Pronghorn: A Coarse Mesh Thermal-Hydraulics Application Based on MOOSE for Advanced Reactor Concepts

NUC Workshop - Innovations in Advanced Reactor Design, Analysis, and Licensing

Pronghorn Development and Analysis Group

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Pronghorn Development and Analysis Group

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Content overview

Content

- Pronghorn application overview, why, how, when.
- Work in progress.
- PBMR-400 phase-1 exercise 2.
- Pronghorn validation for natural circulation: SANA
- Simplified PBR + balance of plant: Pronghorn – RELAP-7 coupling
- Mark-1 Pebble Bed Fluoride-Salt-Cooled High-Temperature Reactor
- Conclusions and future steps
How can we accurately model the engineering-scale phenomena relevant to thermal-hydraulics, 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) tools (e.g. complex geometries, pools, etc.).

2. Avoid lower-length scale phenomena, such as boundary layer and rely on closure relations.

3. Homogenize wherever possible to reduce the number of meshes.

4. No super computer required.

ANSWER ➔ Pronghorn!!!
Pronghorn Coarse Mesh Approach

- **Resolve** large flow and heat transfer
- **Homogenize** small scale features & replace by correlations

- **Homogenized** bottom reflector borings
- **Resolved** CR and Riser channels

HTR-10 core view

Pronghorn HTR-PM mesh of the bottom reflector cone region
Pronghorn History & Activities

**Pronghorn**: Engineering-scale Reactor TH code
- Began as part of the FY-2008 MOOSE LDRD.
- HTGR capability being developed at INL and NRC and funded by NRC and NEAMS.
- FHR capability: UCB and INL and funded by NEUP supporting April Novak
Pronghorn in the MOOSE Ecosystem

Nuclear Energy

Power Distribution

Reactors Physics
MAMMOTH

3D Coarse Mesh TH
PRONGHORN

TRISO Fuel, Pebbles,
Compacts properties

Fuel Performance
BISON

Balance of Plant BCs

HTGRs, FHRs
System Analysis
RELAP-7

SFRs, MSRs
System Analysis
SAM
Pronghorn, External Codes, & Experiments

Improved/dedicated Correlations, Parameterization

NEK-5000

SEPARATE - INTEGRAL EFFECT EXPERIMENTS

COARSE - GRANING

SFRs, MSRs System Analysis

HTGRs, FHRs System Analysis

RELAP-7

3D Coarse Mesh TH PRONGHORN

STAR-CCM+
### Pronghorn Algorithms & Equations

#### Nuclear Energy

#### Fluid flow equations
- Legacy equations
- Fully compressible equations
- Fully expansive, nearly incompressible
- SUPG stabilization

#### Solid heat transfer
- Continuous heat conduction
- Conjugate heat transfer

#### Radiative heat transfer
- Gap heat transfer model

#### Multi-scale pebble/TRISO temperature
- Stainsby's algorithm

#### Miscellaneous:
- Automatic Differentiation
- Various boundary conditions, functions etc. from MOOSE
Pronghorn Correlations

Pebble bed friction coefficients
- KTA
- Ergun
- Eisfeld (wall friction)
- Churchill drag (pipe)

Heat transfer coefficient – Pebble/Coolant
- Gnielinski
- Gunn, KTA
- Petrovic
- Wakao

Heat transfer coefficient – Pebble/Wall
- Wakao
- Achenbach

Bed effective thermal conductivity
(next slide)
## Effective Pebble Bed Conductivity

### Nuclear Energy

<table>
<thead>
<tr>
<th>Solid Conduction</th>
<th>Fluid Conduction</th>
<th>Radiation</th>
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</thead>
<tbody>
<tr>
<td>Hsu</td>
<td>Deissler &amp; Eian</td>
<td>Breitback &amp; Barthels</td>
</tr>
<tr>
<td>Hsu – 2D</td>
<td>Hsu – 2D</td>
<td>Kunii &amp; Smith</td>
</tr>
<tr>
<td>Hsu – 3D</td>
<td>Hsu – 3D</td>
<td>Singh &amp; Kaviany</td>
</tr>
<tr>
<td>ZBS</td>
<td>Krupiczka</td>
<td>Vortmeyer</td>
</tr>
<tr>
<td>Chan-Tien</td>
<td>Kunii &amp; Smith</td>
<td>Wakao &amp; Kato</td>
</tr>
<tr>
<td></td>
<td>ZBS</td>
<td>ZBS</td>
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</tbody>
</table>

- Mixing & matching solid/fluid/radiation from input file
- ZBS: Zehner, Bauer, & Schlunder
Pronghorn Thermo-physical Properties

**Fluids**
- Helium
- Nitrogen
- CO₂
- Water
- Air

**Solids**
- KTAElectricGraphite
- Various SANA insulators

**Liquid salts**
- LiF-BeF₂ (flibe)
- NaF-ZrF
- KF-ZrF₄

- **MOOSE** provides a properties framework.
- Complete set of thermodynamic state variables & functions.
- **Gas mixtures currently** under development.
Coupling within the MOOSE

MOOSE
- Hybrid parallelism (mpi/openmp)
- CFEM/DFEM discretization
- Various time integration schemes
- Automatic timestep control
- Mesh generation & modification
- Flexible multiapp system

MOOSE Modules
- Heat conduction
- Gap heat transfer model

RELAP-7 & SAM
- Balance of plant
- Secondary flows
- RCCS modeling

Rattlesnake/MAMMOTH
- Neutron & power distribution
- Depletion & decay heat capabilities

BISON
- TRISO fuel performance
- Fission product diffusion
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- Work in progress and the view.
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- Conclusions and future steps
Currently in the Development Pipeline

1. Method Development
   - Thermally Expansive, Nearly Incompressible flow equations with AD
   - Legacy equations with AD
   - View factors based radiative heat transfer
   - Reconstructed Discontinuous Galerkin (rDG)
   - Performance & runtime optimization

2. RELAP-7 & SAM coupling, balance of plant, secondary flows
   - Domain overlapping/non-overlapping coupling of Pronghorn & RELAP-7/SAM for Boundary Conditions
   - Comprehensive secondary flow, bypass & leakage flows
     - Star-CCM+/NEK5000 are used for model parameterization,
     - RELAP-7 is used for modeling reflector, control-rod, core flow as pipe network
Currently in the Development Pipeline

Nuclear Energy

3. Assessment of Equations & Correlations

- V&V against experiments, Star-CCM+, Nek-5000.
- Verification against PBMR-400 steady-state & transient exercises
- Near wall correlations, bed entrance correlations, flow reversal, low flow, natural circulation, empty upper plenum.

4. Miscellaneous

- User-friendly actions: custom MOOSE actions
Pronghorn Vision & Future Development

Nuclear Energy

Current focus
Pronghorn: a general-purpose coarse mesh thermal-hydraulics code

Near term
Prismatic VHTRs

Longer term
SFR

FHRs
PBRs
LWR
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The PBMR-400 NEA benchmark

Steady state Phase-1 Ex. #2
- Thermal power: 400 MW.
- Core He inlet/outlet T 500/900 °C.
- Total inlet mass flow rate: 192.7 kg/s.
- Primary coolant Pressure: 9 MPa.
- Modular Pebble Bed Reactor with central reflector.

Benchmark solutions
- Participants from 15 different countries.
- 8 independent full solutions.
- TH solution Codes: THERMIX, TINTE, WIMSTER, FLUENT.
The PBMR-400 NEA benchmark

Benchmark simplifications

- **Flattening** of the pebble bed's upper surface.
- Flat bottom reflector.
- Only **main engineered** flow paths.
- **Stagnant He**: side reflector → barrel and the barrel → RPV.

The Pronghorn model

- 2D (r, z) geometry.
- **Fluid region**: inlet plenum and pebble bed.
- **Solid region**: all the domain except the inlet plenum.
- 7904 Elements
- Estimated runtime ~4 min for a full steady state.
The PBMR-400 NEA benchmark

- **Legacy type** fluid conservation equations: Mass, Momentum, Energy liquid phase, Energy solid phase.
- Fluid-pebble **heat exchange** → KTA correlation.
- Effective pebble **conductivity** → Contact points conduction + ZBS (Zehner and Schlunder)
- Pebble **drag coefficient** → KTA correlation

\[
Nu = 1.27 \frac{Pr^{1/3} Re^{0.36}}{\epsilon^{1.18}} + 0.033 \frac{Pr^{0.5} Re^{0.86}}{\epsilon^{1.07}}
\]

- Radiation + conduction in the stagnating gas cylindrical gap heat transfer model:
  - Side reflector → Core barrel
  - Barrel → RPV

- Fluid BC: 500 °C Inlet T, 192.70 kg/s MFR, 9 MPa outlet P.
- Solid BC: INSULATED top bottom and center, right RCCS → Radiation + Conduction

(Stagnating Air in Reactor Cavity) Surface \( T_{\infty} = 20 \) °C.
The PBMR-400 NEA benchmark results
The PBMR-400 NEA benchmark results
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The SANA experiment - Validation

- **Scaled facility** for natural circulation heat removal (max 28 kW/m³)
- **Electrically heated** bed of ~10,000s graphite pebbles
- ~20 **thermo-couple** readings
- Experiment conducted in **Germany** 1994-1996
- **Focus**: axi-symmetric cases
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
Example Results

- Comparison full/half length heater
- Excellent agreement for **full-length** heater
- More discrepancy for **half-length**
- Pronghorn predictions at least as close as Gamma’s

Partial length heater $T_f$ & streamlines

**$T_s$ full length heater $\text{Al}_2\text{O}_3$**

(o) Measurement
(-) Pronghorn
(…) Gamma
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**Pronghorn-RELAP-7 Coupling**

**Pronghorn**: Multi-dimensional, engineering-scale reactor TH code
- Detailed analysis of multi-dimensional flow regions
- **No balance of plant**

**RELAP-7**: 1D/0D Systems analysis code
- One-dimensional flow channels
- **No detailed multi-dimensional** flow fields
- Balance of plant

**Pronghorn + RELAP-7 = complete HTR tool**
- HTR thermal fluids requires balance of plant
- Secondary, bypass, leakage flows
- Detailed analysis of multi-D regions

Goal: Proof of principle of Pronghorn-RELAP-7 coupling

Pronghorn model:
- Legacy equations, 2 regions (pebble bed & reflector)
- Explicitly modeled riser & control rod channels

RELAP-7 model:
- Ideal pump (constant MFR 24 kg/s)
- Steam w/ constant secondary T = 523K
- Q between riser/cr and PH reflector
Overlapping domain-decomposition

- Create an equivalent RELAP-7 flow channel
- Definition of equivalent flow channel:
  \[\text{Flow channel with properties to match the computed enthalpy, pressure, and momentum of Pronghorn's model averaged over slices orthogonal to the flow direction.}\]

Non-overlapping domain-decomposition

- Pronghorn/RELAP-7 communicate at boundaries

<table>
<thead>
<tr>
<th></th>
<th>To Pronghorn</th>
<th>From Pronghorn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet</td>
<td>MFR, H</td>
<td>pressure</td>
</tr>
<tr>
<td>Outlet</td>
<td>pressure</td>
<td>MFR, H</td>
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Steady-state results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Result</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core mass flow rate</td>
<td>21.0</td>
<td>kg/s</td>
</tr>
<tr>
<td>CR mass flow rate</td>
<td>0.75 (per CR)</td>
<td>kg/s</td>
</tr>
<tr>
<td>Core inlet temp.</td>
<td>673.0</td>
<td>K</td>
</tr>
<tr>
<td>Core outlet temp.</td>
<td>1322.0</td>
<td>K</td>
</tr>
<tr>
<td>Hot leg temp.</td>
<td>1241.0</td>
<td>K</td>
</tr>
<tr>
<td>Average Pebble surface temperature</td>
<td>1014.0</td>
<td>K</td>
</tr>
<tr>
<td>Power</td>
<td>62.5</td>
<td>MW</td>
</tr>
</tbody>
</table>

Transient

- Secondary side upset: reduce htc across steam gen.
- Power evolution modeled via Point Kinetic
- Linear feedback model using pebble surface temp.
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FLiBe and FLiNaK capabilities.

Comparison with TRACE for FLiNaK-cooled ORNL Liquid Salt Test Loop (LSTL).

Mark-1 Pebble Bed Fluoride-Salt-Cooled High-Temperature Reactor (PB-FHR):
- 236 MWt,
- HALEU (19.8 %),
- TRISO fuel in pebbles,
- FLiBe coolant,
- Atmospheric pressure,
- Buoyant Pebbles entering from the bottom.
FLiBe-Cooled PB-FHR in Pronghorn
Conclusions and Future steps

- **SANA** benchmark configuration (helium, full length bed and heater, 30 kW, graphite pebbles) is solved with both *legacy* and *compressible Euler* equations. → Solid temperature and velocities difference acceptable.
- A method for non-overlapping domain decomposition with RELAP-7 has been developed and tested with a full scale PBR problem.
- **A PBMR-400** reactor model has been developed, phase 1 exercise 2 comparison shows good agreement
- **FHR** capabilities has been implemented and used for a prototypical design modeling.
- **Future Steps:**
  - The *compressible* gas equations → SANA experiment with *cavity* → Measurement and STAR-CCM+ comparison → to validate the code *reverse flow natural circulation conditions*.
  - A more realistic **Pronghorn-RELAP-7** plant model is under development that computes feedback from graphite compact and reflector temperatures and not pebble surface temperatures.
  - The **PBMR-400** model will form the basis for modeling PBMR-400 transient exercises.