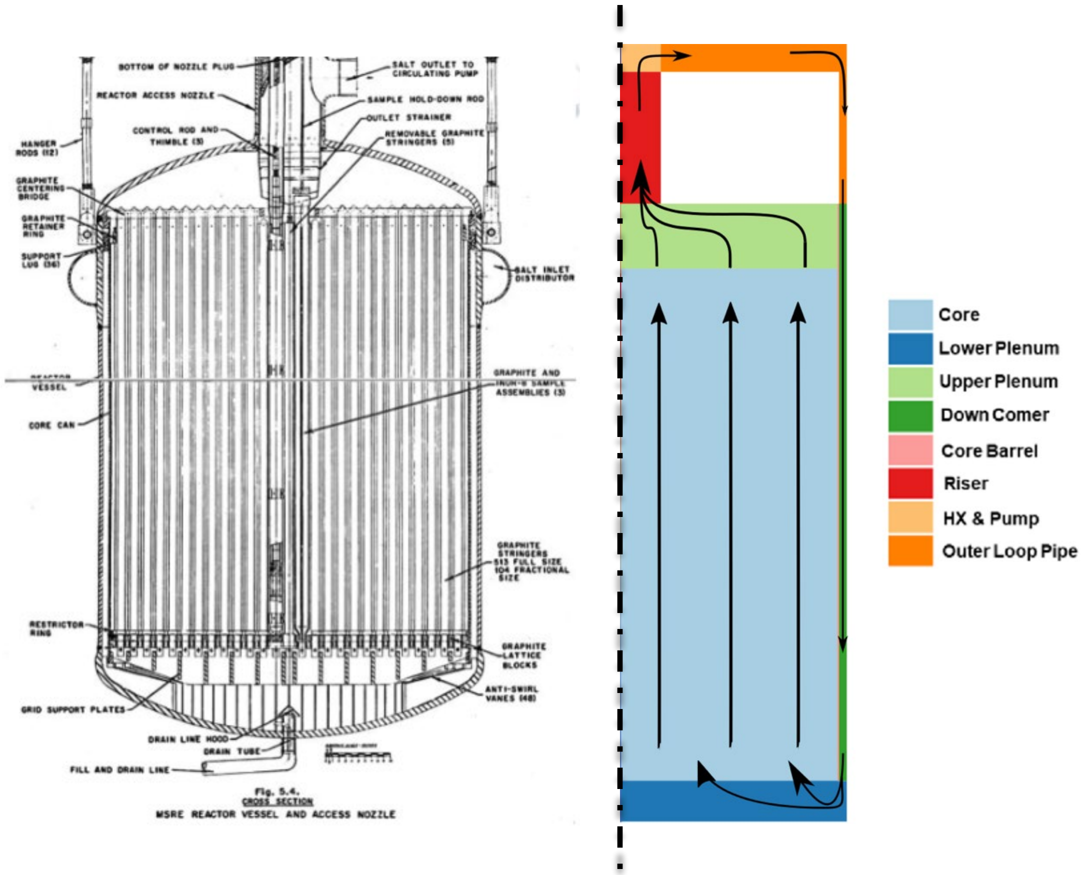
Model	Pressure Drop [kPa]	Effective Multiplication Factor
Expected	63.5 [86]	1.02132 [8]
1D Model	58.1	1.01739
2D axisymmetric Model	63.6	1.02223
3D Model	63.6	1.02211

Case / Reactivity Introduced [pcm]	1D Model	2D axisymmetric Model	3D Model
Case A1 - No void fraction (Reference Case)	-	-	-
Case A2 - Low Void Fraction	-6.2	-82.0	-56.0
Case A3 - Best-estimate Void Fraction	-30.8	-410.7	-263.6
Case A4 - High Void Fraction	-61.3	-824.1	-535.8



6. Ishii, M., & Hibiki, T. (2010). *Thermo-fluid dynamics of two-phase flow*. Springer Science & Business Media.
7. Hibiki, T., Ishii, M., & Xiao, Z. (2001). Axial interfacial area transport of vertical bubbly flows. *International Journal of Heat and Mass Transfer*, *44*(10), 1869-1888.

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

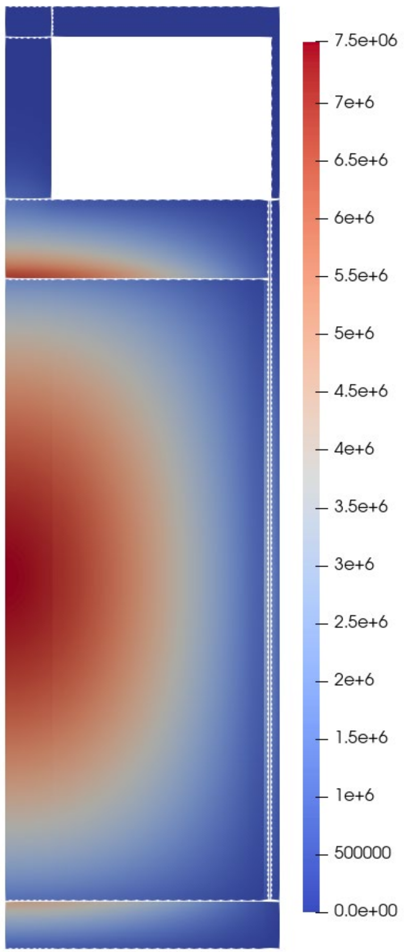
Relative isotopic atomic fractions during the ^{233}U and ^{235}U loads of MSRE

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	-

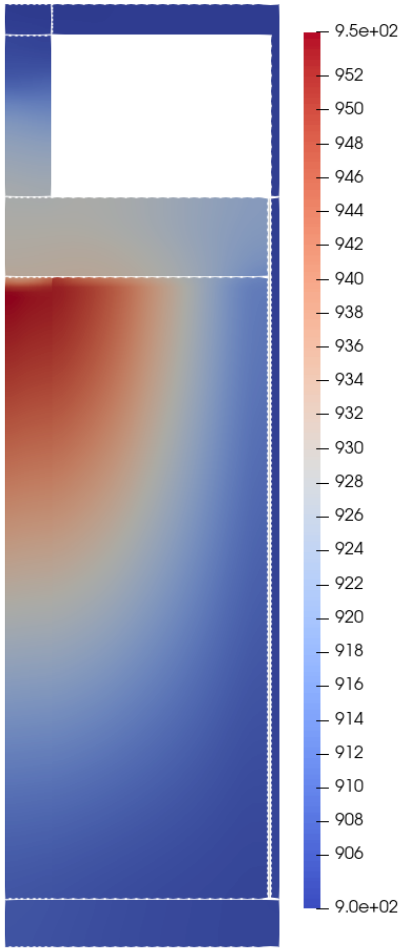
Thermophysical properties of the fuel salt and the moderator

Contacts: Mustafa Jaradat (Mustafa.Jaradat@inl.gov), Philip Pfahl (pjfpf@dtu.dk), Mauricio Tano (Mauricio.TanoRetamales@inl.gov), Ramiro Freile (Ramiro.Freile@inl.gov)

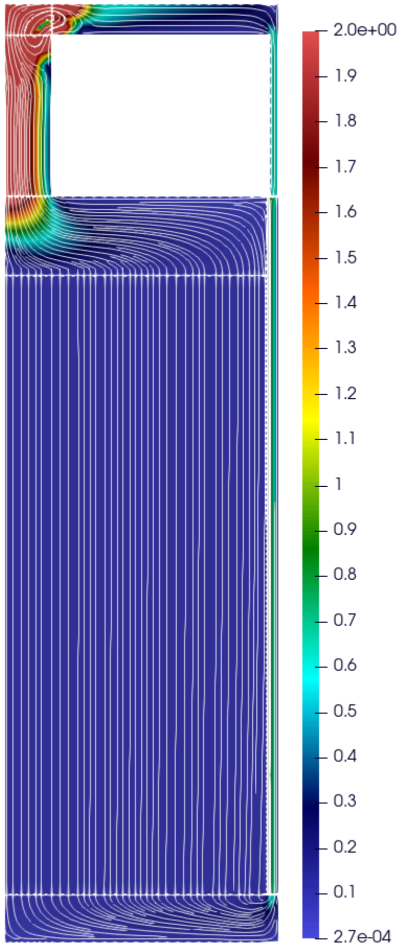
Steady-State Fields



Power density [W/m3]



Temperature [K]

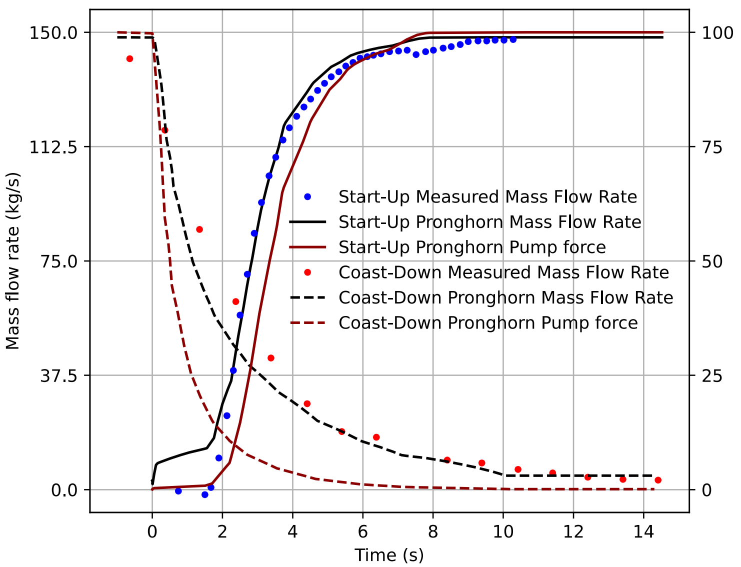


Salt Velocity [m/s]

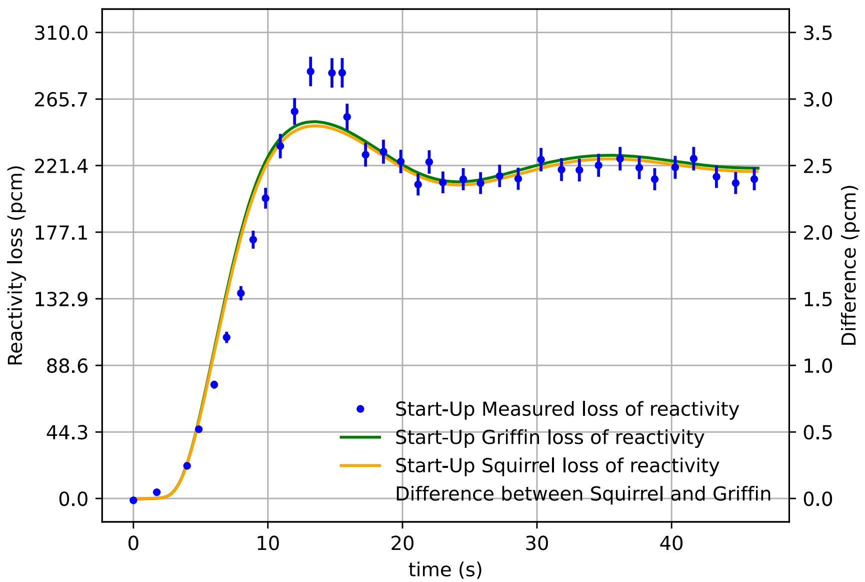
Takeaway: reasonable fields obtained for steady-state operation in Griffin-Pronghorn MSRE model

Contacts: Mustafa Jaradat (Mustafa.Jaradat@inl.gov), Philip Pfahl (pjfpf@dtu.dk), Mauricio Tano (Mauricio.TanoRetamales@inl.gov), Ramiro Freile (Ramiro.Freile@inl.gov)

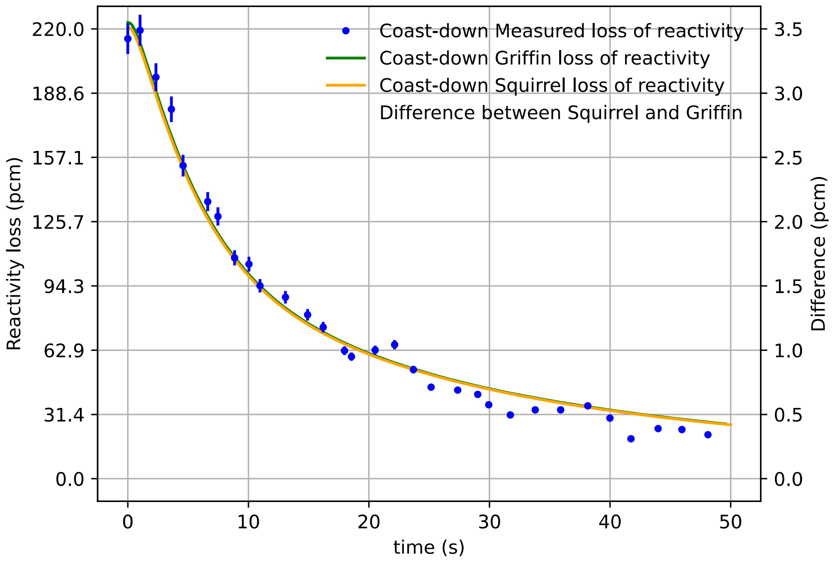
Pump Startup and Coast-Down Transients



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]

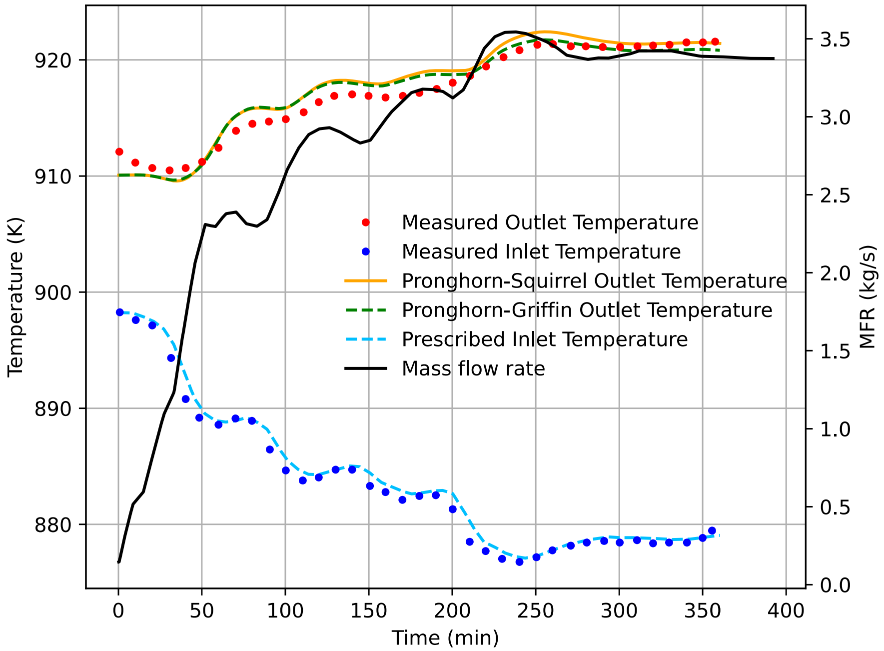


Comparison of **reactivity loss** during pump **coast-down** transient [Prince et al., 1968]

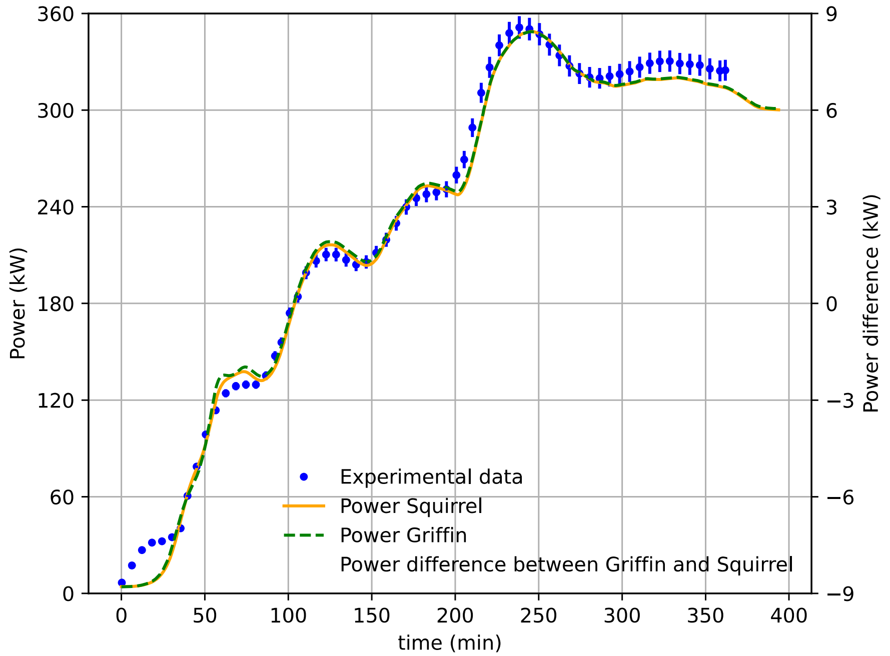
Takeaway: Griffin-Pronghorn MSRE multiphysics model validated for transient flow rate and zero-power pump start-up and shutdown

Contacts: Mustafa Jaradat (Mustafa.Jaradat@inl.gov), Philip Pfahl (pjfpf@dtu.dk), Mauricio Tano (Mauricio.TanoRetamales@inl.gov), Ramiro Freile (Ramiro.Freile@inl.gov)

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

Contacts: Mustafa Jaradat (Mustafa.Jaradat@inl.gov), Philip Pfahl (pjfpf@dtu.dk), Mauricio Tano (Mauricio.TanoRetamales@inl.gov), Ramiro Freile (Ramiro.Freile@inl.gov)

Pronghorn-SAM Domain-Overlapping Coupling 1/2

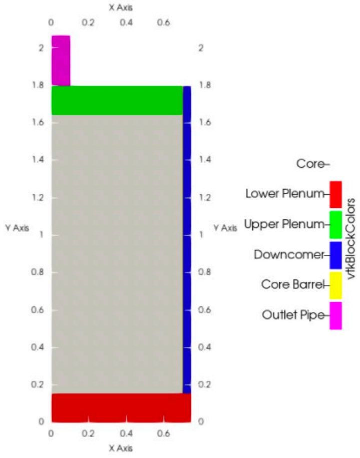
- MOOSE Action developed to couple Pronghorn and SAM*
- The key principle is to automatically generate pipe components in SAM that represent the overlapped Pronghorn component and to match Pronghorn calculated values in SAM:
  - Match pressure drop → Friction factors set in SAM
  - Match enthalpy/temperature rise → heat source set in SAM
  - Adjust passive scalar concentration → volume source set in SAM
- The main components of the coupling action are
  - Geometric description of the coupled boundaries and their area and length
  - Boundary where Pronghorn pressure is pinned
  - Enthalpy function for temperature coupling
  - Passive scalar decay constants
  - Execution parameters, including solution method, coupling start time, and equations of state

Example of Domain Overlapping Coupling Action for MSRE

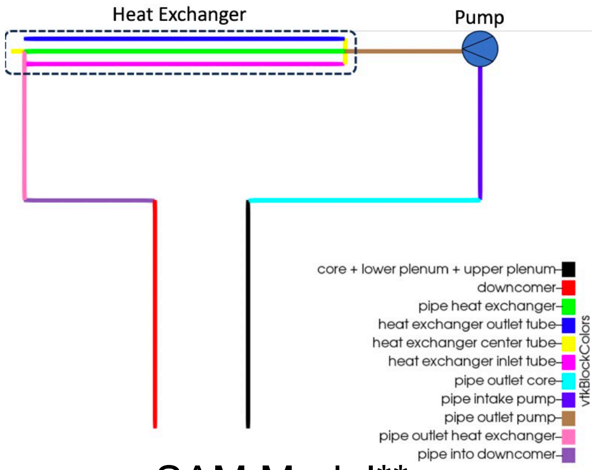
```
[OverlappingDomainCoupling]

  ### Coupled geometry
  boundaries = 'downcomer_inlet pump_outlet'
  component_names = 'downcomer  core'
  component_orientation = 'in   out'
  component_area = '0.1589 0.3512'
  component_length = '1.8015 1.8015'
  connected_component_names = 'pipe3_s2 pipe1_s1'
  subapp_filename = 'MSRE_SAM_TH_v3.i'

  ### Hydraulics coupling
  pinned_pressure_value = pinned_pressure_top
  pinned_pressure_boundary = 'pump_outlet'
  initial_pinned_pressure = '${p_outlet}'
  reference_pressure = reference_plane_pressure
  reference_enthalpy = reference_plane_enthalpy

  ### Thermal coupling
  enthalpy_functor = cp_temp
  boundary_temperature_names = 'T_downcomer T_core'
  initial_boundary_temperatures = '${T_inlet} ${T_inlet}'
```

```
  ### Passive scalar coupling
  passive_scalar_names = 'c1 c2 c3 c4 c5 c6'
  system_level_passive_scalar_names = 'c1 c2 c3 c4 c5 c6'
  boundary_passive_scalar_names = 'from_sam_ps_dc_c1 from_sam_ps_top_c1;
                                   from_sam_ps_dc_c2 from_sam_ps_top_c2;
                                   from_sam_ps_dc_c3 from_sam_ps_top_c3;
                                   from_sam_ps_dc_c4 from_sam_ps_top_c4;
                                   from_sam_ps_dc_c5 from_sam_ps_top_c5;
                                   from_sam_ps_dc_c6 from_sam_ps_top_c6'
  passive_scalar_decay_constant = '${lambda1_m} ${lambda2_m} ${lambda3_m}
                                   ${lambda4_m} ${lambda5_m} ${lambda6_m}'
  initial_boundary_passive_scalar_value = '0 0; 0 0; 0 0; 0 0; 0 0; 0 0'
  passive_scalar_iteration_type = simple

  ### Execution
  hydrodynamic_iteration_type = simple
  thermal_iteration_type = simple
  passive_scalar_iteration_type = simple
  startup_time = 0.5
  eos = fuel_salt_eos
  execute_multiapp_on = 'TIMESTEP_BEGIN'
[]
```

MSRE Model



Pronghorn Model



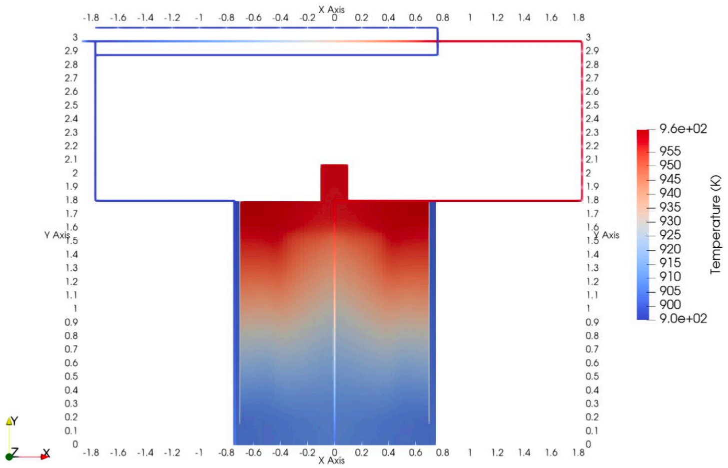
SAM Model**

*) Schunert, S., Tano, M. E., & Mohammad Jaradat, M. K. (2023). *Overlapping Domain Coupling of Multidimensional and System Codes in NEAMS-Pronghorn and SAM* (No. INL/RPT-23-72874-Rev000). Idaho National Laboratory (INL), Idaho Falls, ID (United States).
**) Model developed by Jun Fang and Tingzhou Fei (ANL)

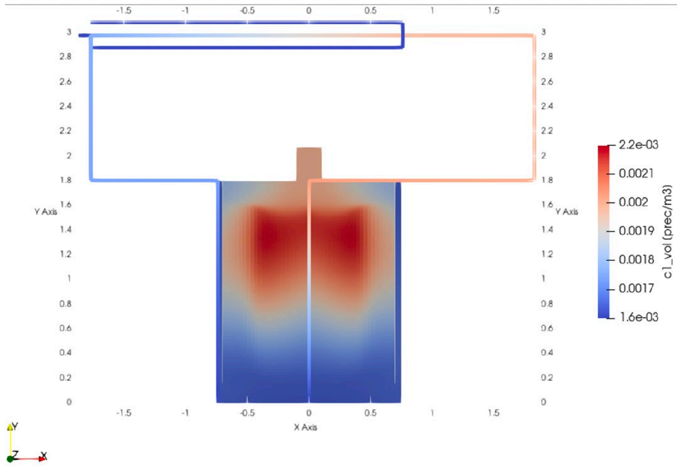
Pronghorn-SAM Domain-Overlapping Coupling 2/2

- Demonstration:
  - Pronghorn-SAM coupling demonstrated for MSRE
  - For steady-state operation, the coupling methodology has been demonstrated and verified for the full reactor model.
- Key limitation:
  - 1D to multiD boundary condition in Pronghorn imposed from SAM models where flow assumptions must be made.
  - The user must still carefully select the boundary where the coupling is performed to avoid the effects of these boundary conditions.
- Coupling validation:
  - The transient model has been validated for reactivity insertion transients in MSRE.
  - Pronghorn SAM results showed improved performance due to the higher resolution of the Pronghorn model.

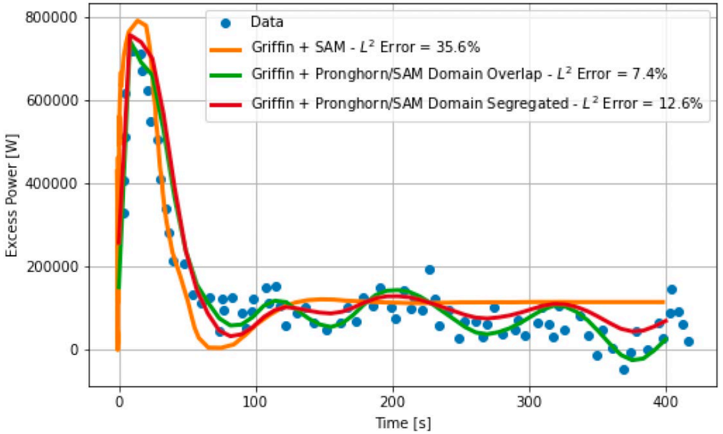
Temperature Field



Delayed neutron precursor concentration for group 1 ($\lambda_1 = 1.3336 \times 10^{-2} 1/s$)



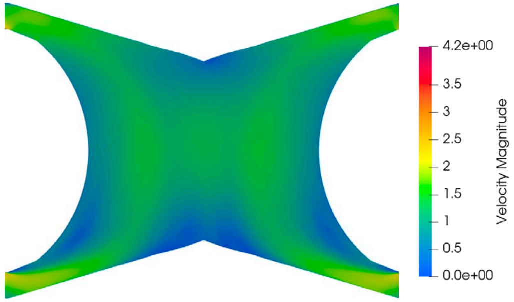
Reactivity Insertion Transient at 5MW of thermal power



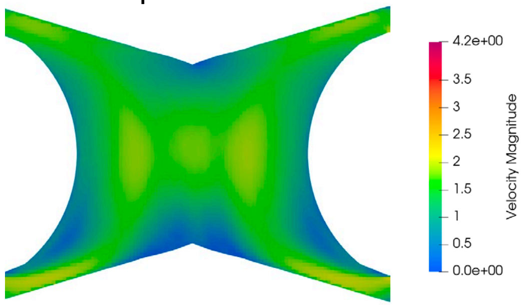
Pronghorn-Nek High-to-Low (HOLO) Coupling

- Pronghorn RANS turbulent closures implemented as *Functors*, which allows for a simple calibration from higher-fidelity models
- Pronghorn implements an inverse Kalman filter for advection, allowing to obtain good performance advection in coarse meshes
- Example for the Molten Salt Fast Reactor (MSFR) core in the right figures

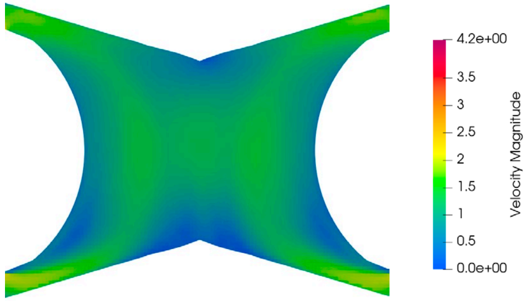
Time-averaged NekRS LES

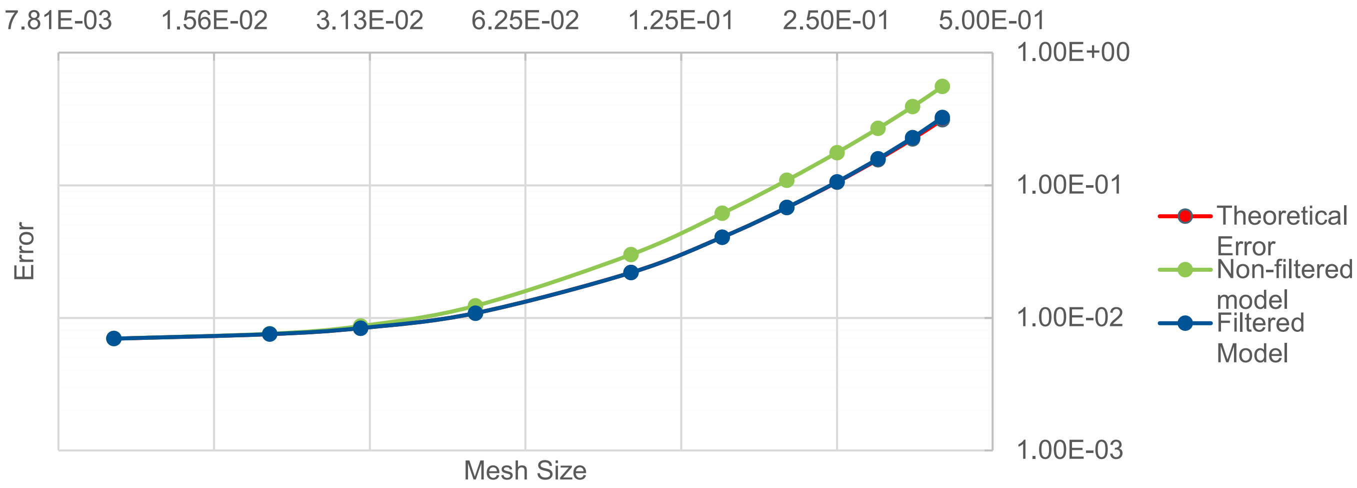


Standard $k-\epsilon$ model in Pronghorn
Mean Squared Error: 6.6%



Calibrated $k-\epsilon$ model in Pronghorn
Mean Squared Error: 0.7%





Tano, M., Walker, S., Abou-Jaoude, A., Fang, J., & Shaver, D. (2023). Nek5000-Pronghorn-SAM multiscale modeling of pool-type Molten Salt Reactors. In *20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, NURETH 2023* (pp. 478-491). American Nuclear Society.

Summary

- Pronghorn has been extended to model pool-like MSRs with coarse-mesh for engineering-scale modeling
- Additions included:
  - Two-equations $k - \epsilon$ and $k - \omega - SST$ RANS turbulence models
  - Near wall modeling for rough walls and swirling flow
  - Two-phase, drift-flux, multi-dimensional modeling
  - Domain-overlapping coupling with SAM
- Current work is targeting:
  - Coupling with Saline for modeling molten salt flows with diverse composition due to varying burnup
  - Two-phase Euler-Euler modeling for accounting for sloshing and larger void fraction transport
  - Continue improving domain-overlapping for cases with large body forces, weak-compressibility, and porosity jumps
  - Validation (salt spill, corrosion modeling, etc.)
  - Coarser computational meshes

Contact: Mauricio Tano (Mauricio.TanoRetamales@inl.gov)

U.S. DEPARTMENT of ENERGY

Office of Nuclear Energy