HTR Neutronics and Thermal-Fluids Analysis with MOOSE-Based Tools

Advanced Reactor Technologies
Idaho National Laboratory

Javier Ortensi, Sebastian Schunert, and Vincent Labouré

Gas-Cooled Reactor
Fuels and Methods Program Review
June 18-19, 2019
Overview

• Computer codes
• Current status of the tools
• Prismatic reactor modeling
• Pebble bed reactor modeling
• HTTR coupled steady state modeling (Vincent Labouré)
• Status of Pronghorn/RELAP-7 (Sebastian Schunert)
• Conclusions Future Work
The Computer Codes

• The MOOSE Applications
  β All INL apps built on the MOOSE framework use processes consistent with NQA-1 requirements
  β Natively coupled with data exchange via MOOSE transfer system
  β MAMMOTH (Reactor physics)
  β Rattlesnake (Radiation transport solver)
  β BISON (Fuel performance)
  β Pronghorn (Porous medium thermal fluids)
  β RELAP-7 (reactor system safety analysis code, multi-phase 1-D flow)

• Non-MOOSE Application
  β Serpent (Monte Carlo reference solutions and cross section generation)
  β LAMMPS (Discrete Element Method – Pebble motion)

• MAMMOTH/Rattlesnake team currently specializes in transient multi-physics calculations, but expanding into other areas
Status

• Funding of MAMMOTH/Rattlesnake/Pronghorn
  - NEAMS funding to improve current capabilities for HTRs
  - Ongoing collaboration with NRC to develop HTR and other reactor models

• Rattlesnake
  - Angular discretization
    - spherical harmonics expansion ($P_N$), including tensor diffusion
    - discrete ordinates ($S_N$)
  - Spatial discretization:
    - Continuous Finite Elements (CFEM)
    - Discontinuous Finite Elements (DFEM)
  - Well benchmarked for eigenvalue, source, adjoint, and transient problems
  - For optically thin regions
    - 1st order DFEM formulations
    - Void treatment for 2nd order formulations
    - Calculation of tensor diffusion coefficient (TDC) capability (for voids)
Status

• MAMMOTH/Rattlesnake

- Superhomogenization well tested and reproduces Monte Carlo reference with diffusion. The use of discontinuity factors is also available, but not as well tested.

- Continued testing of Hybrid/Microscopic depletion capability. 300 isotope decay library available, but can read the ORIGEN data libraries, thus allowing >1600 isotopes, if necessary.

- Decay heat calculations
  - Explicit based on isotopes.

- Multi-scheme capability.
  - Homogenized with heterogeneous regions.
  - Enables low-high order.
  - Currently under testing.
Status

- MAMMOTH/Rattlesnake (continued)

- In use for TREAT core/experiment modeling and simulation support.
- Processes used in HTR simulations have evolved from the TREAT M&S efforts.

<table>
<thead>
<tr>
<th></th>
<th>PCF</th>
<th>% rel. diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>measured</td>
<td>2.24 ± 4.0%</td>
<td>-</td>
</tr>
<tr>
<td>MAMMOTH</td>
<td>2.30</td>
<td>2.61</td>
</tr>
<tr>
<td>MCNP</td>
<td>1.53</td>
<td>-37.7</td>
</tr>
<tr>
<td>SCALE 6.2.1/ STREK</td>
<td>1.76</td>
<td>-21.4</td>
</tr>
</tbody>
</table>
Status

• Pronghorn/RELAP-7
  ß Sebastian and Vincent will discuss

• BISON
  ß Solid heat transfer and mechanics constantly improved by BISON team

• The MAMMOTH and MOOSE teams have been working closely improving the variable transfers in the framework:
  ß High-resolution to low resolution and vice-versa.
  ß Conservative interpolation transfers.
  ß Layered average …
Prismatic Reactor Modeling

Current Workflow

Meshing Scripts

Mesh-file

Mesh-file

Serpent homogenization & tally file

MAMMOTH/SPH

Serpent

Base-model

State point runs

ISOXML file

ISOXML module

MAMMOTH

SPH factors

$p(r)$

$p(r)$

T/F Apps

$T(r)$

T/F Apps

• HTTR
  - Coupled Neutronics T/F ready
  - Start transients soon

• VHTRC
  - Update models with latest capabilities

• MHTGR-350
  - Neutronics ready
  - T/F under development

Hexagonal block reflector

Cylindrical reflector
Pebble-Bed Reactor Modeling

Homogenized

- LAMMPS
- Serpent
- MAMMOTH (diff, SPH)
- Pronghorn
- $p(r)$, $T(r)$, $N(r)$, homog. $XS$

Pebble-Resolved

- LAMMPS
- Serpent
- XSGEN
- MAMMOTH (PTT)
- Pronghorn
- $p(r)$, $T(r)$, $pebble$ $xyz$, $pebble$ $XS$
HTR-10 Benchmark

- Results from report INL/EXT-18-45453.
- Model based on
  - IAEA-TECDOC-1382
  - and IRPhE documentation
- Random pebble distribution from PEBBED (now we use LAMMPS)
- Serpent model agrees very well with experimental values
  - Eigenvalue
  - Rod worth
- Rattlesnake model based on
  - Homogenized regions
  - 13 axial material regions
  - 30 azimuthal material regions
  - 10 energy groups

<table>
<thead>
<tr>
<th>Code (case)</th>
<th>keff</th>
<th>Rod worth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>-</td>
<td>1.4693%</td>
</tr>
<tr>
<td>Serpent (ARO)</td>
<td>0.99102</td>
<td>-</td>
</tr>
<tr>
<td>Serpent (1RI)</td>
<td>0.97693</td>
<td>-</td>
</tr>
<tr>
<td>Serpent</td>
<td>-</td>
<td>1.4558%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Code (case)</th>
<th>keff</th>
<th>uncertainty rel. error [pcm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCNP (ENDFB-VI)</td>
<td>1.01190</td>
<td>±21</td>
</tr>
<tr>
<td>Serpent (ENDFB-VI)</td>
<td>1.01025</td>
<td>±5.1</td>
</tr>
<tr>
<td>Serpent (ENDFB-VII.r1)</td>
<td>1.00023</td>
<td>±2.3</td>
</tr>
<tr>
<td>MAMMOTH TDC-SPH-Diffusion</td>
<td>1.00089</td>
<td>67.3</td>
</tr>
</tbody>
</table>
HTR-10 Benchmark

- Homogenization and energy condensation errors are apparent
  - Transport solutions underpredict control rod worth
  - TDC marginally improves the diffusion solution
  - With SPH TDC becomes negligible

- Improvements to the SPH normalization now produce 0 pcm difference in eigenvalue
  - Reproduction of the Serpent solution

- Temperature coefficient of reactivity consistent with VSOP 3-D (Germany)

<table>
<thead>
<tr>
<th>Solution</th>
<th>Eigenvalue keff</th>
<th>Δ(pcm)</th>
<th>Absorption RMS</th>
<th>max</th>
<th>Generation RMS</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusion</td>
<td>1.02544</td>
<td>2520.8</td>
<td>21.5</td>
<td>153</td>
<td>36</td>
<td>41.1</td>
</tr>
<tr>
<td>TDC-Diffusion</td>
<td>1.03475</td>
<td>3451.3</td>
<td>17.4</td>
<td>117.9</td>
<td>34.7</td>
<td>41.7</td>
</tr>
<tr>
<td>P1</td>
<td>1.03706</td>
<td>3682.3</td>
<td>20.7</td>
<td>144.6</td>
<td>2.849</td>
<td>6.53</td>
</tr>
<tr>
<td>P3</td>
<td>1.04053</td>
<td>4029.0</td>
<td>19.6</td>
<td>134.7</td>
<td>2.976</td>
<td>7.12</td>
</tr>
<tr>
<td>SPH-Diffusion</td>
<td>1.00090</td>
<td>67.3</td>
<td>0.16</td>
<td>0.4</td>
<td>0.062</td>
<td>0.11</td>
</tr>
<tr>
<td>TDC-SPH-Diffusion</td>
<td>1.00089</td>
<td>66.1</td>
<td>0.16</td>
<td>0.4</td>
<td>0.059</td>
<td>0.11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Code</th>
<th>20-120 °C [pcm/°C]</th>
<th>120-250 °C [pcm/°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serpent (INL)</td>
<td>-9.33</td>
<td>-11.28</td>
</tr>
<tr>
<td>MAMMOTH (INL)</td>
<td>-10.31</td>
<td>-11.49</td>
</tr>
<tr>
<td>VSOP (China)</td>
<td>-7.51</td>
<td>-9.28</td>
</tr>
<tr>
<td>VSOP 2-D (Germany)</td>
<td>-10.31</td>
<td>-10.58</td>
</tr>
<tr>
<td>VSOP 3-D (Germany)</td>
<td>-10.65</td>
<td>-11.03</td>
</tr>
<tr>
<td>VSOP_PBMR (SA)</td>
<td>-7.16</td>
<td>-9.25</td>
</tr>
</tbody>
</table>
HTR-PM

- Results from report INL/EXT-18-52269.
- Test coupled neutronics & T/F against legacy codes.
- Calculated effects of the SPH correction on the power density.
- 3-D power distribution, solid and fluid temperatures.
HTTR Overview

(a) HTTR core layout with fuel (columns 1-4), control rods (C, R1, R2, R3), replaceable reflectors (RR), and instrumentation (I).

(b) Description of the four different HTTR fuel columns/stacks (UO₂ wt.% fuel enrichment / burnable poison wt.% enrichment).
Cross-section Generation

- Serpent2 using a full-core heterogeneous model depleted to 390 EFPDs
- Tabulated with fuel and moderator temperature
- SPH correction with MAMMOTH
- Important to get the reactivity coefficients and power profile right

<table>
<thead>
<tr>
<th></th>
<th>Relative Error (no SPH)</th>
<th>Relative Error (with SPH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenvalue</td>
<td>1700 to 2100 pcm</td>
<td>0 pcm</td>
</tr>
<tr>
<td>Power (RMS)</td>
<td>~3%</td>
<td>0%</td>
</tr>
<tr>
<td>Power (MAX)</td>
<td>~6%</td>
<td>0%</td>
</tr>
<tr>
<td>Power (MIN)</td>
<td>~-5%</td>
<td>0%</td>
</tr>
<tr>
<td>Mod. reactivity coef.</td>
<td>-31% to +24%</td>
<td>0%</td>
</tr>
<tr>
<td>Fuel reactivity coef.</td>
<td>1.4% to 4.6%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Results from report INL/EXT-18-51317
BISON representative pin
Height: 58 cm
562 elements
5 stacked on top of each other in each fuel column (30)
*BISON mesh z-axis is scaled by 1/5 on picture*

RELAP-7 representative channel
Height: 522 cm
300 elements
One for each fuel column (30) and for each CR column (16)

Homogenized mesh (clipped to show the location of a fuel block) for MAMMOTH (15,552 elements)
The MOOSE modules mesh is identical, with one more level of refinement (124,416 elements)
Height: 522 cm
RELAP-7 Models for Fuel and CR

- Bypass flow assumed: 8% in CR
- For all CR or all fuel channels, flow divided equally
- CR assumed all the way out
Workflow of the Multiphysics Coupling

Eigenvalue solve

MAMMOTH
- Neutronics
- 3-D, homogenized
- SPH correction

Pseudo-transient solve

MOOSE Modules

RELAP-7
- Thermal-fluids
- 1-D
- Flow for fuel and CR channels

BISON
- Conduction, convection, radiation transfer
- 2-D RZ, heterogeneous
# Data Transfer

## Table 1: Transfers performed between applications

<table>
<thead>
<tr>
<th>To</th>
<th>From</th>
<th>MAMMOTH</th>
<th>MOOSE Modules</th>
<th>BISON</th>
<th>RELAP-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAMMOTH</td>
<td>X</td>
<td>Moderator temperature (for cross-sections)</td>
<td>Fuel temperature (for cross-sections)</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>MOOSE Modules</td>
<td>Power density (homogenized)</td>
<td>X</td>
<td>X</td>
<td>Heat flux removed by coolant (homogenized) Fluid temperature at $z = 0$ (for BC)</td>
<td></td>
</tr>
<tr>
<td>BISON</td>
<td>Power density (scaled to fuel pin)</td>
<td>Moderator temperature (for BC)</td>
<td>X</td>
<td>Fluid temperature</td>
<td></td>
</tr>
<tr>
<td>RELAP-7</td>
<td>X</td>
<td>Outer wall temperature</td>
<td>Inner wall temperature</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
Study of a Fuel Channel

- Fluid temperature
- Moderator temperature
- Fission power density
- Volumetric heat removal rate

Temperature (K) vs. Height (m) and Power density/volumetric heat removal rate (MW/m³)
Comparison to Measurements

- Outlet coolant temperature computed using:

\[
\bar{T}_{\text{fluid}} = \frac{\sum_{i=1}^{l} \dot{m}_i n_{\text{channels},i}}{\bar{M}} T_{\text{fluid},i}
\]

Table 2: Measured and computed values of the outlet coolant temperature.

<table>
<thead>
<tr>
<th></th>
<th>High temperature test operation</th>
<th>Rated operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\bar{M})</td>
<td>10.2 kg/s</td>
<td>12.4 kg/s</td>
</tr>
<tr>
<td>(\bar{T}_{\text{fluid}}^{\text{out}}) (reported in [1])</td>
<td>1223 ±17 K</td>
<td>1123 ±19 K</td>
</tr>
<tr>
<td>(\bar{T}_{\text{fluid}}^{\text{out}}) (computed)</td>
<td>1228 K</td>
<td>1138 K</td>
</tr>
<tr>
<td>Absolute error</td>
<td>5 K</td>
<td>15 K</td>
</tr>
</tbody>
</table>
The need for an effective yet efficient engineering-scale reactor simulator

How can we accurately model the engineering-scale phenomena relevant to thermal-hydraulics, thermal-fluids, nuclear fuel performance and neutronic analysis of advanced nuclear reactor concepts without complete resolution of geometry and material heterogeneity?

1. Must be higher fidelity than traditional nuclear systems/safety analysis (0D-1D).
2. Avoid lower-length scale phenomena, such as boundary layer theory, i.e., rely on closure relations.
3. Apply mixture theory (homogenization) wherever possible.
4. Conserve mass and energy (solve all physics on single mesh).
5. Does not require a super computer.

Answer - Pronghorn
Pronghorn: The Coarse Mesh Multi-Dimensional Reactor Simulator

Pronghorn is designed to provide relatively quick engineering solutions for full core simulations on small clusters or large workstations.

**Pronghorn**: Engineering-scale Reactor Simulator

- Began as part of the FY-2008 MOOSE LDRD.
- MOOSE-based FEM for either r-z or 3D discretizations with application to SFRs, FHRs, MSRs, VHTRs, and LWRs.
- Coarse mesh representation – each finite element may be a combination of coolant, fuel, moderator, core internals, etc. Large flow features are resolved and small flow regimes are homogenized.
- Easily coupled to BISON’s TRISO fuels performance capability.
- Rattlesnake’s PTT method and discrete ordinates method (also MG diffusion capable).
- Closure relations from Nek5000 (loose or tightly coupled)
- Balance of plant from SAM, TRACE, or RELAP-7.
- VHTR capability being developed at INL and NRC and funded by NRC and NEAMS.
- FHR capability is being developed at UCB and INL and funded by NEUP supporting April Novak for her PhD research.
- April’s 2018 Innovations in Nuclear Technology R&D Award to be presented to her by Drs. John Herczeg and Patricia Paviet of DOE-NE.

- Funding Sources: NEAMS, NRC, NEUP
- Collaborators:

---

[Logo of Idaho National Laboratory (INL), United States Nuclear Regulatory Commission (US NRC), and University of California Berkeley]
An Example of a Pronghorn Coarse Mesh Approach

Large flow and heat transfer features are resolved. Small scale features are homogenized. For example, the bottom reflector of the HTR-10 reactor is homogenized CHT (red mesh) and treated as two-phase CHT through the very small holes and pebbles.

Fig. 1. HTR-10 core view.
Governing Equations, Approach #1: Two-Phases with Compressible Flow Phase (compatible with RELAP-7) and a Stationary Solid Phase

Conservation of Mass

\[ \frac{\partial \alpha \rho}{\partial t} + \nabla \cdot (\alpha \rho \vec{u}) = 0 \]

Balance of Momentum

\[ \frac{\partial \alpha \rho \vec{u}}{\partial t} + \nabla \left[ \alpha (\rho \vec{u} \otimes \vec{u} + p \mathbf{I}) \right] = p_i \nabla \alpha + \nabla \cdot (\alpha \mu_{eff} \nabla \vec{u}) + \alpha (1 - \alpha) K_m (\vec{u}_s - \vec{u}) \]

Conservation of Total Energy

\[ \frac{\partial \alpha \rho E}{\partial t} + \nabla \cdot (\alpha \rho \vec{u} H) = p_i \vec{u}_i \cdot \nabla \alpha - \nabla \cdot (\alpha \vec{q}) + \alpha \rho Q + \alpha (1 - \alpha) K_e (T_s - T) + \vec{u} \cdot (\alpha \rho \vec{g}) \]

Solid Phase Energy Balance

\[ (1 - \alpha) \rho_s c_{v,s} \frac{\partial T_s}{\partial t} = \nabla \cdot [(1 - \alpha) \vec{q}_s] + (1 - \alpha) \rho_s Q_s - \alpha (1 - \alpha) K_e (T_s - T) \]

Assumptions:
1. Fully resolve large-scale flow features and homogenize lower length flow features and represent as a two-phase mixture.
2. Continuous heat flux.
3. Volume fraction varies \( 0 > \alpha \leq 1 \).
4. Solid structures (\( \alpha \rightarrow 0 \) such as reflectors, are treated as separate mesh blocks.)
Governing Equations, Approach #2:
Two-Phases with Thermally Expansive, Nearly Incompressible (liquid) Flow Phase (compatible with SAM) and a Stationary Solid Phase

**Conservation of Mass**
\[
\frac{\partial \alpha \rho}{\partial t} + \nabla \cdot (\alpha \rho \vec{u}) = 0
\]

**Balance of Momentum**
\[
\alpha \rho \frac{D \vec{u}}{Dt} = -\alpha \nabla p + \nabla \cdot (\mu_{\text{eff}} \alpha \nabla \vec{u}) - \alpha (1 - \alpha) K_m \vec{u} + \alpha \rho \vec{g}
\]

**Liquid Phase Energy Balance**
\[
\alpha \rho c_p \left( \frac{\partial T}{\partial t} + \nabla \cdot \vec{u} \right) = (p - p_i) \vec{u} \cdot \nabla \alpha + \nabla \cdot (\alpha k_{\text{eff}} \nabla T) + \alpha \rho Q + \alpha (1 - \alpha) K_e (T_s - T)
\]

**Solid Phase Energy Balance**
\[
(1 - \alpha) \rho_s c_{v,s} \frac{\partial T_s}{\partial t} = \nabla \cdot \left[ (1 - \alpha) \vec{q}_s \right] + (1 - \alpha) \rho_s Q_s - \alpha (1 - \alpha) K_e (T_s - T)
\]

**Assumptions:**
1. Single-phase liquid, also cast homogenized CHT, resolved large-scale flow features and homogenized lower length flow features.
2. Continuous heat flux.
3. Volume fraction varies \(0 > \alpha \leq 1\).
4. Solid structures (\(\alpha \rightarrow 0\)) such as reflectors, are treated as separate mesh blocks.
5. Simplified EOS with density a function of internal energy.

Conservation of Mass

$$
\epsilon \frac{\partial \rho}{\partial t} + \nabla \cdot \left[ \frac{\epsilon^2}{W} \left( -\nabla P + \rho_f \vec{g} \right) \right] = 0
$$

Balance Momentum

$$
\epsilon \nabla P - \epsilon \rho_f \vec{g} + W \rho_f \vec{V} = 0
$$

Liquid Phase Energy Balance

$$
\epsilon \rho_f C_{p,f} \frac{\partial T_f}{\partial t} + \epsilon \rho_f C_{p,f} \vec{V} \cdot \nabla T_f - \nabla \cdot (\kappa_f \nabla T_f ) + \alpha (T_f - T_s) + \dot{q}_f = 0
$$

Solid Phase Energy Balance

$$
(1 - \epsilon) \rho_s C_{p,s} \frac{\partial T_s}{\partial t} - \nabla \cdot (\kappa_s \nabla T_s ) + \alpha (T_s - T_f) + \dot{q}_s = 0
$$

Assumptions:
1. Porous flow assumption.
2. No momentum inertia – creeping flow.
3. May not be consistent formulation with either RELAP-7 or SAM.
4. Not appropriate in single phase open flow, non-porous media, such as open plenums.
5. Thus, not easily adaptable to full core analysis.
6. Not appropriate depressurized loss of forced cooling, D-LOFC, accidents in HTRs.
Additional Pronghorn Features

Pronghorn is designed to be reactor concept inclusive:

- VHTR (both prismatic and pebble bed), FHR, SFR, LFR, and even MSR is possible.
  - Anisotropic drag coefficient to permit simulation of 1D reflector coolant channels or other 1D flow paths.
  - Coupling with 1D internal flow channels (TRACE, SAM, RELAP-7).
- LWR (PWR and BWR) and SFR/LFR subchannel capability is under development.
  - 3D subchannel flow, both single and two-phase water.
  - Work with ANL on updated Super Energy (SE2) models in Pronghorn?
- Flow models under development include:
  - A general, compressible porous model based on Navier-Stokes equations with a simplified low-advection model (elliptic) for comparison to legacy codes (i.e. THERMIX)
  - A stabilized hyperbolic two-phase representation for compressible flows, such as LB-LOCAs for gas-cooled reactors. Primitive variable formulation for low Mach number flows.
- Fluid properties are currently available (or under development) for:
  - Two-phase water, Helium, Carbon Dioxide, iNitrogen, and FLiBe.
  - Na, K, and NaK under development (ANL).
**HTR-PM: Towards a more realistic Gas-Cooled PBR model**

**Pronghorn/RELAP-7 steady-state model of HTR-PM:**
- Flow up the riser channels, mixing in upper plenum
- Flow distribution into core and secondary cooling channels (control rod channels)
- Flow through the pebble bed, cone, & bottom reflector cone region
- Explicit cone and porous bottom reflector geometry
- RELAP-7 riser and secondary flow paths
- Next steps:
  - Coupling with MAMMOTH neutronics
  - Include barrel, RPV, stagnant gas gaps in Pronghorn model
  - Physically more accurate model of lower plenum
HTR-PM: Details and Results

• Pseudo-transient ran out to $10^6$ seconds
• Tightly coupled, Pronghorn is master app, RELAP-7 is sub app
• RELAP-7 channels are explicitly meshed in the Pronghorn model, a side-set is created around them
• Coupling:
  – Layered average of graphite temperature is computed on sidesets and transferred to RELAP-7’s heat structure
  – RELAP-7 fluid temperature is transferred & then used in convective heat transfer boundary condition (Robin type BC)
  – Mass flow rate distribution is computed in RELAP-7 and then transferred to Pronghorn
• Pronghorn model:
  – 463,250 dof
  – Legacy equations
• RELAP-7 model:
  – 183,185 dof
  – Contains FlowChannels, Junction, heat structures
The SANA experiment - Validation

**Transient**
- Scaled facility for natural circulation heat removal (max 28 kW/m³)
- Electrically heated bed of ~1000s graphite pebbles
- ~20 thermo-couple readings
Example Results

SANA Experiments Experiment Matrix

- Types of pebbles:
  - $\text{Al}_2\text{O}_3$
  - graphite
  - graphite

- Coolant:
  - helium
  - nitrogen

- Heater and bed configurations:
  - full length
  - half-height in top
  - half-height in bottom
  - open upper plenum

- Experiment Matrix:
  - 52 Experiments
  - 1300 $T_s$ data points

- Heater power (kW):
  - 5
  - 10
  - 15
  - 20
  - 25
  - 30
  - 35
# SANA Pronghorn Result Summary

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sample: Flownex results</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flownex</td>
<td>19.8</td>
<td>51.4</td>
<td>207</td>
</tr>
<tr>
<td>Pronghorn</td>
<td>-7.8</td>
<td>47.5</td>
<td>-156</td>
</tr>
<tr>
<td><strong>Sample: Gamma results</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gamma</td>
<td>4.3</td>
<td>50.9</td>
<td>147.5</td>
</tr>
<tr>
<td>Pronghorn</td>
<td>-1.6</td>
<td>48.7</td>
<td>148.4</td>
</tr>
<tr>
<td><strong>All Pronghorn results</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pronghorn</td>
<td>22.6</td>
<td>54.6</td>
<td>198.6</td>
</tr>
</tbody>
</table>

Frequency of solid temperature error (predicted - measured)
How efficient is Pronghorn

Timing study for SANA benchmark

Currently further improvement efforts:
- Automatic differentiation for modern Eqs. operational
- Automatic differentiation for legacy equations under development

Efficient solution method for steady state:
- Solve a coarsely converged pseudo transient
- User results as initial guess for steady solve

<table>
<thead>
<tr>
<th>Power [kW]</th>
<th>Coolant</th>
<th># Elements</th>
<th>Exec. Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>He</td>
<td>800</td>
<td>35</td>
</tr>
<tr>
<td>10</td>
<td>He</td>
<td>3200</td>
<td>175</td>
</tr>
<tr>
<td>10</td>
<td>He</td>
<td>12800</td>
<td>899</td>
</tr>
<tr>
<td>30</td>
<td>N</td>
<td>2808</td>
<td>194</td>
</tr>
</tbody>
</table>

Single Core Execution Time
Conclusions

• NEAMS tools are being benchmarked and tested to model both a variety of reactors, including prismatic and pebble-bed HTRs.
  ◆ Transient modeling has been successful for TREAT with MAMMOTH/Rattlesnake.
  ◆ Results from HTR-10 benchmark are very good.
  ◆ HTR-PM results show that reference T/F calculations are needed to determine fidelity of Pronghorn.
  ◆ Pronghorn has been tested against legacy codes and one experimental benchmark.
  ◆ HTTR steady-state results agree well with experimental data
    • Steady-state multiphysics model of HTTR
    • Essential to start transient with self-sustaining solution
    • Accurate fuel/moderator reactivity coefficients thanks to SPH procedure
    • Reasonable value of the outlet fluid temperature despite the approximations in the model
Future Work

• Future development/testing:
  - MHTGR-350 thermal fluids and coupled neutronics,
  - HTTR Depressurized Loss of Forced Cooling,
    - Microscopic depletion in MAMMOTH to track poisons (Xe, I, Sm, Pm)
    - More accurate determination of by-pass flow, cross flow, radiation between fuel blocks
  - Multi-scale heat transfer (TRISO to compact/pebble),
  - Subgroup method for cross sections,
  - Radiation heat transfer (Reflector gap heat transfer methods)
    - Approach: contact resistance interface kernels & discontinuous temperatures
    - Axial, radial & azimuthal gaps in reflectors under varying flow conditions
    - Informed by reflector flow
  - Non-local heating (gamma)
  - Thermally Expansive, Nearly Incompressible flow equations with AD
  - Comprehensive secondary flow, bypass & leakage flows
  - Star-CCM+ is used for model parameterization
  - RELAP-7 is used for modeling reflector, control-rod, core flow as pipe network
  - Develop overlapping and non-overlapping domain decomposition coupling between RELAP-7 & Pronghorn
Javier Ortensi

javier.ortensi@.inl.gov
(208) 526-4256
ART.INL.GOV