U.S. DEPARTMENT OF ENERGY | Nuclear Energy

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

Raleigh NC, Sep 18, 2019

NEAMS
NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

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Nuclear Energy

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

Pronghorn: Coarse-mesh Multi-Dimensional TH code

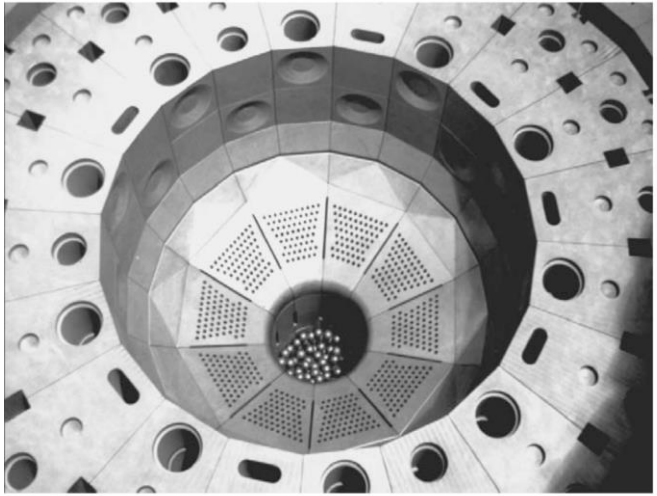
***How** can we **accurately** model the **engineering-scale phenomena** relevant to thermal-hydraulics, of **advanced nuclear reactor** concepts **without** complete resolution of **geometry** and material **heterogeneity**?*

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.

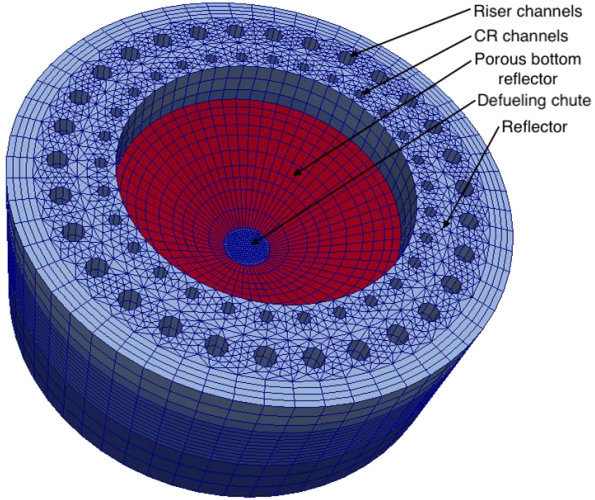
ANSWER → **Pronghorn!!!**

Pronghorn Coarse Mesh Approach

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



HTR-10 core view



Pronghorn HTR-PM mesh of the bottom reflector cone region

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

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

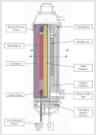
Idaho National Laboratory

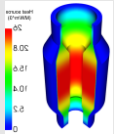
Berkeley UNIVERSITY OF CALIFORNIA

U.S.NRC United States Nuclear Regulatory Commission *Protecting People and the Environment*

Pronghorn in the MOOSE Ecosystem

3D Coarse Mesh TH
PRONGHORN

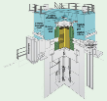




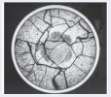
Power Distribution

TRISO Fuel, Pebbles, Compacts properties

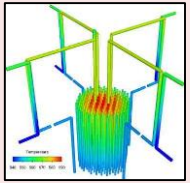
Reactor Physics
MAMMOTH



Fuel Performance
BISON

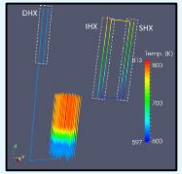


HTGRs, FHRs System Analysis
RELAP-7

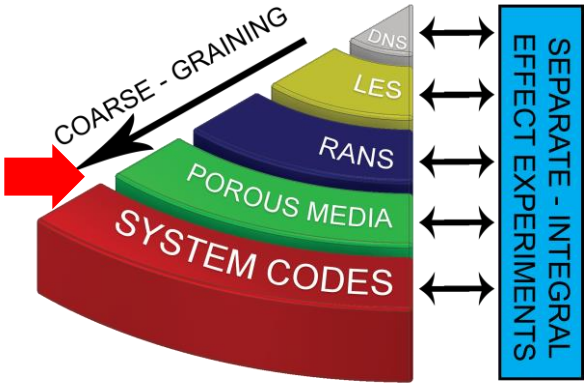


Balance of Plant BCs

SFRs, MSRs System Analysis
SAM



Pronghorn, External Codes, & Experiments



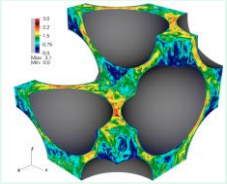
STAR-CCM+

CD-adapco

STAR-CCM+

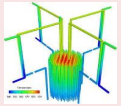
EXPERIMENTS

NEK-5000

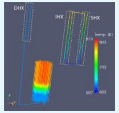


Improved/dedicated Correlations, Parameterization

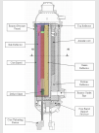
HTGRs, FHRs System Analysis
RELAP-7

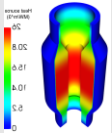


SFRs, MSRs System Analysis
SAM



3D Coarse Mesh TH
PRONGHORN





Pronghorn Algorithms & Equations

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)

Bed effective thermal conductivity

(next slide)

Heat transfer coefficient – Pebble/Coolant

- Gnielinski
- Gunn, KTA
- Petrovic
- Wakao

Heat transfer coefficient – Pebble/Wall

- Wakao
- Achenbach

Effective Pebble Bed Conductivity

Solid Conduction

- Hsu
- Hsu – 2D
- Hsu – 3D
- ZBS
- Chan-Tien

Fluid Conduction

- Deissler & Eian
- Hsu – 2D
- Hsu – 3D
- Krupiczka
- Kunii & Smith
- ZBS

Radiation

- Breitback & Barthels
- Kunii & Smith
- Singh & Kaviany
- Vortmeyer
- Wakao & Kato
- ZBS

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

Pronghorn Thermo-physical Properties

Fluids

- Helium
- Nitrogen
- CO_2
- Water
- Air

Solids

- KTAElectricGraphite
- Various SANA insulators

Liquid salts

- $LiF\text{-}BeF_2$ (flibe)
- NaF-ZrF
- $KF\text{-}ZrF_4$

- **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 capabilites

BISON

- TRISO fuel performance
- Fission product diffusion

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- **Work in progress and the view.**
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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

3. Assessment of Equations & Correlations

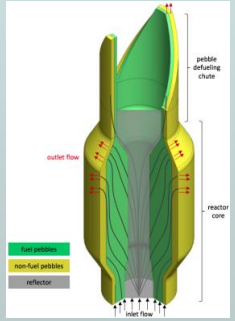
- **V&V** against **experiments**, **Star-CCM+, Nek-5000.**
- Verification against **PBMR-400 steady-state & transient exercises**
- **Near wall correlations**, **bed entrance correlations**, **flow reversal, low flow**, **natural circulation, empty upper plenum.**

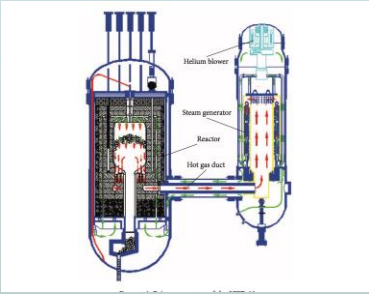
4. Miscellaneous

- User-friendly **actions**: **custom MOOSE** actions

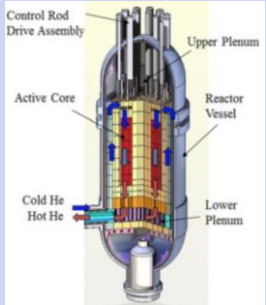
Pronghorn Vision & Future Development

FHRs





PBRs

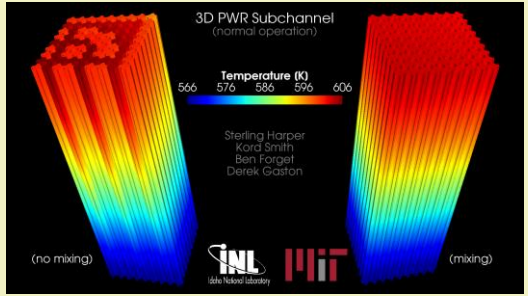


Prismatic VHTRs

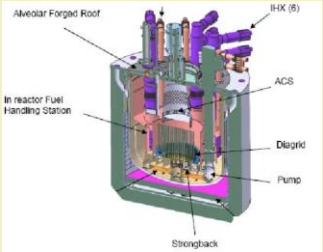
Current focus

Near term

LWR



SFR



Longer term

Pronghorn: *a general-purpose coarse mesh thermal-hydraulics code*

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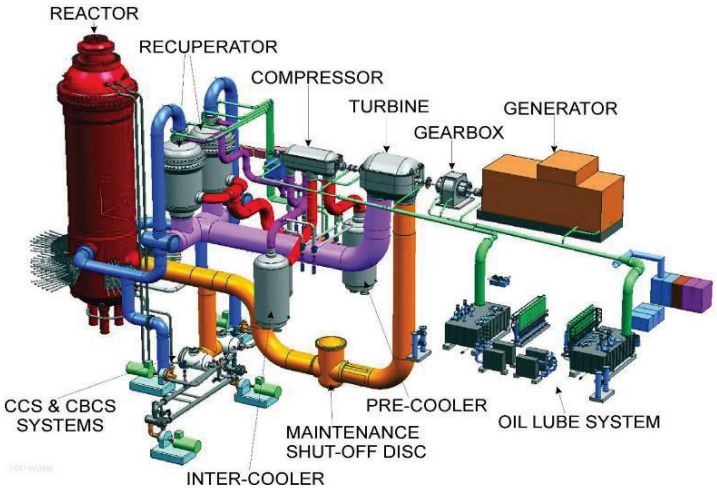
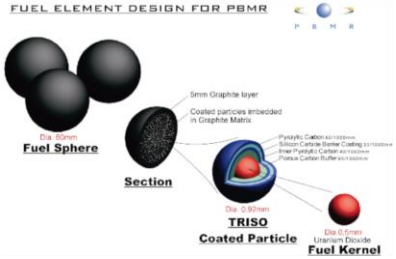
The PBMR-400 NEA benchmark





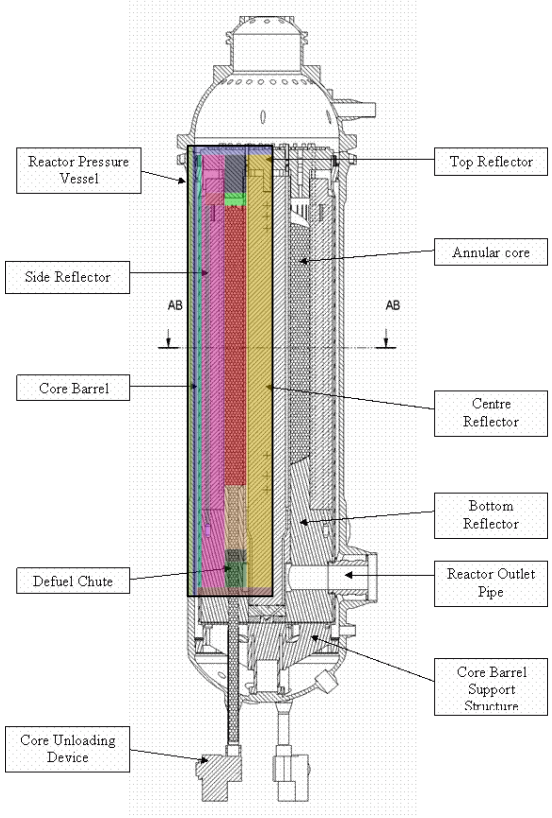
Steady state Phase-1 Ex. #2

- 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



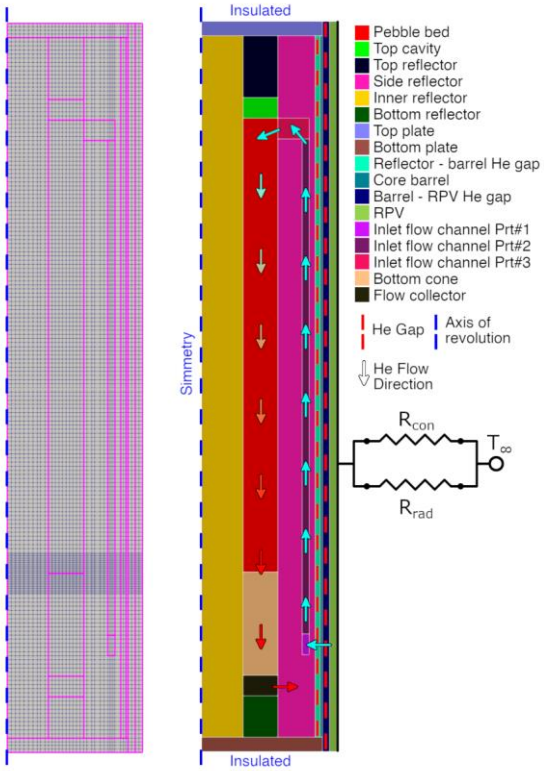
Benchmark simplifications

- **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

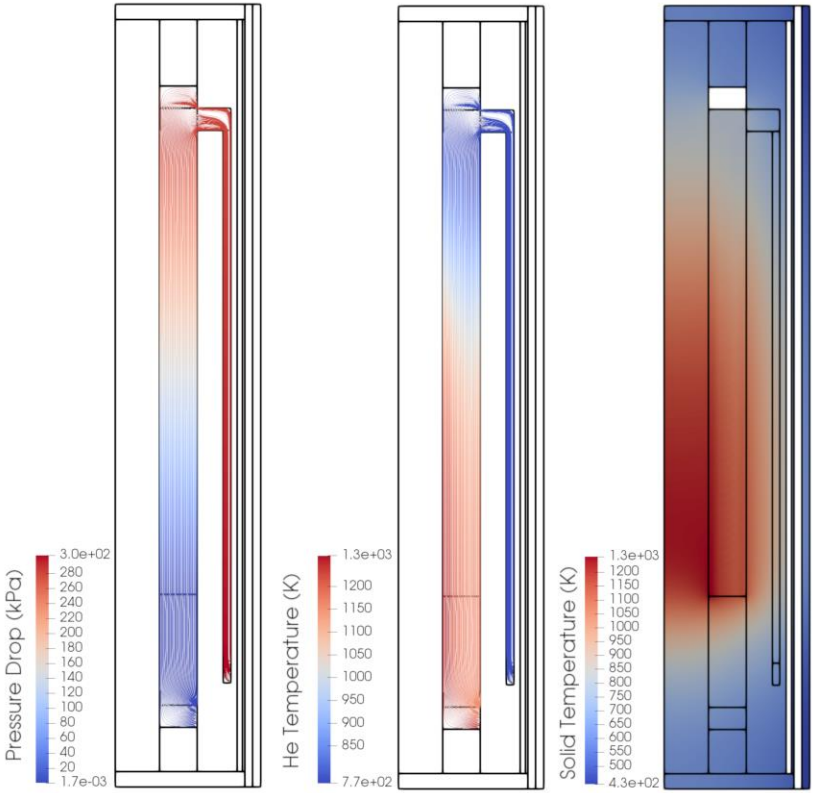


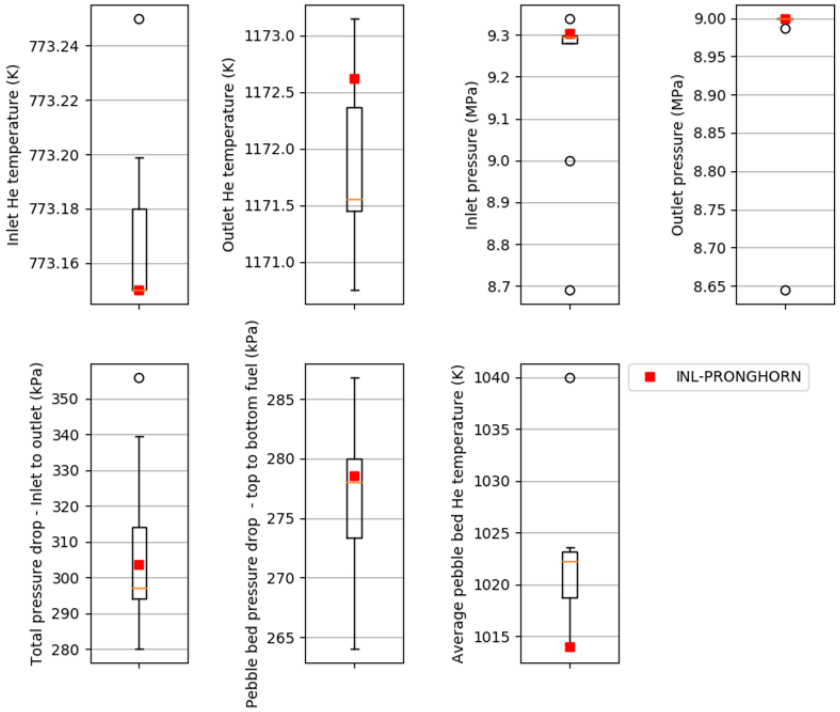
- **Legacy type** fluid conservation equations: Mass, Momentum, Energy liquid phase, Energy solid phase.
- Fluid-pebble **heat exchange** → KTA correlation. $Nu = 1.27\frac{Pr^{1/3}Re^{0.36}}{\varepsilon^{1.18}} + 0.033\frac{Pr^{0.5}Re^{0.86}}{\varepsilon^{1.07}}$
- Effective pebble **conductivity** → Contact points conduction + ZBS (Zehner and Schlunder)
- Pebble **drag coefficient** → KTA correlation: $\varepsilon\nabla P = \Psi\frac{1-\varepsilon}{2d_p}\rho_f|\vec{V}|\vec{V}$

- 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_∞ = 20 ˚C.

The PBMR-400 NEA benchmark results





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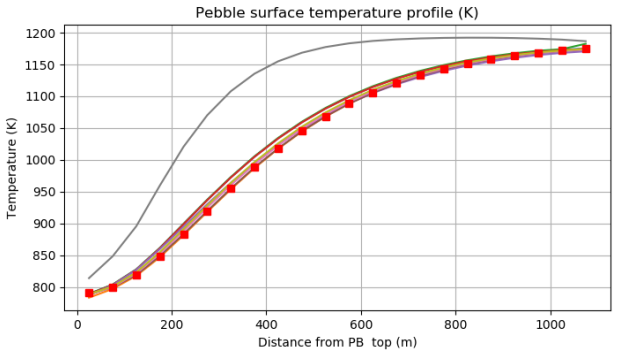

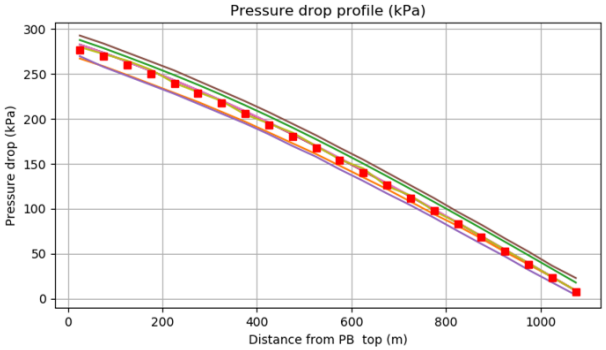

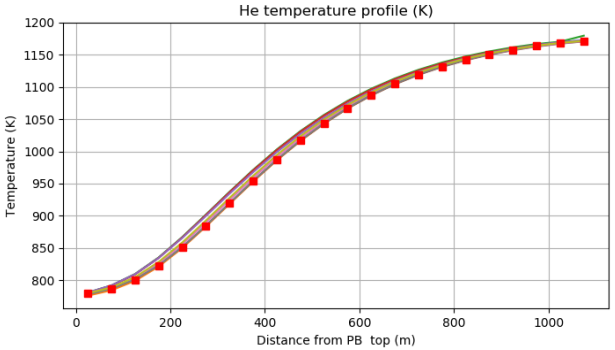

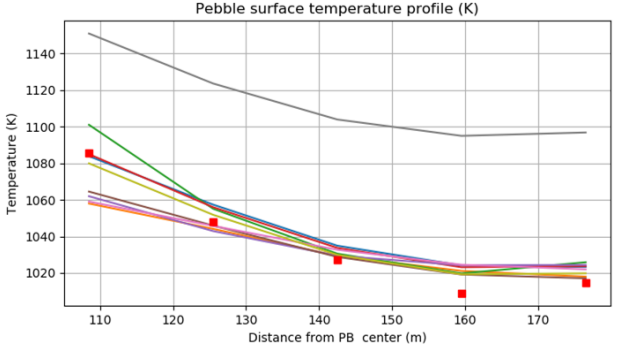

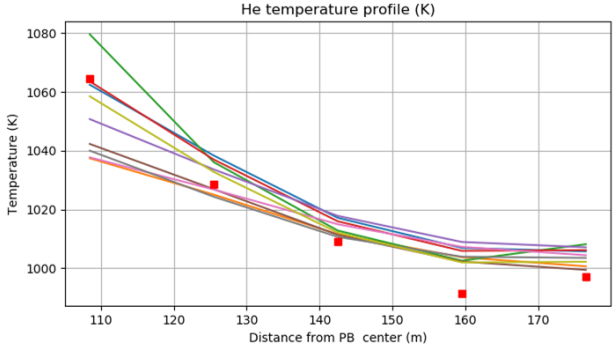

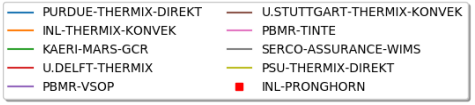

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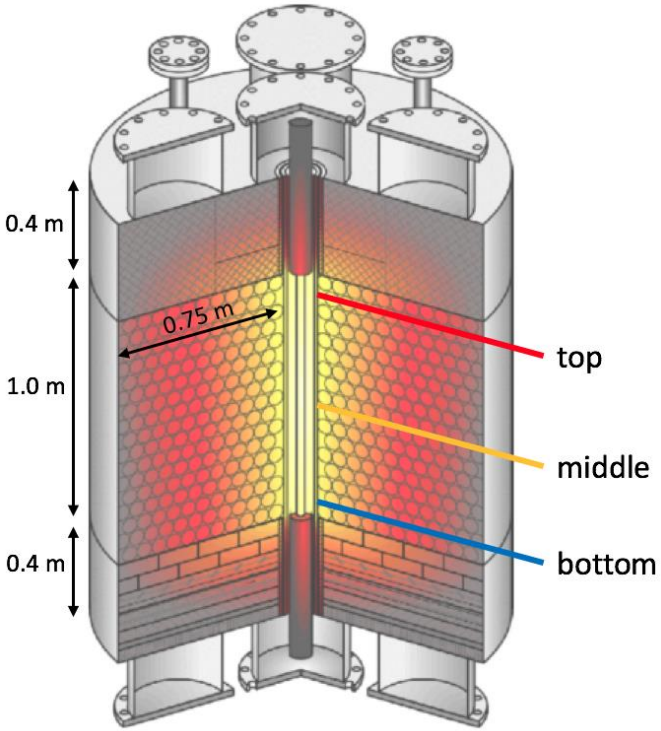
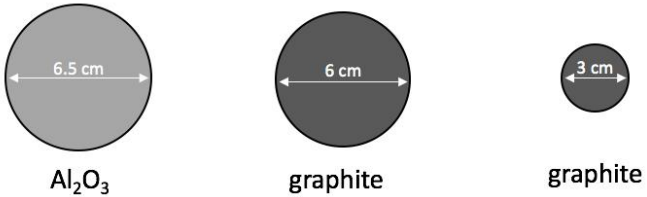
The SANA experiment - Validation



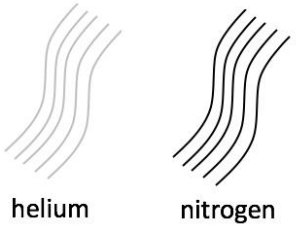
- **Scaled facility** for natural circulation heat removal (max 28 kW/m^3)
- **Electrically heated** bed of ~10,000s graphite pebbles
- **~20 thermo-couple** readings
- Experiment conducted in **Germany** 1994-1996
- **Focus**: axi-symmetric cases

SANA Experiments Experiment Matrix

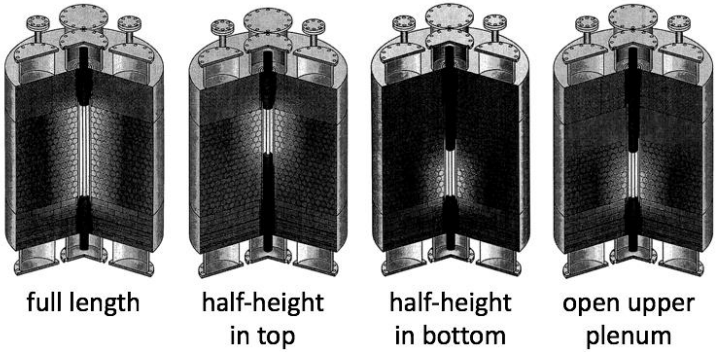
Types of pebbles



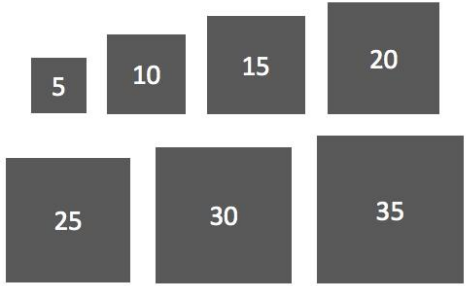
Coolant



Heater and bed configurations



Heater power (kW)



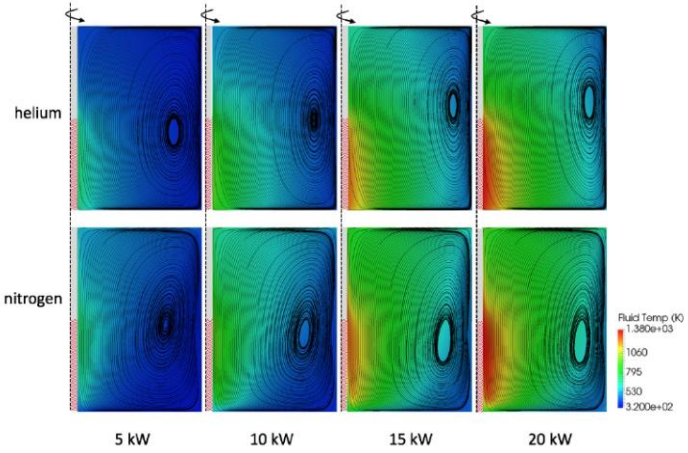
Experiment Matrix

- 52 Experiments
- 1300 T_s data points

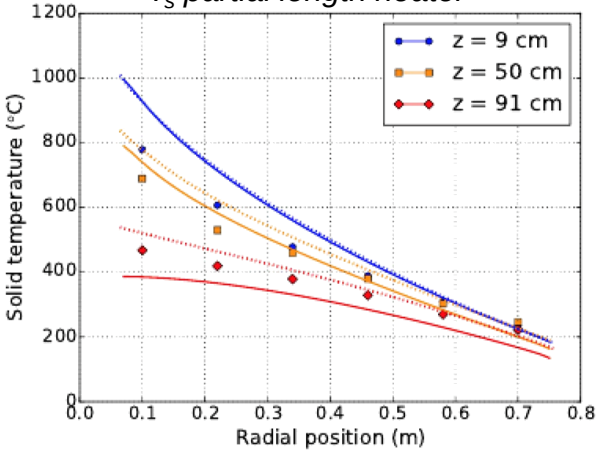
Example Results

- 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**

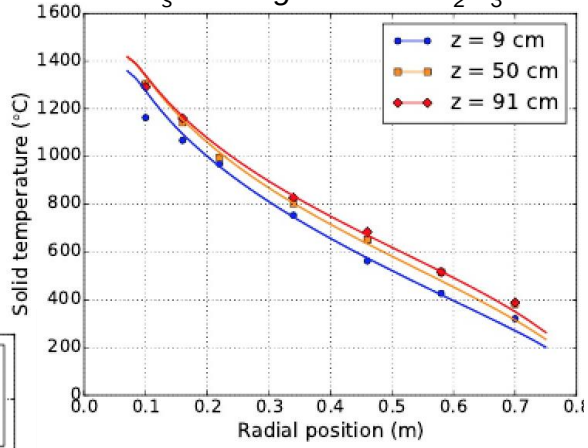
Partial length heater T_f & streamlines



T_s partial length heater



T_s full length heater Al_2O_3



(o) Measurement
(-) Pronghorn
(…) Gamma

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Pronghorn-RELAP-7 Coupling

Pronghorn: Multi-dimensional, engineering-scale reactor TH code

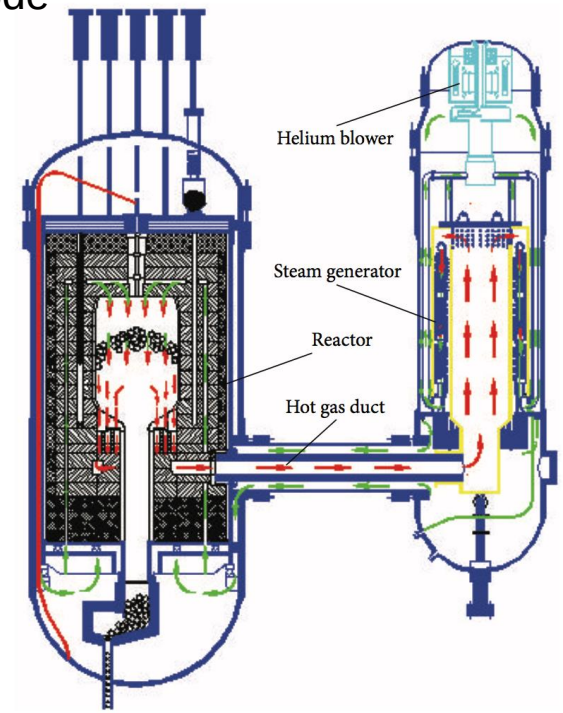
- Detailed analysis of multi-dimensional flow regions
- **No balance of plant**

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*

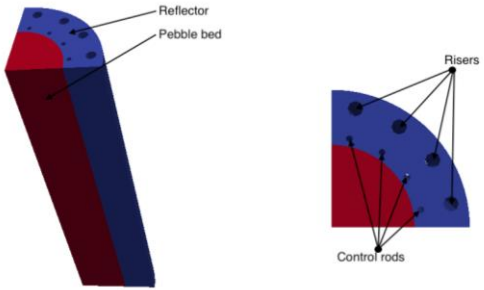


Chen, Dong, Zhang, "Temperature response of the HTR-10 during the Power Ascension test", Science & Technology of Nuclear Inst., 2015.

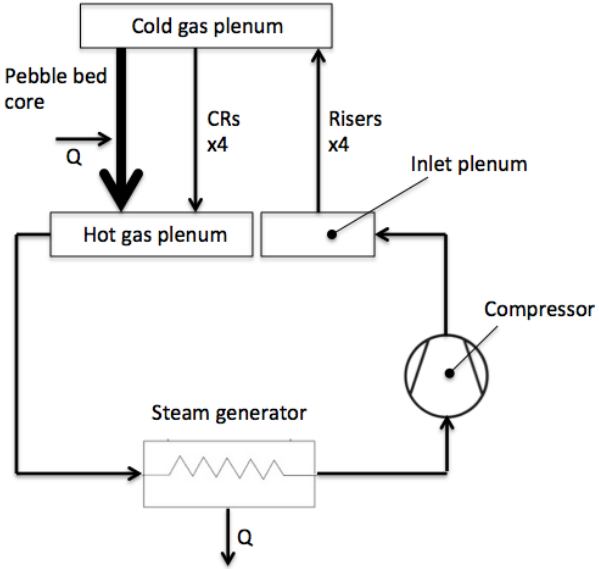
Simplified PBR with Balance of Plant

- **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

Simplified Pronghorn domain



Process flow diagram of VHTR

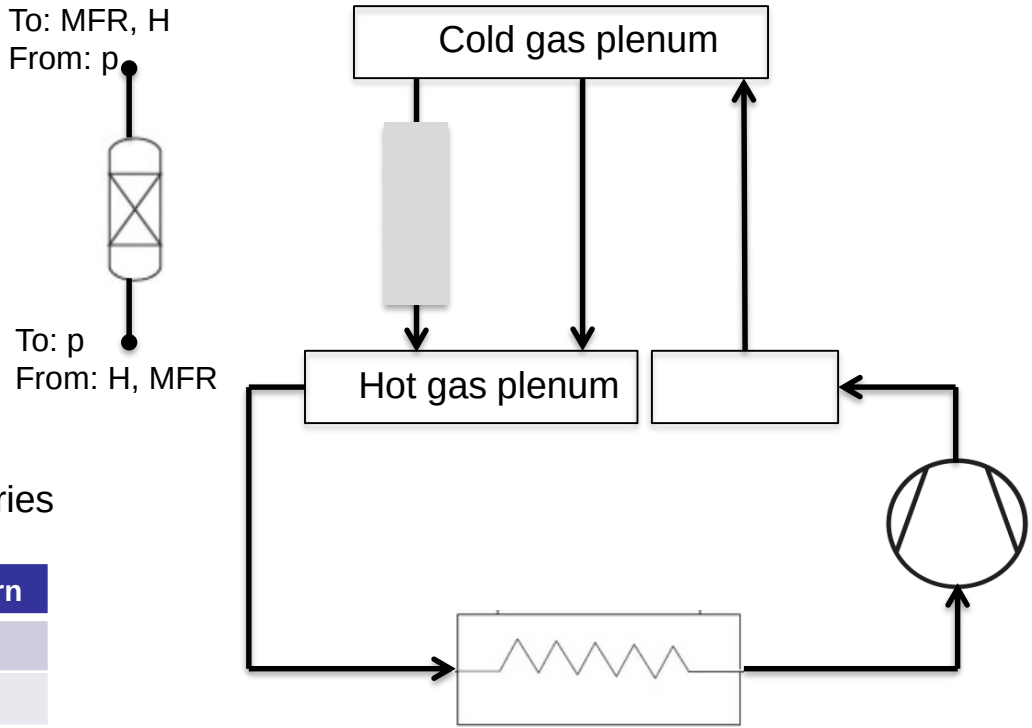


Overlapping & Non-overlapping Domain Decomposition

- Overlapping domain-decomposition
  - Create an equivalent RELAP-7 flow channel
  - Definition of equivalent flow channel:

  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

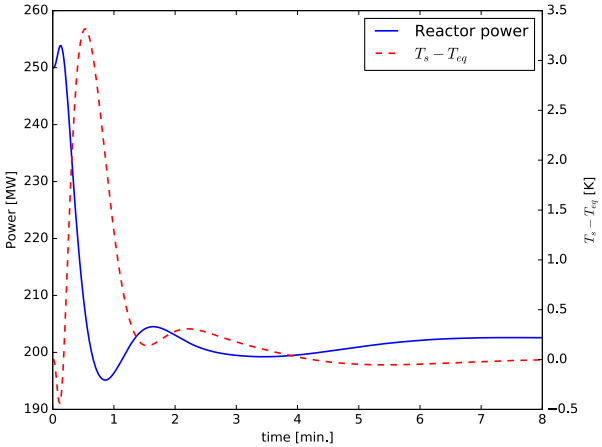
	To Pronghorn	From Pronghorn
Inlet	MFR, H	pressure
Outlet	pressure	MFR, H

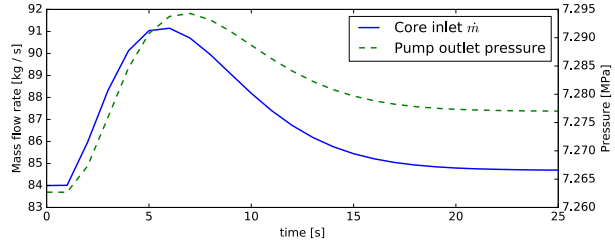


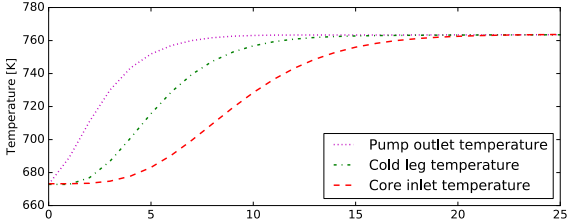
PBR w/ Balance of Plant

Steady-state results

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







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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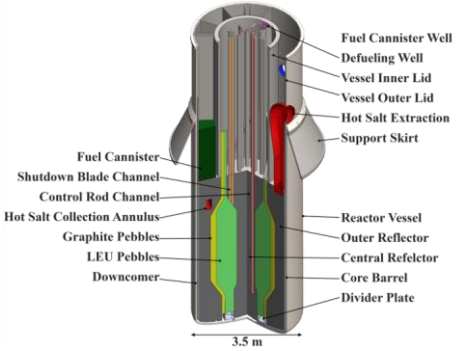
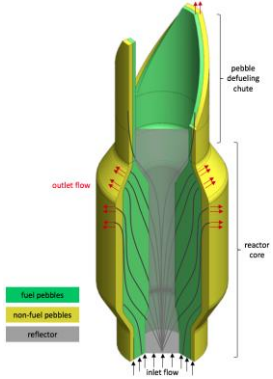
Liquid Salt Pebble Modeling

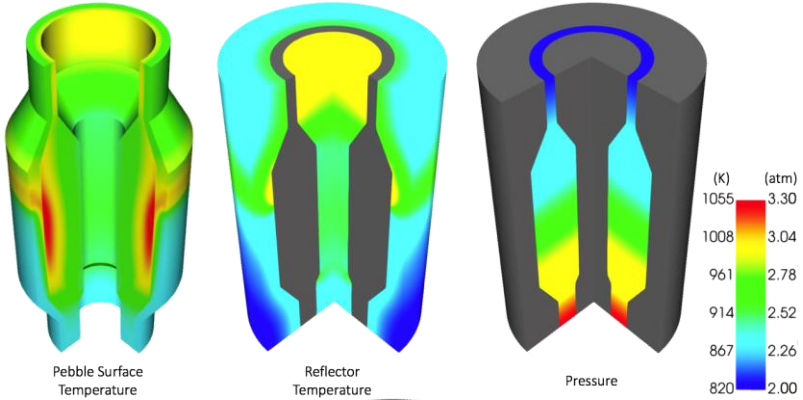
- **FLiBe** and **FLiNaK** capabilities.
- Comparison with **TRACE** for FLiNaK-cooled **ORNL Liquid Salt Test Loop** (LSTL).
- **Mark-1 Pebble Bed Fluoride-Salt-Cooled High-Temperature Reactor (PB-FHR):**
  - 236 MWt,
  - HALEU (19.8 %),
  - TRISO fuel in pebbles,
  - FLiBe coolant,
  - Atmospheric pressure,
  - Buoyant Pebbles entering from the bottom.

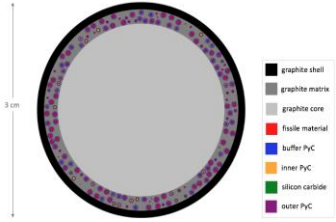
Courtesy of UCB by
April Novak
Berkeley
UNIVERSITY OF CALIFORNIA

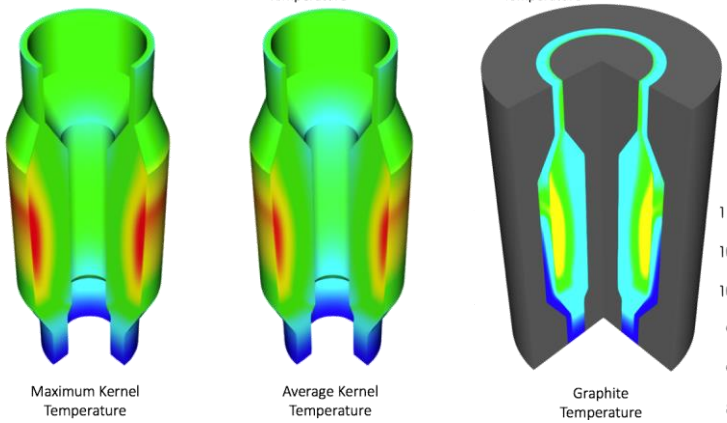
FLiBe-Cooled PB-FHR in Pronghorn











NEAMS
NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

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.