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Release on the Virtual Test Bed of an MSRE thermal hydraulics model

November 2023

Changing the World's Energy Future

Andres Nicolas Fierro Lopez, Guillaume Louis Giudicelli

Idaho National Laboratory

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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Molten Salt Reactor Experiment (MSRE) Description

Contact: Mauricio Tano, mauricio.tanoretamales.at.inl.gov

Model summarized, documented, and uploaded by Andres Fierro

The MSRE was a graphite moderated flowing salt type reactor with a design maximum operating power of 10 MW(th) developed by Oak Ridge National Laboratory (Robertson, 1965). The reactor ran for more than 13,000 hours at full power before its final shut down in 1969. The general layout of the experiment is shown in Figure 1.

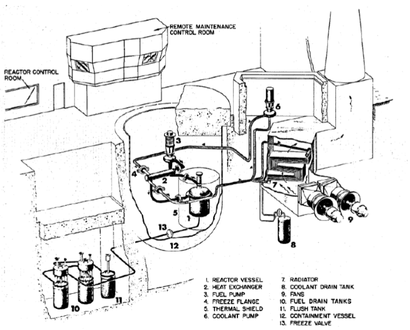

Figure 1: Schematic design of MSRE loops (Fratoni et al., 2020).

The fuel salt was a fluoride based ionic liquid containing lithium, beryllium, zirconium and uranium fuel. The coolant salt was a mixture of lithium fluoride and beryllium fluoride. The reactor consisted of two flow loops: a primary loop and a secondary loop. The primary loop connected the reactor vessel to a fuel salt centrifugal pump and the shell side of the shell-and-tube heat exchanger. The secondary loop connected the tube-side of the shell-and-tube heat exchanger to a coolant salt centrifugal pump and the tube side of an air-cooled radiator. Two axial blowers supplied cooling air to the radiator. Piping, drain tanks and “freeze valves” made up the remaining components of the heat transport circuits. The heat generated in the core was transferred to the secondary loop through the heat exchanger and ultimately rejected to the atmosphere through the radiator.

The three main features of this experiment are:

- The core circulation system, where the molten salt fuel flows through rounded-rectangular channels in the vertical graphite moderator stringers
- The centrifugal pump that provided continuous circulation, facilitated heat transfer and the removal of fission products
- The two-loop heat exchanger system with an approximately 25-second fuel loop circulation time in the reactor.

We note that the MSRE was a thermal reactor with a highly negative reactivity temperature coefficient. The vertical graphite stringers are shown in Figure 2.

Table 1: MSRE Reactor Specifications

Parameter	**Value**
Core Power	10 MW_{th} (MegaWatt Thermal)|
Core height	1.63 m
Core diameter	1.39 m
Fuel Salt	LiF-BeF_2-ZrF_4-UF_4
Fuel salt molar mass	65.0%-29.1%-5.0%-0.9%
Fuel salt enrichment	33.0%

Parameter	Value
Channels in graphite moderator	3.05 cm × 1.016 cm
Channels' rounded corners radii	0.508 cm
Vertical graphite stringers	5.08 cm × 5.08 cm

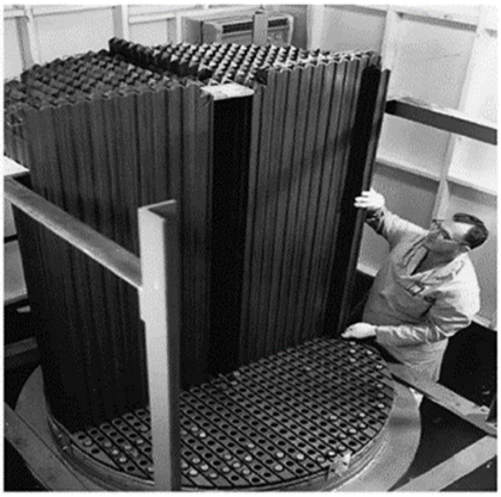

Figure 2: Picture of MSRE core graphite stringers (Fratoni et al., 2020)

Material Properties and MSRE Setup

The fuel salt in the MSRE primary loop was LiF-BeF4-ZrF4-UF4 according to the design specifications of the MSRE (E. et al., 1964; Cantor, 1968), of which the thermophysical properties are listed in Table 2.

Table 2: Thermophysical properties of the fuel salt

		Unit	$LiF-BeF_4-ZrF_4-UF_4$
Melting temperature	T_{melt}	K	722.15
Density	ρ	kg/m^3	$2553.3 - 0.562 \bullet T$
Dynamic viscosity	μ	$Pa \bullet s$	$8.4 \times 10^{-5} exp(4340/T)$
Thermal conductivity	k	$W/(m \bullet K)$	1.0
Specific heat capacity	c_p	$J/(kg \bullet K)$	2009.66

A conventional, cross-baffled, shell-and-tube type heat exchanger was used in MSRE. The fuel salt flows on the shell side while the coolant salt flows through the tube side. The coolant salt in the heat changer is $LiF-BeF_2$ (0.66-0.34) (Guymon, 1973), of which the major thermophysical properties are summarized in Table 3. Due to the space limitation in the reactor cell, a U-tube configuration is adopted, which results in a heat exchanger of roughly 2.5 m in length. The shell diameter is 0.41 m while the tube has a diameter of 1.27 cm and a thickness of 1.07 mm. Given a triangular arrangement of the tubes, the hydraulic diameters are 2.09 cm (shell-side) and 1.06 cm (tube-side). The construction material of heat exchanger is Hastelloy® N alloy with the properties listed in Table 4. All the connecting pipes have a default diameter of 0.127 m. A centrifugal pump is utilized, and its head is adjusted to sustain the flow circulation. The downcomer and lower plenum to the MSRE core are modeled with SAM 1-D components.

Table 3: Thermophysical properties of the coolant salt in heat exchanger.

		Unit	$LiF-BeF_2$ (0.66-0.34)
Melting temperature	T_{melt}	K	728
Density	ρ	kg/m^3	$2146.3 - 0.488 \bullet T$
Dynamic viscosity	μ	$Pa \bullet s$	$1.16 \times 10^{-4} exp(3755/T)$
Thermal conductivity	k	$W/(m \bullet K)$	1.1
Specific heat capacity	c_p	$J/(kg \bullet K)$	2390.0

Table 4: Thermophysical properties of Hastelloy® N alloy used in the heat exchanger.

		Unit	Hastelloy® N alloy
Density	ρ	kg/m^3	8860
Thermal conductivity	k	$W/(m \bullet K)$	23.6
Specific heat capacity	c_p	$J/(kg \bullet K)$	578

References

1. S. Cantor. Physical Properties of Molten-Salt Reactor Fuel, Coolant, and Flush Salts. Technical Report ORNL-TM-2316, Oak Ridge National Laboratory, Oak Ridge, TN, 1968. URL: https://www.osti.gov/biblio/4492893 https://www.osti.gov/servlets/purl/4492893, doi:10.2172/4492893. [BibTeX]

```
@techreport{Cantor1968,
    author = "Cantor, S.",
    address = "Oak Ridge, TN",
    doi = "10.2172/4492893",
    institution = "Oak Ridge National Laboratory",
    number = "ORNL-TM-2316",
    title = "{Physical Properties of Molten-Salt Reactor Fuel, Coolant, and Flush Salts}",
    url = "https://www.osti.gov/biblio/4492893 https://www.osti.gov/servlets/purl/4492893",
    year = "1968"
}
```

2. Beall S. E., Haubenreich P. N., Lindauer R. B., and Tallackson J. R. MSRE Design and Operations Report. Part V. Reactor Safety Analysis Report. Technical Report ORNL-TM-732, Oak Ridge National Laboratory, Oak Ridge, TN, 1964. [BibTeX]

```
@techreport{Beall1964,
    author = "E., Beall S. and N., Haubenreich P. and B., Lindauer R. and R., Tallackson J.",
    address = "Oak Ridge, TN",
    number = "ORNL-TM-732",
    institution = "Oak Ridge National Laboratory",
    title = "{MSRE Design and Operations Report. Part V. Reactor Safety Analysis Report}",
    year = "1964"
}
```

3. M. Fratoni, D. Shen, G. Ilas, and J. Powers. Molten Salt Reactor Experiment Benchmark Evaluation. 5 2020. URL: https://www.osti.gov/biblio/1617123, doi:10.2172/1617123. [BibTeX]

```
@article{osti_1617123,
    author = "Fratoni, M. and Shen, D. and Ilas, G. and Powers, J.",
    title = "{Molten Salt Reactor Experiment Benchmark Evaluation}",
    doi = "10.2172/1617123",
    url = "https://www.osti.gov/biblio/1617123",
    journal = "",
    place = "United States",
    year = "2020",
    month = "5"
}
```

4. R. H. Guymon. MSRE systems and components performance. Technical Report ORNL-TM-3039, Oak Ridge National Laboratory, Oak Ridge, TN, 1973. [BibTeX]

```
@techreport{Guymon1973,
    author = "Guymon, R. H.",
    address = "Oak Ridge, TN",
    number = "ORNL-TM-3039",
    institution = "Oak Ridge National Laboratory",
    title = "{MSRE systems and components performance}",
    year = "1973"
}
```

5. Robertson. MSRE design and operations report. Part I. Description of reactor design. Technical Report ORNL-TM-728, Oak Ridge National Laboratory, Oak Ridge, TN, 1965. [BibTeX]

```
@techreport{Robertson1965,
    author = "Robertson",
    address = "Oak Ridge, TN",
    number = "ORNL-TM-728",
    institution = "Oak Ridge National Laboratory",
    title = "{MSRE design and operations report. Part I. Description of reactor design}",
    year = "1965"
}
```


- Material Properties …

Molten Salt Reactor Experiment (MSRE) Pronghorn Model of the Core

Contact: Mauricio Tano, mauricio.tanoretamales.at.inl.gov

The Pronghorn multidimensional core model is described to contextualize the overlapping of the SAM primary loop model and the Pronghorn core.

This model of the MSRE utilizes Pronghorn to create a 2D, RZ (cylindrical coordinates), steady-state, medium-fidelity, coarse mesh thermal-hydraulics analysis of the core (Schunert et al., 2023). The parts of the core are represented in Figure 1.

The core is represented with a vertical porosity of 0.22283. No rugosity is assumed when computing the friction factor. This model's normalized power source can be calculated by Griffin (Jaradat and Ortensi, 2023), but in this instance we used a cosine-shaped power source, shown in Figure 3.

The salt flows down the `Downcomer`, through the `Lower Plenum` and up into the `Core`, is collected at the `Upper Plenum` and goes through the system through the `Outlet Pipe`. In the core, an anisotropic friction source coefficient keeps the flow approximately 1-Dimensional.

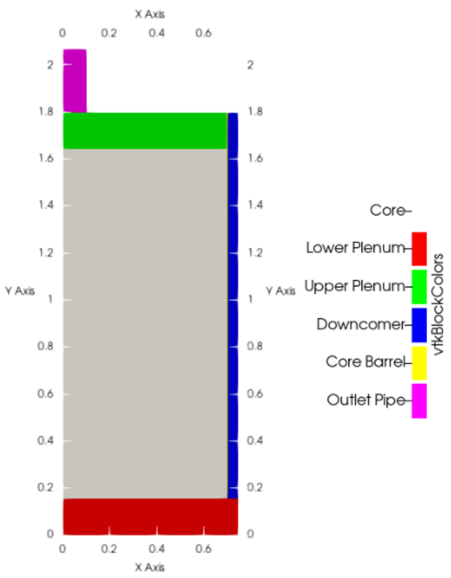

Figure 1: Subdomain in the axisymmetric Pronghorn model.

Computational Model Description

The Pronghorn input file adopts a block structured syntax. This section covers the important blocks in the input file.

Problem Parameters

The beginning of the input file lists the problem parameters the user can edit including the model's physical properties and initial conditions.

We first define a few geometrical parameters for the core dimensions, which can be referred to lower in the input file.

```
# Geometry ---------------------------------------------------------------------
#geometric_tolerance  = 1e-3   # Geometric tolerance to generate the side-sets (m).
#inner_radius         = 0.0
core_radius = 0.69793684
#outer_radius         = 0.74352625
#core_height          = 1.63
#reactor_height       = 1.973
core_top = 1.8115
```

(msr/msre/SAM_Pgh/steady_state_pgh/MSRE_pgh_steadyState.i)

The physical properties are defined in the next block. The core porosity is defined at a ration of 0.222831, calculated as the quotient of flow area by total core area. The porosity for the rest of the components is set to 1, full fluid region, but is editable by the user.

```
# Properties -------------------------------------------------------------------
#global_emissivity              = 0.80          # All the materials has the same emissivity (//).
core_porosity = 0.222831853 # core porosity salt VF=0.222831853, Graphite VF=0.777168147
down_comer_porosity = 1.0 # downcomer porosity
lower_plenum_porosity = 1.0 # lower pelnum porosity
upper_plenum_porosity = 1.0 # upper pelnum porosity
riser_porosity = 1.0 # riser porosity
pump_porosity = 1.0 # pump porosity
elbow_porosity = 1.0 # elbow porosity
```

(msr/msre/SAM_Pgh/steady_state_pgh/MSRE_pgh_steadyState.i)

The hydraulic diameters of the bypass fuel channel and of the downcomer were respectively defined at 19.1 mm (milimeters) and 512.7 mm. The fluid blocks are defined to indicate the fluid regions.

```
# Hydraulic diameter -----------------------------------------------------------
D_H_fuel_channel = 0.0191334114 # Hydraulic diameter of bypass
D_H_downcomer = 0.512700504 # Hydraulic diameter of riser

fluid_blocks = '1  2  3  4  7' # fluid blocks define fluid vars and solve for them
scaling = 10.0 # friction scaling
```

(msr/msre/SAM_Pgh/steady_state_pgh/MSRE_pgh_steadyState.i)

The following section focuses on the operational parameters. The mass flow rate was defined at 191.19 kilograms per second, with a core outlet pressure approximately atmospheric at 101.325 kiloPascals. The salt core inlet temperature is defined at to be 908.15 Kelvin (K) with an ambient room temperature defined to be 300K. Finally, this section defines the centrifugal pump force to be 98.2 kiloNewton (kN). Alpha is the heat exchange coefficient utilized in the convection fluid heat exchanger.

```
mfr = 191.1900 # Salt mass flow rate (kg/s).
p_outlet = 1.01325e+05 # Reactor outlet pressure (Pa)
T_inlet = 908.15 # Salt inlet temperature (K).
T_amb = 300.0 # Salt inlet temperature (K).
alpha = 5000.0

pump_force = 98200.0 # pump force functor
```

(msr/msre/SAM_Pgh/steady_state_pgh/MSRE_pgh_steadyState.i)

The end of the first section defines the delayed neutron group properties.

```
lambda1_m = 0.0133104
lambda2_m = 0.0305427
lambda3_m = 0.115179
lambda4_m = 0.301152
lambda5_m = 0.879376
lambda6_m = 2.91303
beta1 = 8.42817e-05
beta2 = 0.000684616
beta3 = 0.000479796
beta4 = 0.00103883
beta5 = 0.000549185
beta6 = 0.000184087

Sc_t = 1 # turbulent Schmidt number
```

(msr/msre/SAM_Pgh/steady_state_pgh/MSRE_pgh_steadyState.i)

Mesh

This block defines the geometry of the core, as shown in Figure 2. The mesh is defined in 2D cylindrical coordinates, 'RZ'. The first section associates a number ID to the name of a block so the subdomain id in the cartesian mesh can be defined in terms of the IDs.

The large white region in the mesh is called the core. The lower plenum is in red, the upper plenum is in green, the downcomer is the dark blue, and the riser (outlet pipe) is shown hot pink. The core barrel, the metallic shell that wraps the core is in bright yellow (between the core and downcomer).

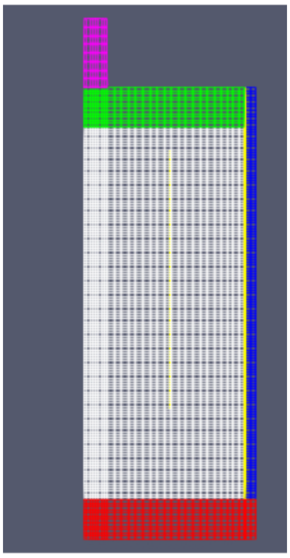

Figure 2: Mesh of the axisymmetric Pronghorn model.

```
[Mesh]
  coord_type = 'RZ'
  type = MeshGeneratorMesh
  block_id = '1 2 3 4 6 7 8 9'
  block_name = 'core  lower_plenum  upper_plenum  down_comer  core_barrel riser pump elbow'
  uniform_refine = 1

  [cartesian_mesh]
    type = CartesianMeshGenerator
    dim = 2
    dx = '0.1016  0.496855718  0.098795213  0.005 0.045589414'
    ix = '4           8            2         1          1'
    dy = '0.1715   0.100   0.100   0.246   0.246   0.246
         0.246   0.246   0.100   0.100   0.1715 0.3 0.1016'
    iy = '6  4  4  10  10  10  10  10  4  4  6  4 4'
    subdomain_id = ' 2  2  2  2  2
                     1  1  1  6  4
                     1  1  1  6  4
                     1  1  1  6  4
                     1  1  1  6  4
                     1  1  1  6  4
                     1  1  1  6  4
                     1  1  1  6  4
                     1  1  1  6  4
                     1  1  1  6  4
```

(msr/msre/SAM_Pgh/steady_state_pgh/MSRE_pgh_steadyState.i)

Constant Fields

Through the `Auxiliary Variables`, developers can define the variable type for porosity, power density, and the fission sources, along with their domain. The variable types, functions, and scaling factors are explained in detail here.

The porosity variable is a constant field defined in the fluid blocks across the domain. The fluid blocks are defined at the top of the header and are substituted using the `$` sign. Recall that the `$` sign refers to variable substitutions.

The power density is a constant field defined in the core and plena blocks. The initial conditions for both the power density and the fission source are a cosine guess, defined below. The neutron precursors, group C1 through C6, are also defined in the `Auxiliary Variable` block.

```
[AuxVariables]
  [porosity_var]
    type = MooseVariableFVReal
    block = ${fluid_blocks}
```

```
  []
  [power_density]
    type = MooseVariableFVReal
    [InitialCondition]
      type = FunctionIC
      function = 'cosine_guess'
      scaling_factor = '${fparse 2.9183E+6}'
    []
    block = '1 2 3'
  []
  [fission_source]
    type = MooseVariableFVReal
    [InitialCondition]
      type = FunctionIC
      function = 'cosine_guess'
      scaling_factor = '${fparse 1.0}'
    []
    block = '1 2 3'
  []
  [rho_var]
```

(msr/msre/SAM_Pgh/steady_state_pgh/MSRE_pgh_steadyState.i)

This model's distribution of fission for the core and the sources are editable so developers can try their own fission distributions. The power function is defined radially and axially with the cosine shape. The cosine shape, or "guess," is defined as an object under the function system.

```
[cosine_guess]
  type = ParsedFunction
  expression = 'max(0, cos(x*pi/2/1.0))*max(0, cos((y-1.0)*pi/2/1.1))'
[]
```

(msr/msre/SAM_Pgh/steady_state_pgh/MSRE_pgh_steadyState.i)

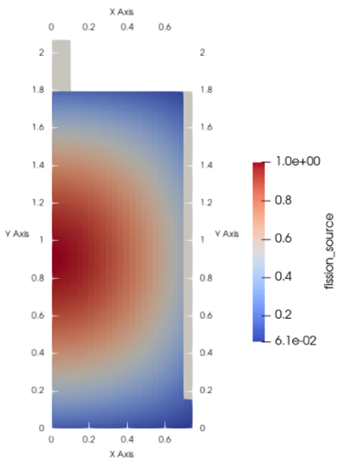

Figure 3: Normalized power source at steady state.

Fluid Properties

This block contains parameters applied to all the core components. The `fluid_properties_obj` refers to the primary salt F-Li-Be (Flibe), already defined within MOOSE.

```
[FluidProperties]
  [fluid_properties_obj]
    type = FlibeFluidProperties
  []
[]
```

(msr/msre/SAM_Pgh/steady_state_pgh/MSRE_pgh_steadyState.i)

Fluid properties are further defined within the `Navier Stokes Finite Volume` action and the Materials block.

```
# fluid properties
density = 'rho'
dynamic_viscosity = 'mu'
thermal_conductivity = 'kappa'
specific_heat = 'cp'
```

(msr/msre/SAM_Pgh/steady_state_pgh/MSRE_pgh_steadyState.i)

```
## Fluid properties and non-dimensional numbers
[fluid_props_to_mat_props]
  type = GeneralFunctorFluidProps
```

```
    pressure = 'pressure'
    T_fluid = 'T_fluid'
    speed = 'speed'
    # mu_rampdown = 'mu' #'mu_ramp_fn'  # To initialize with a high viscosity
    characteristic_length = characteristic_length
    block = ${fluid_blocks}
```
(msr/msre/SAM_Pgh/steady_state_pgh/MSRE_pgh_steadyState.i)

Porous Media Navier Stokes Equations

The `Navier Stokes Finite Volume` action was added to define fluid properties, compute the "weakly-compressible" flow, and to set up boundary conditions and the passive scalar advection.

```
[Modules]
  [NavierStokesFV]
    # Basic settings
    block = ${fluid_blocks}
    compressibility = 'weakly-compressible'
    porous_medium_treatment = true
    add_energy_equation = true

    #Scaling
    energy_scaling = 1e-6
    momentum_scaling = 1e-3
    mass_scaling = 10
    # Gravity
    # gravity = '0.0 0.0 0.0' #'0.0 -9.81 0.0'

    # Numerical schemes
    pressure_face_interpolation = average
    momentum_advection_interpolation = upwind
    mass_advection_interpolation = upwind
    energy_advection_interpolation = upwind
    velocity_interpolation = rc
    velocity_variable = 'vel_x vel_y'

    # Porous & Friction treatement
    use_friction_correction = true
```
(msr/msre/SAM_Pgh/steady_state_pgh/MSRE_pgh_steadyState.i)

Results

The multi-dimensional velocity field becomes approximately 1D due to the anisotropic friction coefficient blocking flow in the horizontal direction. Figure 3 and Figure 4 show the power source distribution calculated by Griffin and the resultant velocity field respectively. Figure 5 and Figure 6 show the predicted pressure variation across the entire model and the core.

The pressure of the salts is highest after the cooling in the heat exchanger as they flow down the downcomer. The pressure in the lower plenum is about equal as the salts commence to flow up the core, but the pressure drops in slightly different gradients depending on the proximity to the outlet pipe. The gravity term has arbitrarily been turned off.

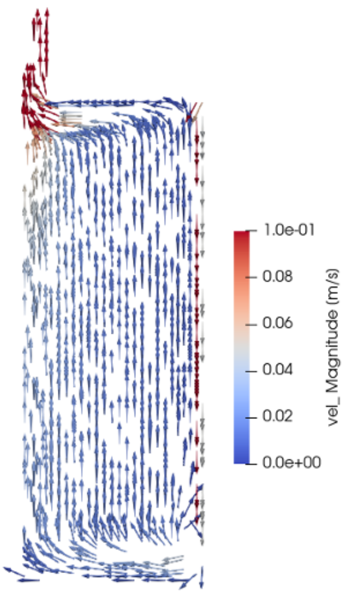

Figure 4: Vector plot of the velocity field colored with velocity magnitude (m/s).

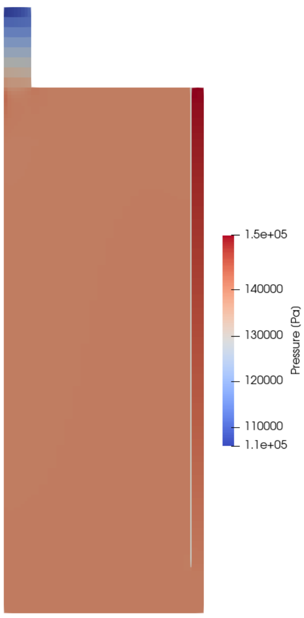

Figure 5: Pressure variation across Pronghorn model (Pa).

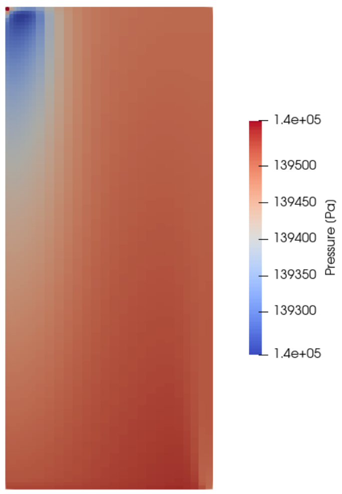

Figure 6: Pressure variation across Pronghorn core (Pa).

Execution

To apply for access to Pronghorn and HPC, please visit NCRC. To run the Pronghorn model on:

INL HPC:

```
module load use.moose moose-apps pronghorn

mpiexec -n 6 pronghorn-opt -i MSRE_pgh_steadyState.i
```

Local Device:

Note: need at least NCRC level 2 access to Pronghorn

```
mamba deactivate

mamba activate pronghorn

mpiexec -n 6 pronghorn-opt -i MSRE_pgh_steadyState.i
```

Note: With source-code access to Pronghorn

```
mpiexec -n 6 ~/projects/pronghorn/pronghorn-opt -i MSRE_pgh_steadyState.i
```

References

1. M. Jaradat and J. Ortensi. Thermal Spectrum Molten Salt-Fueled Reactor Reference Plant Model. *Idaho National Laboratory*, 07 2023. [BibTeX]

```
@article{Javi23,
    author = "Jaradat, M. and Ortensi, J.",
    title = "{Thermal Spectrum Molten Salt-Fueled Reactor Reference Plant Model}",
    journal = "Idaho National Laboratory",
    volume = "INL/RPT-23-72875",
    year = "2023",
    month = "07",
    publisher = "OSTI"
}
```

2. Sebastian Schunert, Mauricio Tano Retamales, and Mustafa Jaradat. Overlapping Domain Coupling of Multidimensional and System Codes in NEAMS - Pronghorn and SAM. Technical Report INL/RPT-23-72874, Idaho National Laboratory, 2023. [BibTeX]

```
@techreport{Mau23,
    Author = "Schunert, Sebastian and Retamales, Mauricio Tano and Jaradat, Mustafa",
    Institution = "Idaho National Laboratory",
    Number = "INL/RPT-23-72874",
    title = "{Overlapping Domain Coupling of Multidimensional and System Codes in NEAMS - Pronghorn and SA
    Year = "2023"
}
```


(msr/msre/SAM_Pgh/steady_state_pgh/MSRE_pgh_steadyState.i)

```
# ==============================================================================
# Model description
# ------------------------------------------------------------------------------
# Steady state MSRE model Created by Mauricio Tano, 2023
# ==============================================================================
# MSRE: reference plant design based on 10MW of MSRE Experiment.
# ==============================================================================
# MODEL PARAMETERS
# ==============================================================================
# Problem Parameters -----------------------------------------------------------
# Geometry ---------------------------------------------------------------------
#geometric_tolerance  = 1e-3   # Geometric tolerance to generate the side-sets (m).
#inner_radius         = 0.0
core_radius = 0.69793684
#outer_radius         = 0.74352625
#core_height          = 1.63
#reactor_height       = 1.973
core_top = 1.8115
core_bottom = 0.1615

# Properties -------------------------------------------------------------------
#global_emissivity              = 0.80          # All the materials has the same emissivity (//).
core_porosity = 0.222831853 # core porosity salt VF=0.222831853, Graphite VF=0.777168147
down_comer_porosity = 1.0 # downcomer porosity
lower_plenum_porosity = 1.0 # lower pelnum porosity
```

Close

(msr/msre/SAM_Pgh/steady_state_pgh/MSRE_pgh_steadyState.i)

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#core_height          = 1.63
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```

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(msr/msre/SAM_Pgh/steady_state_pgh/MSRE_pgh_steadyState.i)


```
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(msr/msre/SAM_Pgh/steady_state_pgh/MSRE_pgh_steadyState.i)

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Close

Molten Salt Reactor Experiment (MSRE) Sam-Pronghorn Domain Overlapping Coupling

Contact: Mauricio Tano, mauricio.tanoretamales.at.inl.gov

This model features the Overlapping Domain Coupling method, through the `Action` in BlueCRAB `[OverlappingDomainCoupling]`, to couple the thermal hydraulics of the system and core over a wide range of reactor operating conditions. SAM offers a 1D plant-wide view, Pronghorn offers a detailed multi-dimensional analysis of advanced reactor cores and integral loops. The action overlaps the `Downcomer`, `Core`, and `Plena` to automatically make Pronghorn incorporate volumetric sources into the overlapped SAM components.

SAM and Pronghorn are available independently or together via BlueCRAB. Pronghorn simulates the multi-dimensional core thermal hydraulics and SAM simulates the 1D system representation. Figure 1 shows the coupled models. Note that the SAM model collapse the 2D mesh into 1D simplifications.

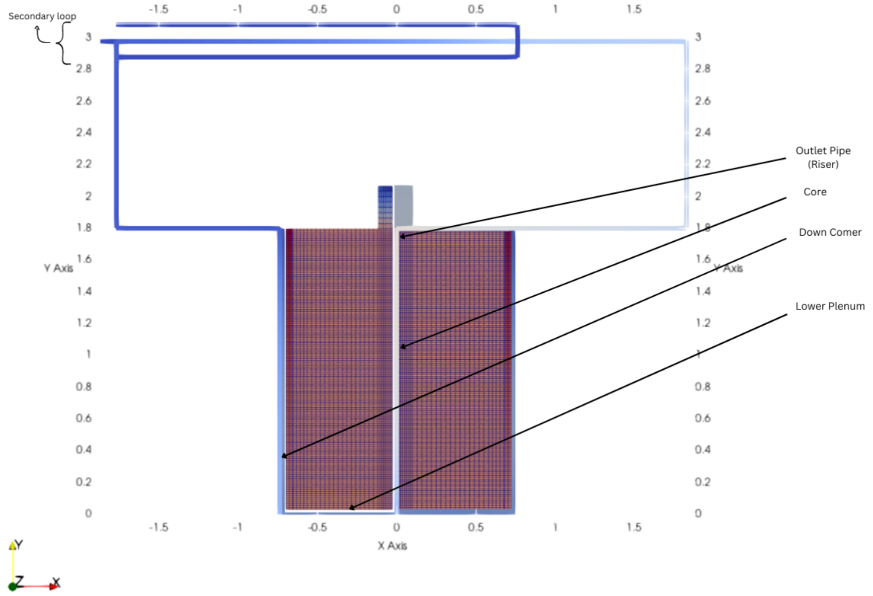

Figure 1: Coupled SAM-Pronghorn labeled mesh.

Overlapping Domain Coupling Description

The overlapping domain multi-dimensional coupling action, described in Schunert et al. (2023), couples the SAM System model to the Pronghorn core model. The domain overlapping coupling abstracts the Pronghorn core in an overlapping SAM component. It also automatically sets up boundary conditions for the multi-dimensional core simulation.

To perform a steady state relaxation transient, to obtain initial conditions, the `Action` transfers information between SAM and Pronghorn until they are equivalent: their differences converge within a tolerance. The behavior of the multi-dimensional core and the approximate components converge within a tolerance in terms of pressure drop temperature increase.

The transient method uses the same information transfer between SAM and Pronghorn, but they are iterated every time-step through a fixed-point iteration method until they are equivalent.

Through the custom action `[OverlappingDomainCouplings]`, provided the user has access to BlueCRAB in addition to Pronghorn and SAM, the `Action` will set up all additional objects and equations required. This action adds versatility by allowing multiple inlets and outlets, complex geometries, dealing with inertial forces implicitly, among other features.

Computational Model Parameters

Overlapping Domain Coupling Action

This action block defines the overlapping boundaries, the information to transfer, and gives the command to execute on the SAM MultiApp. The boundaries and the volumetric information is collected via `Postprocessors`, some of which are automatically added by the action.

The boundaries are specified as the $downcomer\_inlet$ and the $pump\_outlet$. The boundaries are oriented as in and out respectively. Their cross-sectional areas are defined along with corresponding connected components $pipe3\_s2$ and $pipe1\_s1$.

```
[OverlappingDomainCoupling]

  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'
```

(msr/msre/SAM_Pgh/coupled/MSRE_coupled.i)

Subsequently, the names of the `Postprocessors` evaluating the properties at the boundaries are defined. Some initial conditions are provided for the first step.

```
boundary_massflowrate_names = 'mfr_downcomer mfr_core'
boundary_pressure_names = 'p_downcomer p_core'
initial_boundary_massflowrate = '${mfr} ${fparse -mfr}'
initial_boundary_pressure = '${p_outlet} ${p_outlet}'
```

(msr/msre/SAM_Pgh/coupled/MSRE_coupled.i)

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

(msr/msre/SAM_Pgh/coupled/MSRE_coupled.i)

The block relates the names of the passive scalars to the transfer action that sends and receives them in SAM. Here, the decay constant and the initial conditions are defined.

```
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
```

(msr/msre/SAM_Pgh/coupled/MSRE_coupled.i)

Finally, the action calls the SAM file "MSRE_coupled.i" to perform the information transfer through the `Postprocessors`.

```
hydrodynamic_iteration_type = simple
thermal_iteration_type = simple

show_pps = true
sub_cycling = true
print_sub_cycles = true

startup_time = 0.5
```

```
  eos = fuel_salt_eos
  execute_multiapp_on = 'TIMESTEP_BEGIN'
```

(msr/msre/SAM_Pgh/coupled/MSRE_coupled.i)

Postprocessing

When reading this file, the user must note that the `Postprocessors` are divided into two `Postprocessors` blocks. The first block is dedicated to receiving the precursors passive scalars from SAM (this will not be utilized until the Domain-overlapping coupling), and the second `Postprocessors` block is dedicated to sending information like pressure, enthalpy, temperature, and mass-flow-rate to the SAM model.

Shown below is the second `Postprocessors` block:

```
[Postprocessors]

  [reference_plane_pressure]
    type = SideAverageValue
    variable = pressure
    boundary = 'lower_plenum_to_core'
  []
  [reference_plane_enthalpy]
    type = MfrWeightedAverage
    vel_x = vel_x
    vel_y = vel_y
    advected_quantity = cp_temp
    density = rho
    rhie_chow_user_object = pins_rhie_chow_interpolator
    boundary = 'lower_plenum_to_core'
  []
  [outlet_T]
    type = SideAverageValue
    variable = 'T_fluid'
    boundary = 'pump_outlet'
  []
  [inlet_p]
    type = SideAverageValue
    variable = 'pressure'
    boundary = 'downcomer_inlet'
```

(msr/msre/SAM_Pgh/coupled/MSRE_coupled.i)

Steady State Results

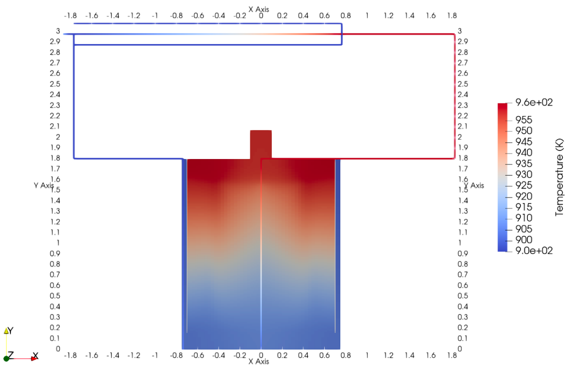

Figure 2: Coupled SAM-Pronghorn temperature model (K), (Schunert et al., 2023).

The Overlapping domain coupling method achieves a MSRE model that provides consistent pressure, mass flow-rate, enthalpy, and passive scalars between the two apps. In Figure 2, we find that the heat source incorporated by Pronghorn into the the overlapped SAM components matches SAM's response. The simulation predicts a temperature increase of about 60 K (kelvin) in the core. The temperature variation predicted across the downcomer is small. The mass-flow averages, velocities, and accelerations predicted by Pronghorn at the exit of the core match the SAM predictions.

Transient Results

For the transient results, we tested a reactivity insertion of 19 percent-mili (pcm) at 5 MegaWatts, from ORNL (Oak Ridge National Laboratory) reports (Steffy and Wood, 1969). Note: because there are no control rods in the Griffin model, the increase was achieved by temporarily artificially increasing the fission cross-section of the fuel. The Pronghorn model successfully captured the thermal oscillations induced by the density-Doppler power-temperature relationship.

The method converges reliably and efficiently, with a maximum of 15 iterations but usually less than ten iterations in the tested case. This coupling method converges faster than comparable methods, achieving less error than the domain-segregated method or a standalone SAM model. This may be due to the improved temperature resolution in the core. Note that as the limit of the time-step goes to zero, the domain-overlapping and the domain-segregated should yield same results.

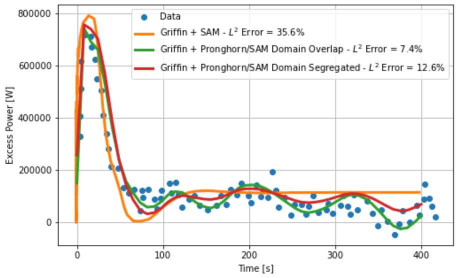

Figure 3: Error Comparison, (Schunert et al., 2023).

Execution

To apply for access to SAM, Pronghorn, and HPC (INL's High Performance Computing supercomputer), please visit NCRC. To run the coupled model:

INL HPC:

```
module load use.moose moose-apps bluecrab

mpiexec -n 6 bluecrab-opt -i MSRE_coupled.i
```

Local Device:

Note: Need at least NCRC level 2 access to BlueCRAB

```
mamba deactivate

mamba activate bluecrab


mpiexec -n 6 bluecrab-opt -i MSRE_coupled.i
```

Note: With source-code access to BlueCRAB

```
mpiexec -n 6 ~/projects/bluecrab/bluecrab-opt -i MSRE_coupled.i
```

References

1. Sebastian Schunert, Mauricio Tano Retamales, and Mustafa Jaradat. Overlapping Domain Coupling of Multidimensional and System Codes in NEAMS - Pronghorn and SAM. Technical Report INL/RPT-23-72874, Idaho National Laboratory, 2023. [BibTeX]

```
@techreport{Mau23,
    Author = "Schunert, Sebastian and Retamales, Mauricio Tano and Jaradat, Mustafa",
    Institution = "Idaho National Laboratory",
    Number = "INL/RPT-23-72874",
    title = "{Overlapping Domain Coupling of Multidimensional and System Codes in NEAMS - Pronghorn and SA
    Year = "2023"
}
```

2. RC Steffy and PJ Wood. Theoretical dynamic analysis of the MSRE with 233U fuel. *ORNL-TM-2571*, 1969. [BibTeX]

```
@article{steffy1969,
    author = "Steffy, RC and Wood, PJ",
    title = "{Theoretical dynamic analysis of the MSRE with 233U fuel}",
    journal = "ORNL-TM-2571",
    year = "1969",
    publisher = "Oak Ridge National Laboratory"
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# ==============================================================================
# Model description
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# Steady state MSRE model Created by Mauricio Tano, 2023
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# MSRE: reference plant design based on 10MW of MSRE Experiment.
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# MODEL PARAMETERS
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# Problem Parameters -----------------------------------------------------------
# Geometry ---------------------------------------------------------------------
#geometric_tolerance  = 1e-3   # Geometric tolerance to generate the side-sets (m).
#inner_radius         = 0.0
core_radius = 0.69793684
#outer_radius         = 0.74352625
#core_height          = 1.63
#reactor_height       = 1.973
core_top = 1.8115
core_bottom = 0.1615

# Properties -------------------------------------------------------------------
#global_emissivity              = 0.80          # All the materials has the same emissivity (//).
core_porosity = 0.222831853 # core porosity salt VF=0.222831853, Graphite VF=0.777168147
down_comer_porosity = 1.0 # downcomer porosity
lower_plenum_porosity = 1.0 # lower pelnum porosity
```


Close