Introduction to Molten Salt Reactors Modeling

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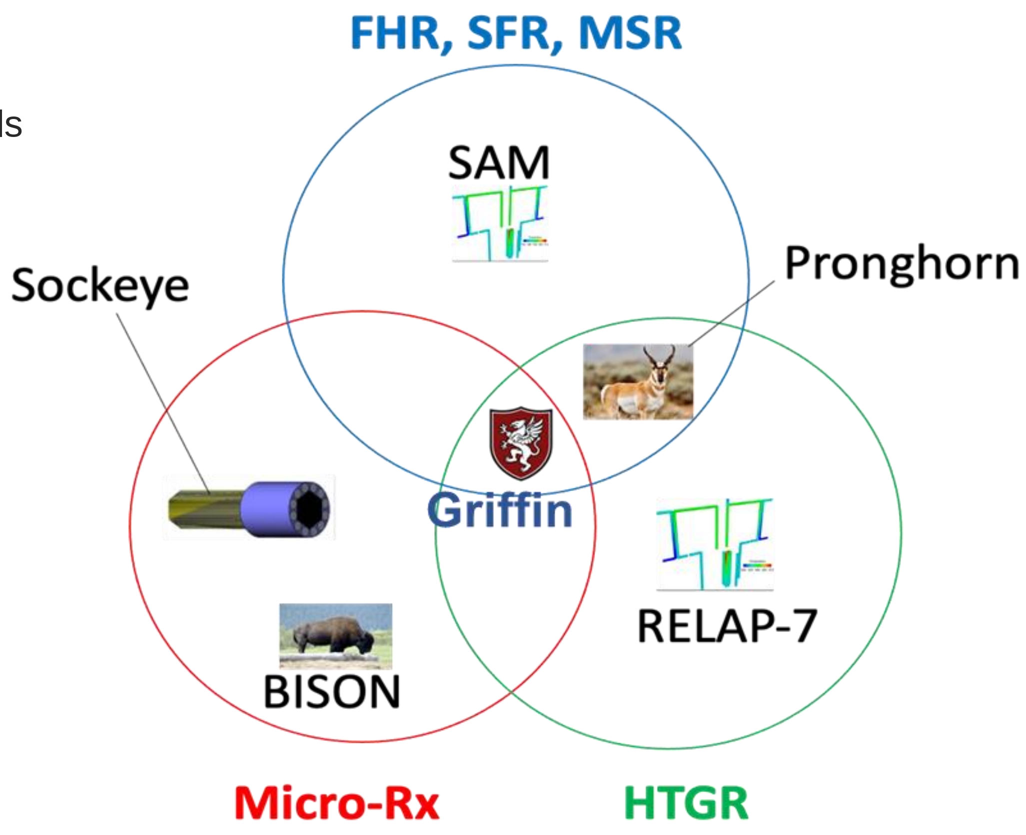
MOOSE-Based Applications: Griffin-Pronghorn-SAM

- Griffin a MOOSE-based application for
  - A generalized tool for reactor physics/ neutronics (non-LWR reactors)
  - Multiphysics-oriented: Provides native coupling to all MOOSE-based tools
  - Flexible and Extendable
    - Regular and unstructured geometries
    - Easy addition of functionality (e.g., advection term for MSR)

- Pronghorn is a MOOSE-based application for
  - Coarse-mesh tool for thermal-hydraulics calculations.
  - Solves multidimensional compressible/incompressible Euler equations
  - Handle porous and non-porous flow configurations.
  - Model the transport of DNPs with advection through the system.



Part of the U.S. NRC’s Comprehensive Reactor Analysis Bundle (CRAB)

Flowing Fuel Governing Equations of / Steady State

- Multigroup neutron diffusion equation of **stationary fuel** is given as**:**

$$-\nabla\cdot D_g\nabla\phi_g+\Sigma_{tg}\phi_g=\sum_{g'=1}^{G}\Sigma_{sg'g}\phi_{g'}+\frac{\chi_g}{k_{eff}}\sum_{g'=1}^{G}\nu\Sigma_{fg'}\phi_{g'}$$

Total fission neutrons fraction

$$\chi_g=\frac{\chi_{pg}\sum_{g'=1}^{G}\nu_p\Sigma_{fg'}\phi_{g'}+\sum_{k=1}^{K}\chi_{dkg}\sum_{g'=1}^{G}\nu_{dk}\Sigma_{fg'}\phi_{g'}}{\sum_{g'=1}^{G}\nu\Sigma_{fg'}\phi_{g'}}$$

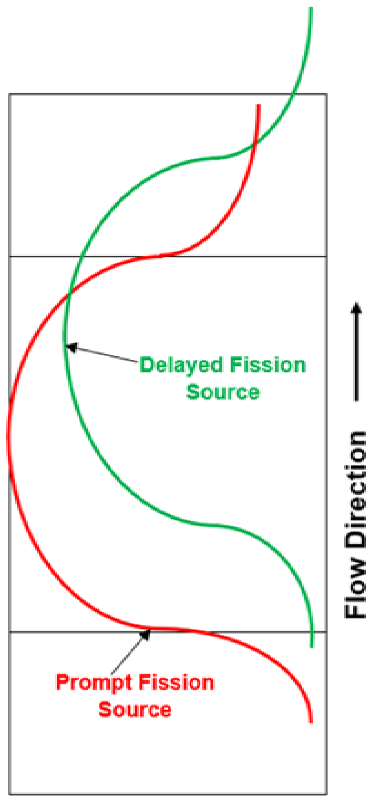
- Multigroup neutron diffusion equation and delayed neutron precursor equation of **flowing fuel** are given as:

$$-\nabla\cdot D_g\nabla\phi_g+\Sigma_{tg}\phi_g=\sum_{g'=1}^{G}\Sigma_{sg'g}\phi_{g'}+\underbrace{\frac{\chi_{pg}}{k_{eff}}\sum_{g'=1}^{G}\nu_p\Sigma_{fg'}\phi_{g'}}_{\text{Prompt Fission Source}}+\underbrace{\sum_{k=1}^{K}\chi_{dkg}\lambda_k C_k}_{\text{Delayed Fission Source}}$$

$$\nabla\cdot[\vec{u}(\vec{r})C_k(\vec{r})]+\lambda_k C_k(\vec{r})=\frac{1}{k_{eff}}\psi_k(\vec{r})$$

$$\psi_k(\vec{r})=\sum_{g'=1}^{G}\nu_{dk}\Sigma_{fg'}(\vec{r})\phi_{g'}(\vec{r})$$

$$C_k(r,0)=\frac{\int_{A_{out}}dAu(r,H)C_k(r,H)e^{-\lambda_k\tau}}{\int_{A_{in}}dAu(r,0)}$$



Flowing Fuel Governing Equations of / Time Dependent

- **Neutron flux:**

$$\frac{1}{v_g}\frac{\partial}{\partial t}\psi_g(\vec{r},\Omega,t)+\Omega\cdot\nabla\psi_g(\vec{r},\Omega,t)+\Sigma_{tg}(\vec{r},t)\psi_g(\vec{r},\Omega,t)=\sum_{g'=1}^{G}\Sigma_{sg'\to g}(\vec{r},\Omega'\cdot\Omega,t)\psi_{g'}(\vec{r},\Omega',t)$$

$$+\underbrace{\frac{1}{k_{eff}}\frac{\chi_{pg}(\vec{r},t)}{4\pi}\sum_{g'=1}^{G}\nu_p\Sigma_{fg'}(\vec{r},t)\phi_{g'}(\vec{r},t)}_{\text{Prompt Fission Source}}+\underbrace{\frac{1}{4\pi}\sum_{k=1}^{K}\chi_{dkg}(\vec{r},t)\lambda_k C_k(\vec{r},t)}_{\text{Delayed Fission Source}},\quad g=1,2,\cdots,G$$

- **DNPC**

$$\frac{\partial}{\partial t}C_k(\vec{r},t)+\underbrace{\nabla\cdot[\vec{u}(\vec{r},t)C_k(\vec{r},t)]}_{\text{Precursor Drift}}+\lambda_k C_k(\vec{r},t)=\frac{1}{k_{eff}}\sum_{g'=1}^{G}\nu_{dk}\Sigma_{fg'}(\vec{r},t)\phi_{g'}(\vec{r},t),\quad k=1,2,\cdots,K$$

- **Nuclide depletion:**

$$\frac{\partial N_i}{\partial t}+\underbrace{\nabla\cdot[\vec{u}N_i]}_{\text{Nuclide Drift}}+\left(\lambda_i+\underbrace{\lambda_i^R}_{\text{Reprocessing}}\right)N_i+N_i\sum_{g'=1}^{G}\sigma_{a,g'}^{i}\phi_{g'}=\sum_{j=1}^{Niso}\gamma'_{ij}\sum_{g'=1}^{G}N_j\sigma_{g'}^{j}\phi_{g'}+\sum_{j=1}^{Niso}\gamma_{ij}\lambda_j N_j+\underbrace{F_i}_{\text{Refueling}}$$

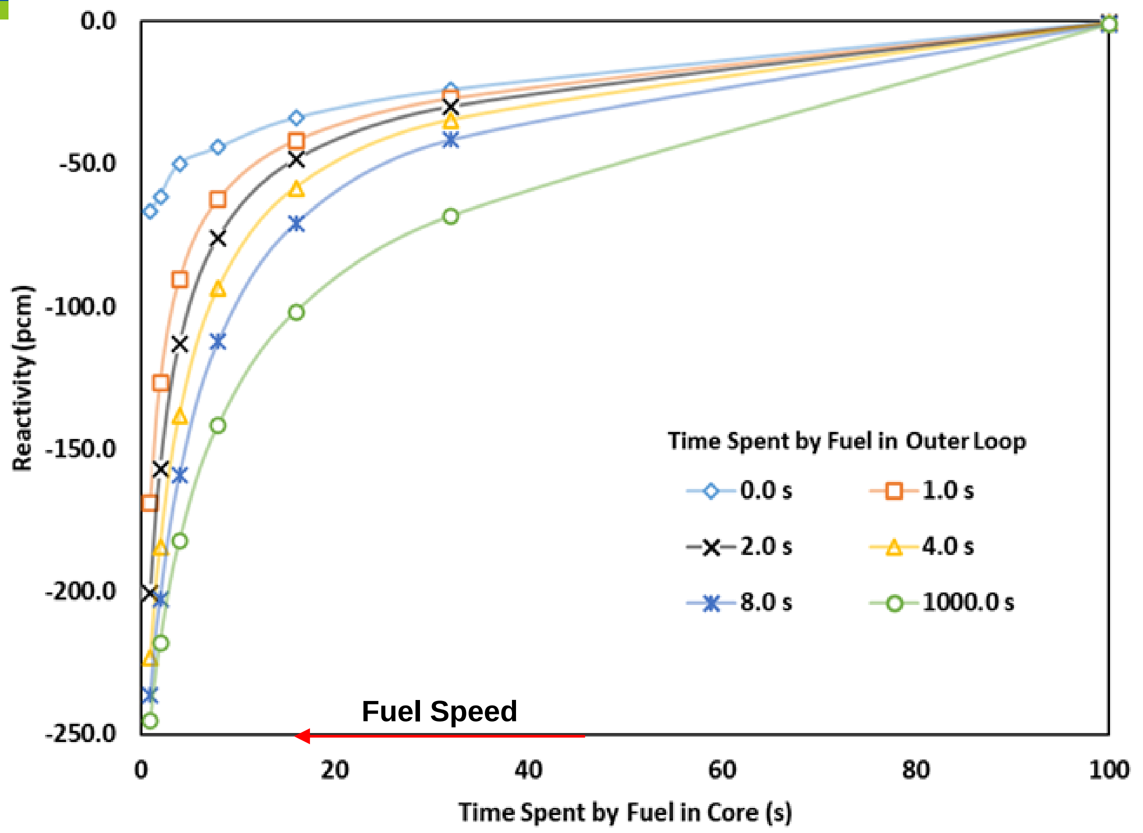
- **Decay Heat:**

$$\frac{\partial}{\partial t}h_k+\underbrace{\nabla\cdot[\vec{u}h_k]}_{\text{Decay Heat Precursor Drift}}+\lambda_k h_k=f_k\sum_{g=1}^{G}\kappa_f\Sigma_{fg}\phi_g$$

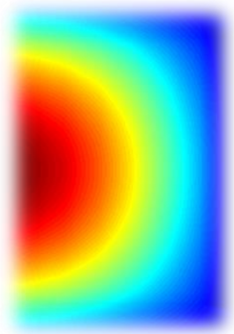
- **Nuclide Distribution:**

$$\frac{\partial}{\partial t}N_i(\vec{r},t)+\underbrace{\nabla\cdot[\vec{u}(\vec{r},t)N_i(\vec{r},t)]}_{\text{Nuclide Drift}}=S_i(\vec{r},t)$$

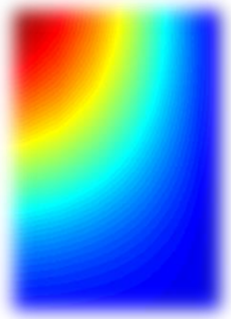
Reactivity Loss with Fuel Flow



$$\beta_{circ} = \frac{\sum_i V_i \sum_{g=1}^{G} \phi^*_{g,i} \sum_{k=1}^{K} \chi_{dkg} \lambda_k C_{k,i}}{\sum_i V_i \sum_{g=1}^{G} \phi^*_{g,i} \chi_{pg,i} \sum_{g'=1}^{G} \nu_p \Sigma_{fg',i} \phi_{g',i} + \sum_i V_i \sum_{g=1}^{G} \phi^*_{g,i} \sum_{k=1}^{K} \chi_{dkg,i} \lambda_k C_{k,i}}$$



$$\cancel{\nabla \cdot [\vec{u} C_k]} + \lambda_k C_k = \sum_{g'=1}^{G} \nu_{dk} \Sigma_{fg'} \phi_{g'}$$



$$\beta_{loss} = \beta_{eff} - \beta_{circ} = \rho_{loss}$$

$$\rho_{loss} = \frac{1}{k_{eff}^{circ}} - \frac{1}{k_{eff}^{static}} = \beta_{loss}$$

$$\beta_{eff} = \frac{\sum_i V_i \sum_{g=1}^{G} \phi^*_{g,i} \sum_{k=1}^{K} \chi_{dkg} \sum_{g'=1}^{G} \nu_{dk} \Sigma_{fg'} \phi_{g',i}}{\sum_i V_i \sum_{g=1}^{G} \phi^*_{g,i} \chi_g \sum_{g'=1}^{G} \nu \Sigma_{fg'} \phi_{g',i}}$$

Idaho National Laboratory

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