Multidomain Multiphysics Analysis of Transients in the Molten Salt Reactor Experiment: Saline, Pronghorn, SAM, and Griffin

ART MSR Program Review 2026

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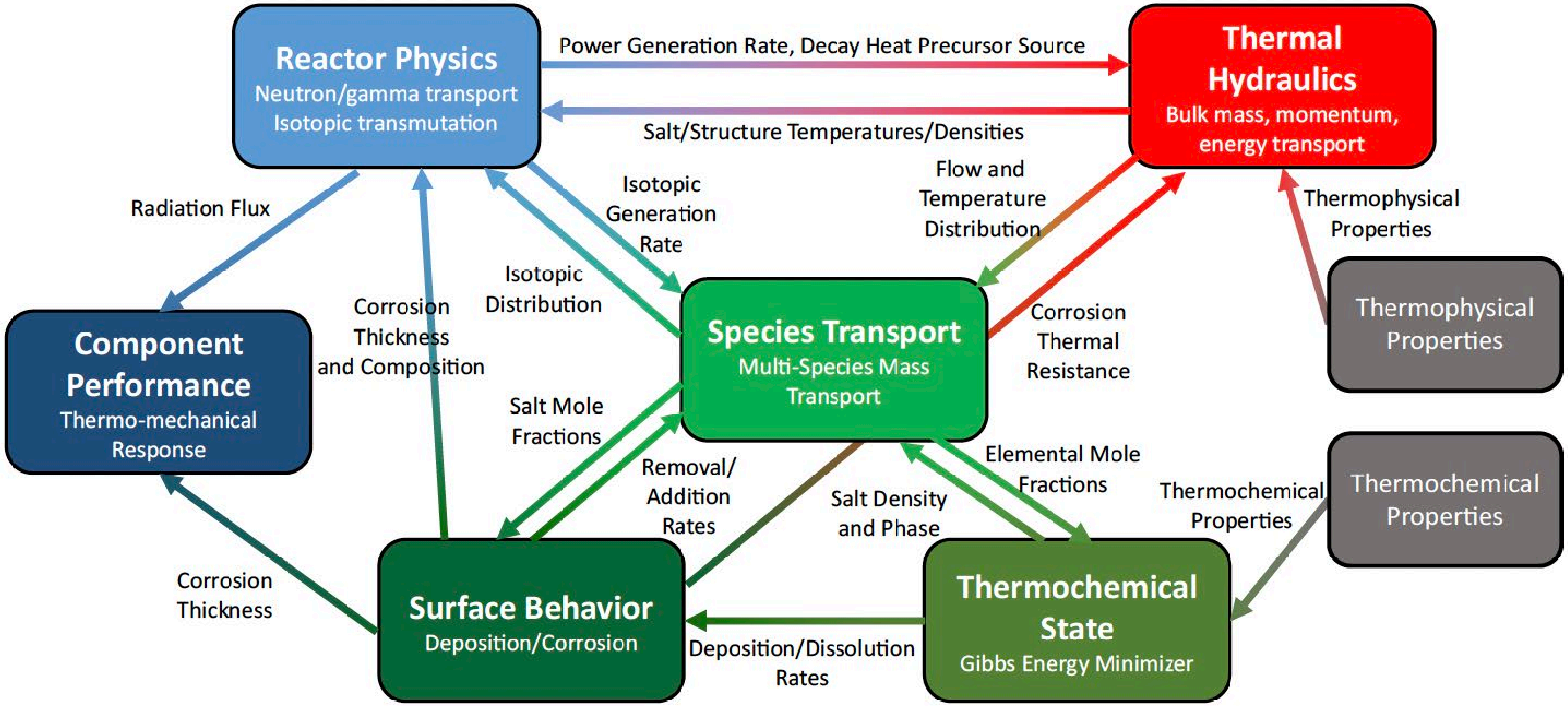
INL/MIS-26-89885

Molten Salt Reactor Modeling Needs



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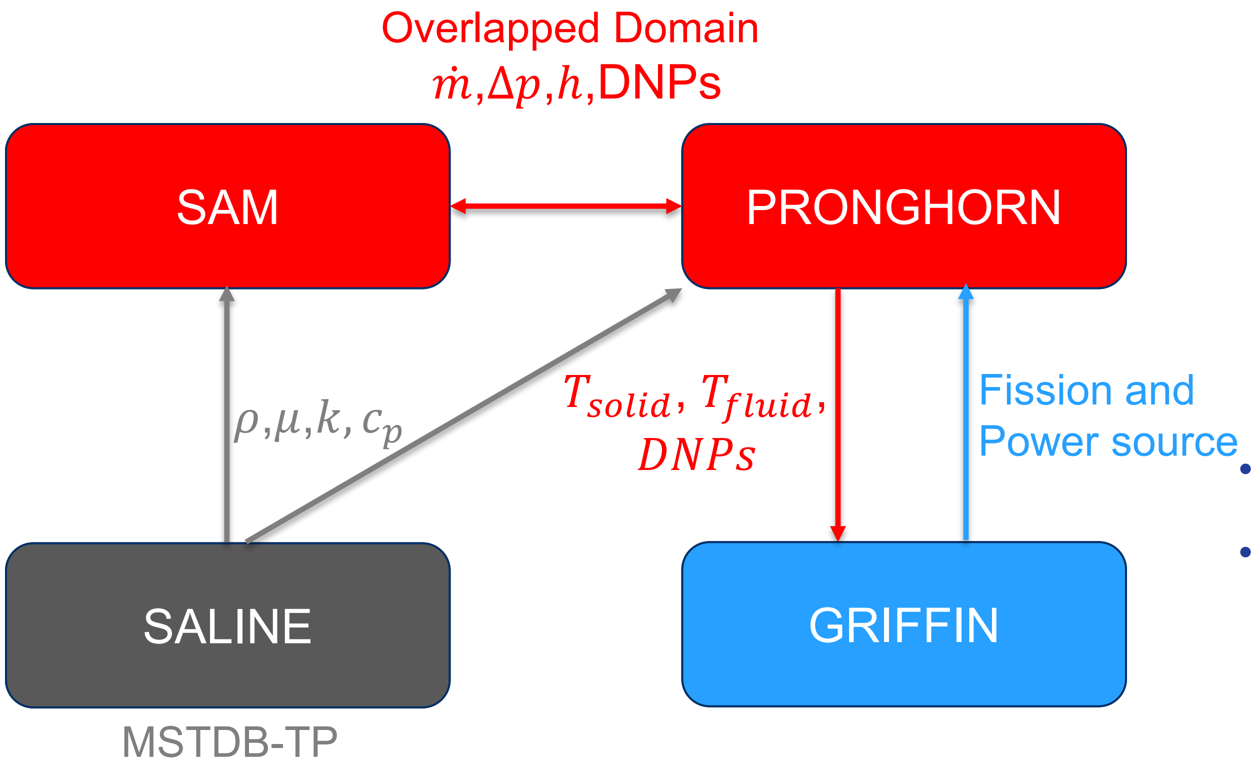
SAM-Pronghorn-Griffin-Saline coupling scheme



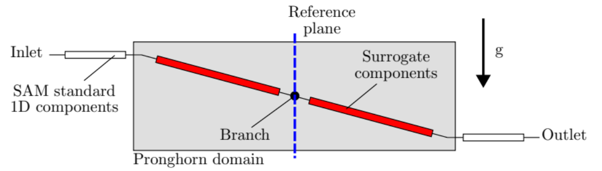
- **SAM-Pronghorn:** Domain overlapping action

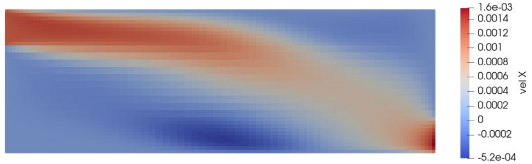
```
[OverlappingDomainCoupling]

 ### 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}'
```





- **Griffin-Pronghorn:** MOOSE Multi-App Transfers
- **Saline-Pronghorn:** MOOSE Fluid Properties module

```
[FluidProperties]
  [salt]
    type = SalineMoltenSaltFluidProperties
    comp_name = "NaCl UCl3"
    comp_val = "0.7 0.3"
    prop_def_file = "Molten_Salt_Thermophysical_Properties_.csv"
  []
[]
```

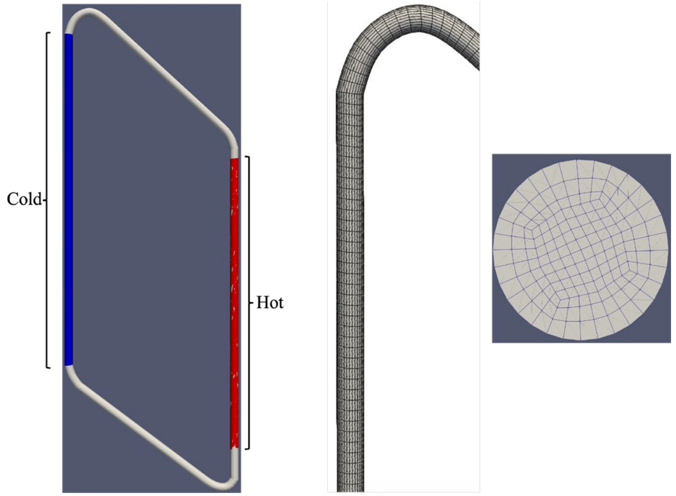
- **Saline-SAM:** EOS interface

```
[MaterialProperties]
  [salt]
    type = SalineMoltenSaltFluidProperties
    comp_name = "LiF BeF2 ZrF4 UF4"
    prop_def_file = "Molten_Salt_Thermophysical_Properties_.csv"
  []
[]
```

```
[EOS]
  [fuel_salt_eos]
    type = PTFluidPropertiesEOS
    fp = salt
    p_0 = pressure
    eos_test = true
  []
[]
```

Pronghorn-Saline: Application Case

- Thermophysical properties of the salt are a function of isotopic evolution.
- **Demonstration case**: 3D chloride (NaCl-UCl_3 0.67-0.33) molten salt natural convection loop using Pronghorn-Saline Coupling.
- PIMPLE solver with generalized buoyancy solver.




```
[FluidProperties]
  [salt]
    type = SalineMoltenSaltFluidProperties
    comp_name = "NaCl UCl3"
    comp_val = "0.7 0.3"
    prop_def_file = "Molten_Salt_Thermophysical_Properties_.csv"
  []
[]
```

```
[FunctorMaterials]
  [fluid_props_to_mat_props]
    type = GeneralFunctorFluidProps
    fp = salt
    pressure = 1e5
    T_fluid = 'T_fluid'
  []
[]
```

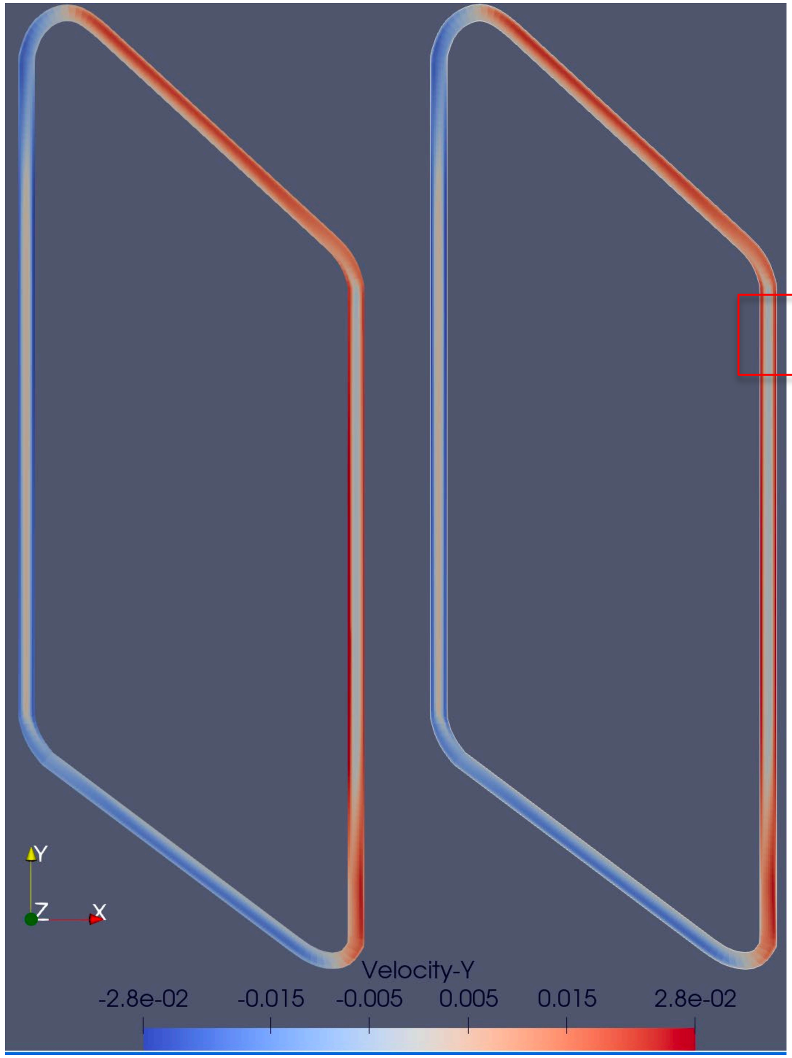
Property	Low Burnup	Medium Burnup	High Burnup
Molecular weight [g/mol]	153.66	144.22	139.65
Density [kg/m^3]	4220 - 1.03*T	3960 - 0.925*T	3850 - 0.885*T
Viscosity [Pa.s]	$10^{\left(-1.23+\frac{1602}{T}\right)}$	$10^{\left(-1.218+\frac{1557}{T}\right)}$	$10^{\left(-1.18+\frac{1388}{T}\right)}$
Specific Heat [J/kg mol]	102.9	88	85
Thermal Conductivity [W/mK]	0.4	0.35	0.3

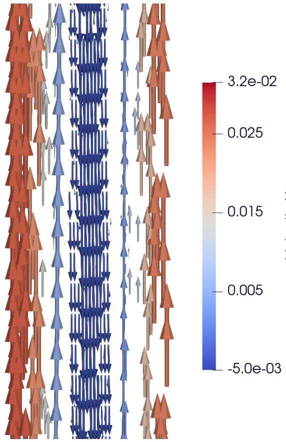
Velocity in Hot Leg

Velocity in Cold Leg

Pronghorn-Saline (continued)

- Uranium molar burnup evolution in the 0, 50, 150 MWd/kgU range.
- Annular natural convective flow is observed due to the high salt Prandtl number of 30.
- Lower buoyancy force and decreased viscosity with burnup create opposing effects.
- From 0 to 50 MWd/kgU burnup, reduced buoyancy decreases mass flow rate.
- From 50 to 150 MWd/kgU burnup, mass flow rate remains similar due to lower viscosity reducing viscous resistance.



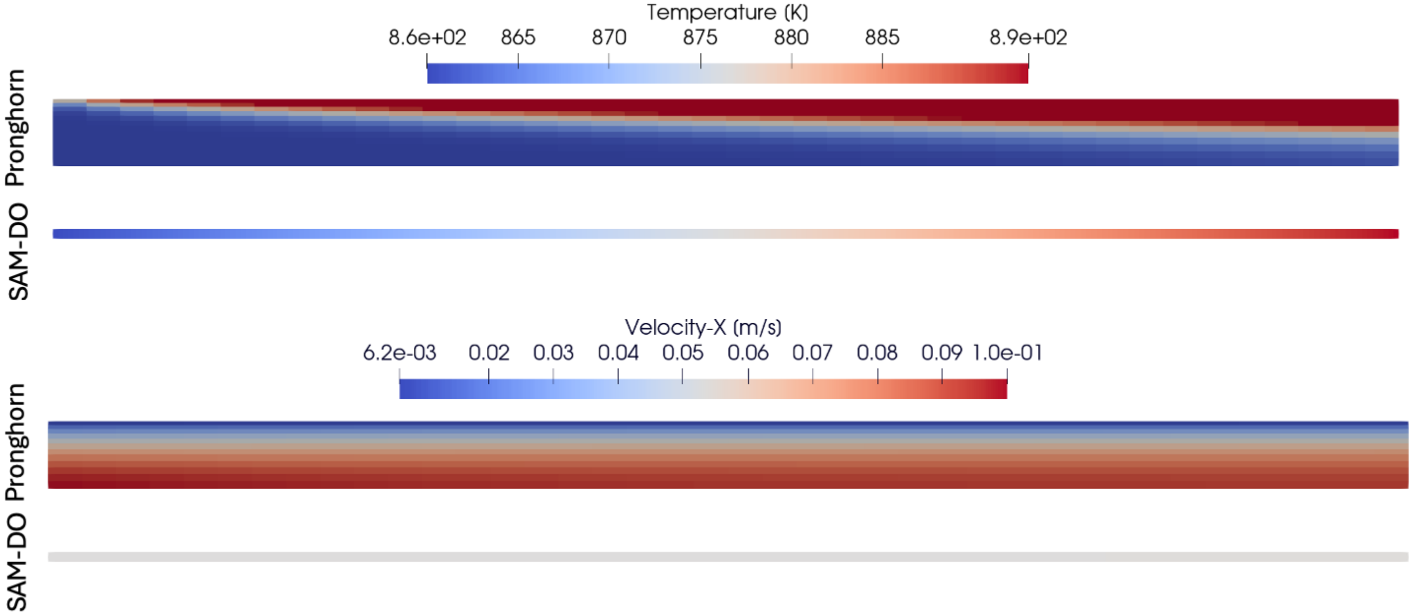


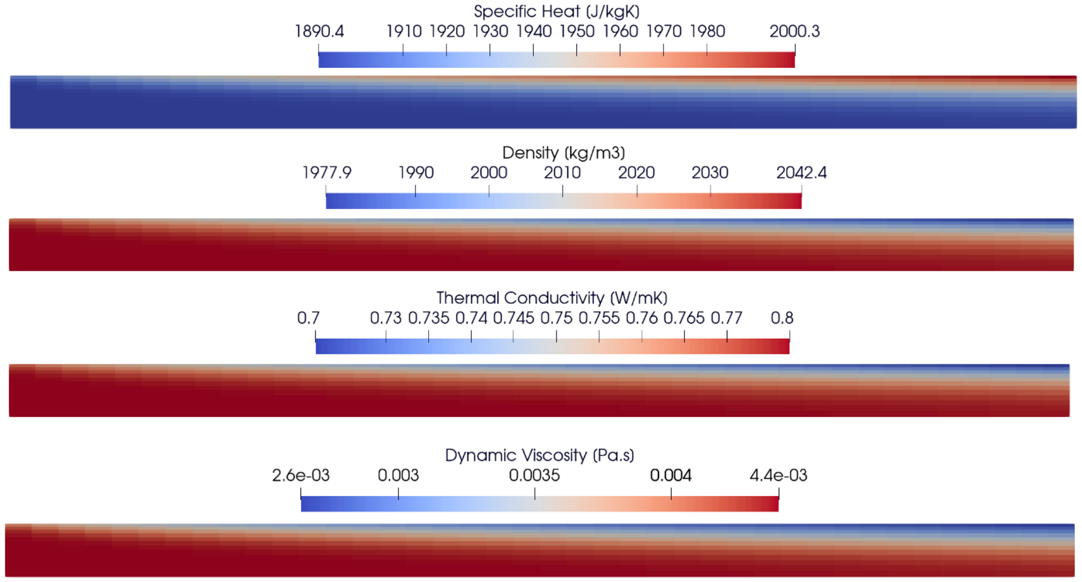
Velocity in Cold Leg

Burnup [MWd/kgU]	Hot Leg Temperature [K]	Cold Leg Temperature [K]	Mass Flow [kg/s]
0	904.0	896	1.62e-2
50	903.9	896.1	1.48e-2
150	903.5	896.5	1.51e-2

SAM-Pronghorn-Saline Verification

- **Three-code-coupling:** Verification of the SAM-Pronghorn Domain Overlapping with the Saline interface for enthalpy solvers.
- Constant heat flux and temperature boundary layer development.
- FLiNaK thermophysical properties.

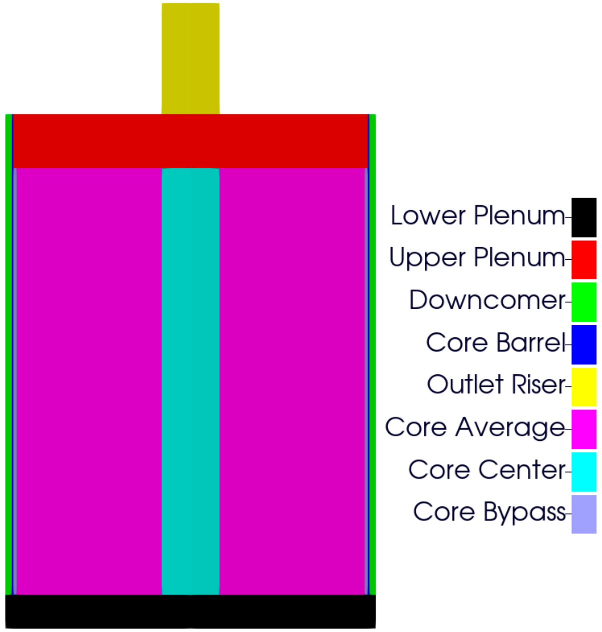


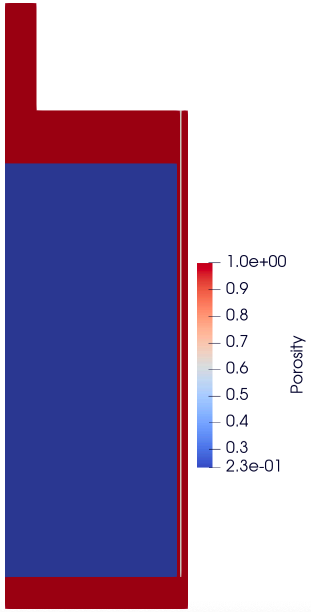


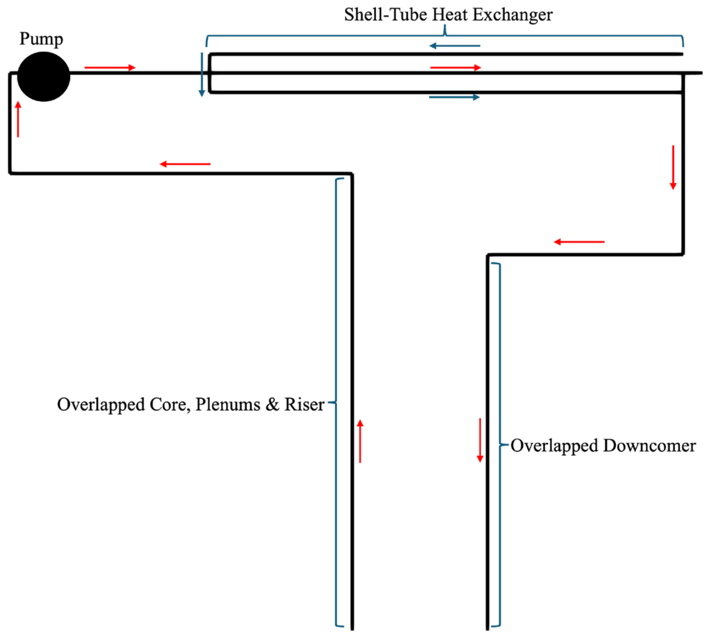
	Pronghorn-2D rz	SAM-1D
Mass Flow	0.0321 kg/s	0.0322 kg/s
Enthalpy	1.7359 MJ/kg	1.7363 MJ/kg
Temperature	892.4K	892.6K

SAM-Pronghorn-Griffin-Saline application case: Molten Salt Reactor Experiment (MSRE)

- Validation of the **SAM-Pronghorn-Griffin Domain Overlapping** with the **Saline** interface against the MSRE experiment.
- **Pronghorn (Core)**: Porous media model with mixing length turbulence model solving for momentum, pressure, enthalpy and Delayed Neutron Precursor (DNP).
- **Griffin (Core)**: SP1 neutron diffusion equation with DNP source.
- **SAM (1^{ry} and 2^{ry} System):** 1D solver for momentum, pressure, enthalpy and passive scalars (w/decay).







Property	Value
Molecular weight	40.05 g/mol
Density [kg/m^3]	2710 - 0.562*T
Viscosity [Pa.s]	$1.24e^{-4}$ *exp($3.13e^4$/(R*T))
Specific Heat [J/kg mol]	57.84 + 0.0259*T + $4.7441e^6$*T^{-2} - $7.51e^{-6}$*T^2
Thermal Conductivity [W/mK]	1.22

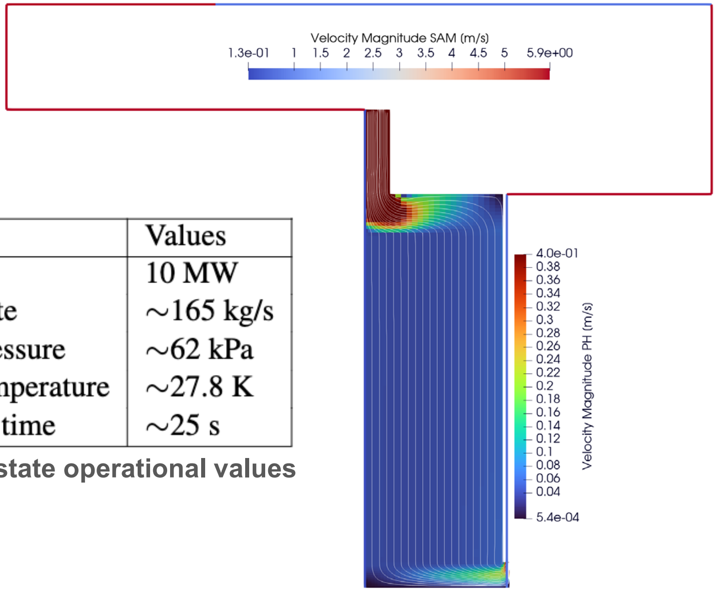
LiF-BeF2-ZrF4-UF4 salt thermophysical properties

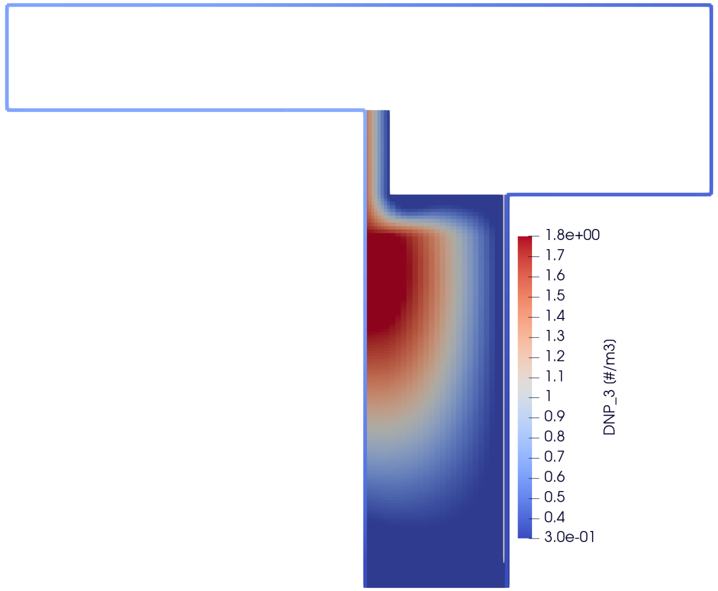
SAM-Pronghorn-Griffin-Saline application case: Molten Salt Reactor Experiment (MSRE)

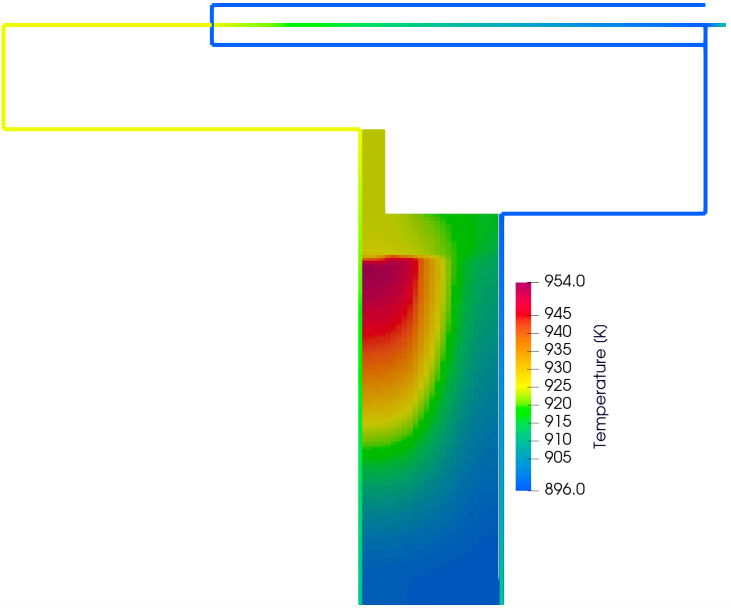
- Pump head sets the 165 kg/s mass flow rate with a 25 s recirculation time. One-dimensional flow is achieved in the core. Core pressure difference is 62.5 kPa.
- Fuel salt absorbs heat in reactor core, with a 27.8 K temperature difference between inlet and outlet. Primary loop temperature constant until heat exchanger, which then exits at 896 K.
- Domain Overlapping Approach integrates passive scalar advection and radioactive decay of the six DNP groups for reactivity prediction. DNPs follow fission source profile, decay over time, and are advected by velocity field.

Parameter	Values
Power	10 MW
Mass Flow rate	~165 kg/s
Delta core pressure	~62 kPa
Delta core temperature	~27.8 K
Recirculation time	~25 s

MSRE steady state operational values

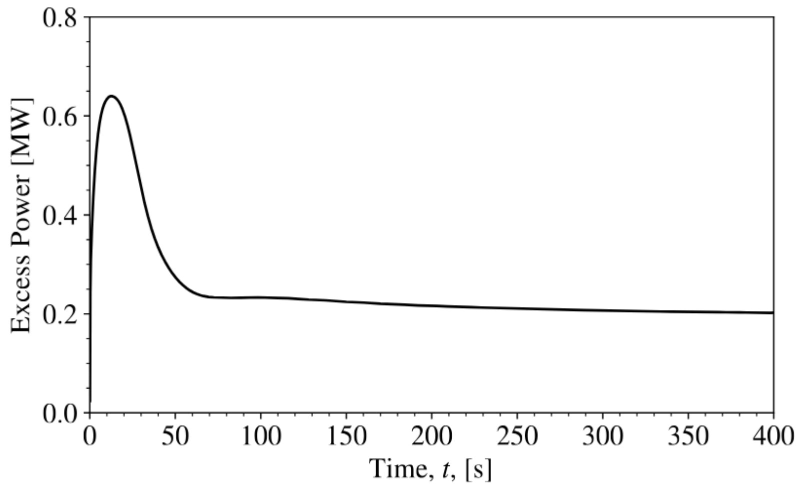






SAM-Pronghorn-Griffin-Saline application case: Molten Salt Reactor Experiment (MSRE)

- Pump startup transient at zero-power conditions. Void is not considered. We solve for an eigenvalue problem at each timestep. The reactivity evolution is compared to an equivalent rod worth extraction. A 6 pcm difference at steady state conditions is observed.
- Pump coast down transient at zero-power conditions. As flow rate decreases, neutron contributions from DNP decay increase. Domain-overlapped MSRE model aligns well with experimental reactivity loss values.
- Reactivity Insertion Transient. A 19 pcm insertion is introduced in the Griffin model by adjusting fuel fission cross section. Initial insertion causes rapid power and temperature increase, with negative density-Doppler feedback stabilizing power at ~5.2 MW.



Reactivity insertion transient.

Zero-Power pump startup reactivity transient.

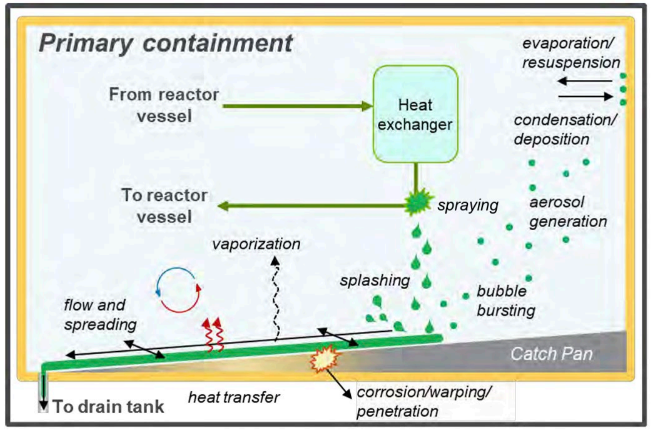
Zero-Power pump coast down reactivity transient.

Summary

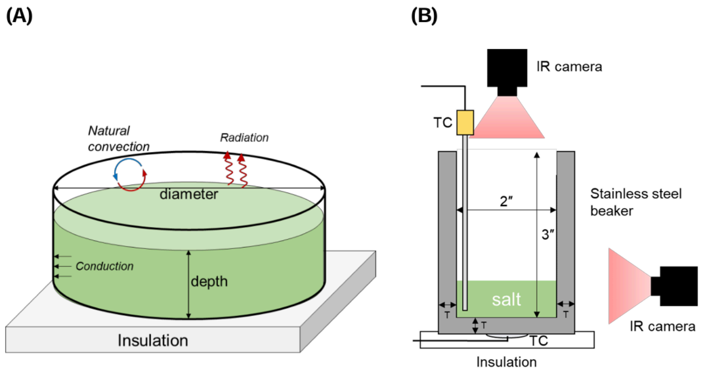
- Coupling of Pronghorn, SAM and Griffin with Saline to account for temperature-dependent thermophysical properties.
  - Enthalpy solver for $c_p(T)$ in the Finite Volume framework
  - Varying salt composition in the Saline Fluid Properties module.
  - BlueCrab compatibilization of passive scalar transfers in the Domain overlapping approach.
- Verification and Validation of the SAM-Pronghorn-Griffin-Saline coupled approach for the MSRE.
  - Steady state conditions
  - Pump startup, coast down and reactivity insertion.
- Ongoing work includes:
  - Continuation of the Domain Overlapping validation.
  - Development of 3D models of the MSRE with Domain Overlapping
  - Physical models for salt spill modeling.

FY25/26: Initial Salt Spill Modeling Capabilities

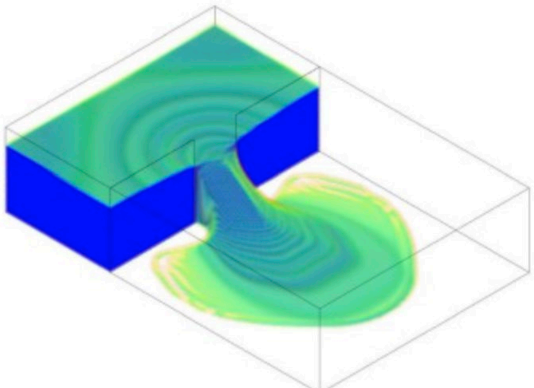
- **Radiation** modeling improvements:
  - Participating Media Radiation P1 model.
  - Surface to Surface Radiation in the Finite Volume formulation.
    - Ray Tracing Module to compute the view factors.
- **Solidification** modeling improvements:
  - Implementation in the Linear Finite Volume formulation.
- **Free-Surface** Modeling:
  - Eulerian Method: Volume of Fluid formulation
- **Aerosol Transport** Modeling



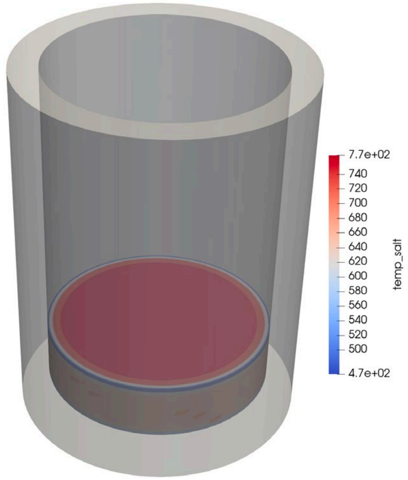
Salt Spill phenomena. Figure from [2]



Salt Spill experiment. Figure from [2]



Partial dam break simulation. Figure from [1]



[1] Issakhov, Alibek, and Medina Imanberdiyeva. "Numerical simulation of the movement of water surface of dam break flow by VOF methods for various obstacles." *International Journal of Heat and Mass Transfer* 136 (2019): 1030-1051.
[2] Thomas, Sara, and Josh Jackson. *MSR Salt Spill Accident Testing Using Eutectic NaCl-UCl3*. No. ANL/CFCT-22/32. Argonne National Laboratory (ANL), Argonne, IL (United States), 2022.

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