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HTGR Simulation Methods and International Collaborations

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ART
Advanced Reactor Technologies

Presentation Overview

- Overview of FY21 ART-GCR Methods Activities
- Generation of Equilibrium Core Pebble Bed HTGR Cross Sections
- Prototype Pebble Bed HTGR Startup Capability
- HTTR LOFC Experiment Simulation Results
- Two Examples of Validation Collaborations with Universities.
  - Randomly Distributed Pebble Bed Reconstruction
  - Validation for NEAMS Tools for Natural Circulation in the Reactor Cavity
- International Collaborations

Overview: ART-GCR Methods, Modeling and Validation

- FY21 activities in three focus areas; funded by ART-GCR and Regulatory Development (RD) R&D:
  - *Experimental Validation Studies (next two presentations today):*
    - NSTF: Continue matrix testing for the water-based Natural Convection Shutdown Heat Removal Test Facility (NSTF) at ANL, along with development of computational models in RELAP5 and Star-CCM+.
      - Additional RD R&D funding is used to accelerate test matrix by completing two-phase network and riser-loss coefficient parametric cases earlier than planned.
    - HTTF: Continue validation of RELAP5-3D for HTGR reactor and plant simulation against benchmarks and experimental data from the Oregon State University (OSU) High Temperature Test Facility (HTTF). FY-21 work focuses on assessment of PG 27 Loss of Forced Cooling (LOFC) test.
  - *Core Simulation:*
    - Pebble bed HTGRs: Develop a methodology for generating equilibrium pebble bed HTGR cross-sections in a consistent and efficient manner. The RD-funded activity applies this methodology to start-up and running-in of a pebble bed core.
    - HTR-PM benchmark: Prepare Griffin models for the Chinese HTR-PM pebble bed first-critical core benchmark (FY22).
    - OECD and IAEA code-to-code benchmarks: Finalize IAEA TECDOC report on HTGR Uncertainties in Modeling (sub-contract through NCSU).
  - *International Collaborations:*
    - Gen-IV: Participation in various OECD Generation-IV activities.
    - Japan bilateral: Under CNWG, various experimental data exchanges and simulation efforts are ongoing.

Generation of Consistent and Efficient Equilibrium Core Pebble Bed HTGR Cross Sections

- The task involves the development of HTGR pebble bed cross sections to preform equilibrium core calculations using NEAMS tools.

FY21 Focus:

1. How well do we know the uncertainty in the dependency of the cross sections?

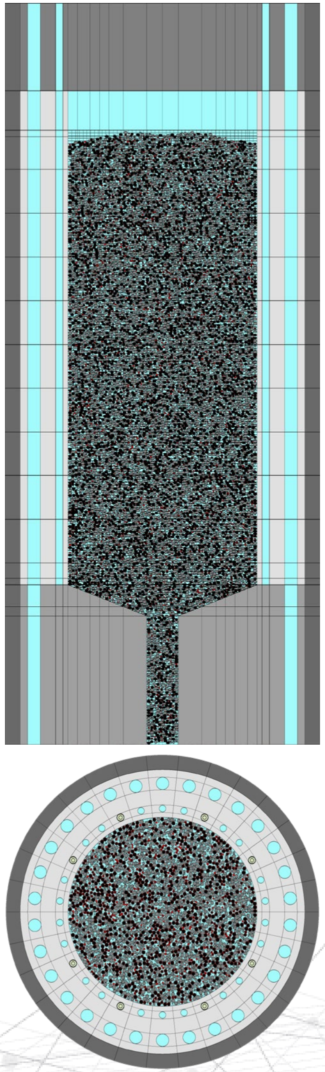
- First, we need to identify the sensitivity of cross sections to different assumptions.
- Then, identify error range of parameters such as fuel and moderator temperature produced by thermal-fluid models.
- Objective is to develop a cross-section generation procedure that will introduce a comparable error (or lower) to the one from the thermal hydraulic assumption, in order to optimize the computational efforts.

2. What methods should we use?

- Deterministic methods can be potentially faster than Monte Carlo codes but rely on several approximations to determine an accurate neutron spectrum.
- Modern Monte Carlo methods can model the exact geometry without energy, angular, and spatial discretization errors; BUT …
- Obtaining a fine-group structure cross section and modeling the various feedbacks can be a challenge.

- Will report on FY21 results and methodology selected in September.

HTR-PM



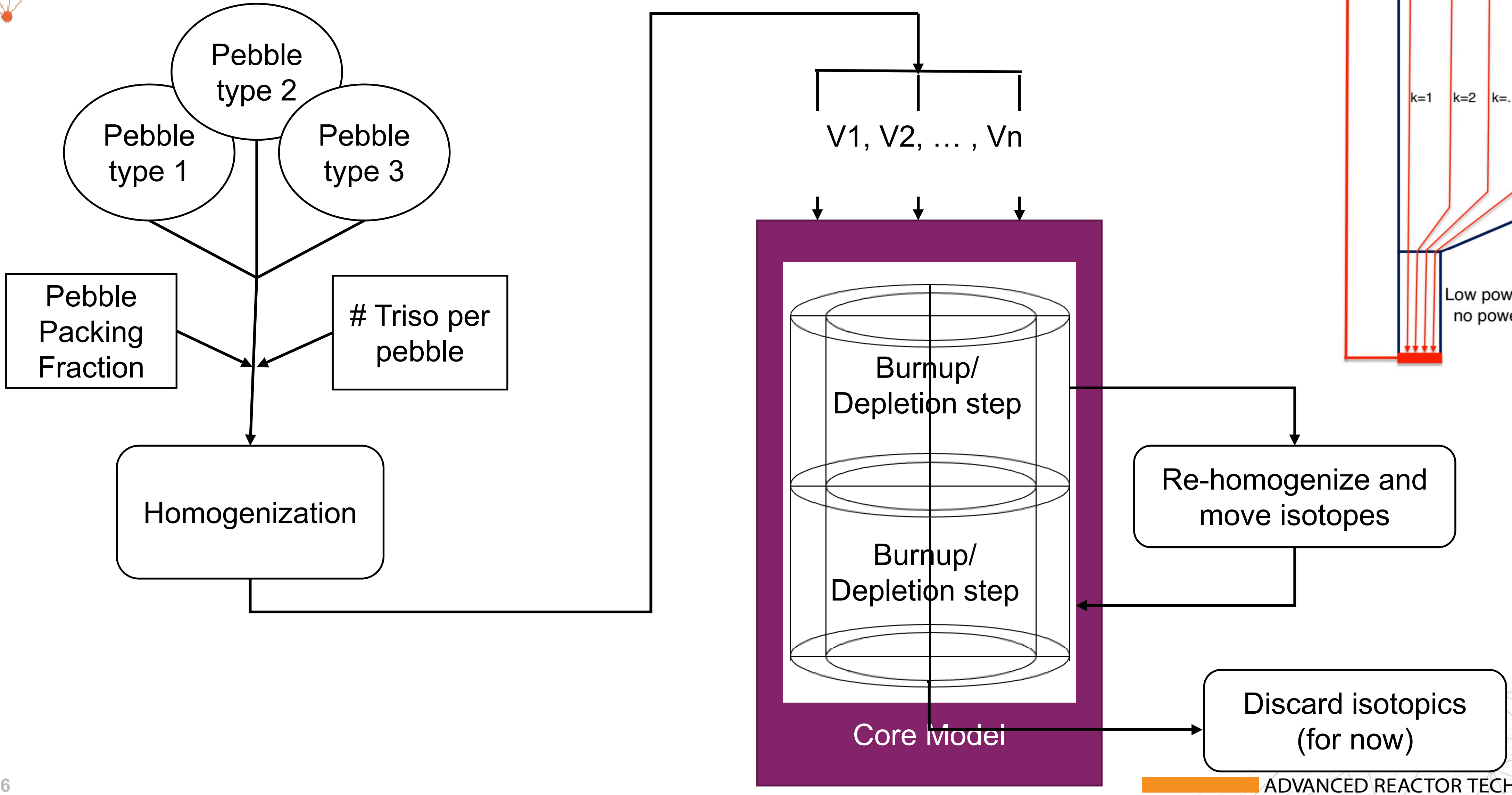
Prototype Pebble Bed HTGR Startup Capability

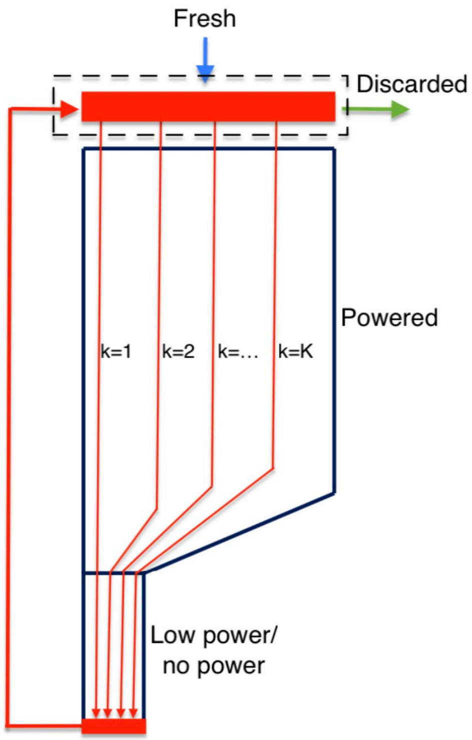
- Developing a methodology that wraps MCNP or Serpent to perform a simulated pebble bed “startup” with depletion as isotopic concentrations are migrated through the core.
- Prototype capability will simulate a pebble bed core startup from initial loading to the equilibrium core.
- The initial prototype method will be able to:
  - Use up to 3 types of pebbles with varying material definitions that can be mixed in different concentrations (e.g., pure graphite pebble, fuel pebble with startup enrichment, fuel pebble with equilibrium enrichment)
  - Use different velocities of isotopic migration through the core for different channels of pebble travel
  - Specify the number of radial, azimuthal, and axial depletion zones
  - Model a single pass fueling scheme
  - Produce fast run-times for quick analysis

Future work:

- Representative geometry of pebbles and TRISO particles (will not capture pebble self-shielding or other geometric effects)
- Temperature distributions of isotopes as they progress within core
- Multi-pass fueling scheme
- Decay of radioisotopes outside of core

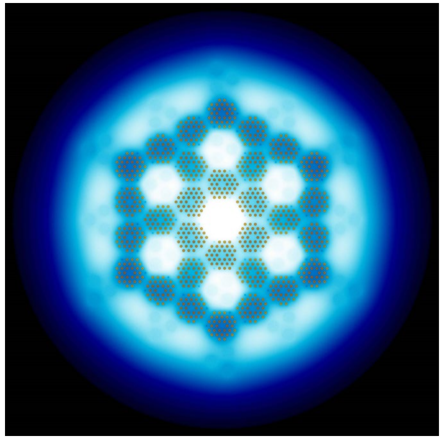
Prototype Start-Up Methodology Workflow



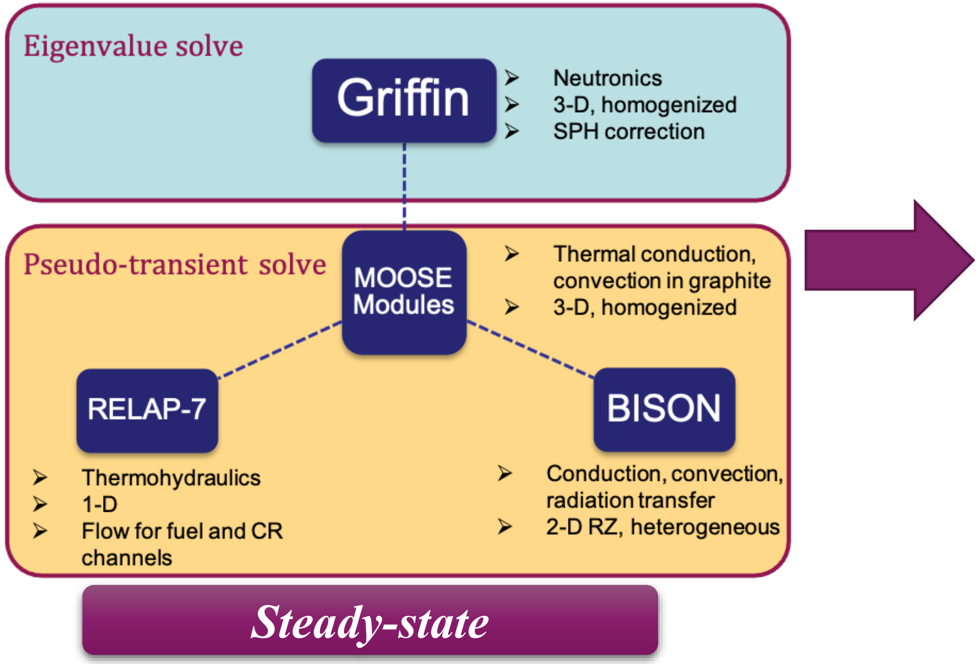


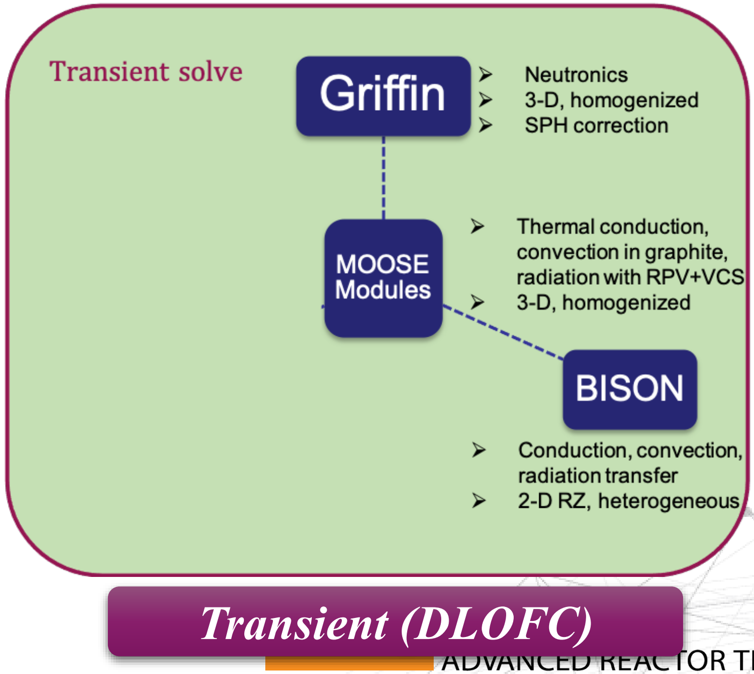
HTTR LOFC Modeling

- First (in a series of three) Loss of Forced Cooling (LOFC) experiments were preformed in 2010 by JAEA at the High Temperature Test Reactor (HTTR).
- Next two tests will be finalized later in 2021 when HTTR restarts as part of OECD/NEA benchmark, with NRC and DOE participating.
- *FY21 Objective:* Validation of Griffin and MOOSE Modules against HTTR LOFC#1 dataset.
- Cross Section (XS) generation with 3D heterogeneous Serpent model.
- Multiphysics calculation with MOOSE tools (Griffin, BISON, RELAP-7).



HTTR flux – MAMMOTH results from report INL/EXT-18-51317





DLOFC #1 (9 MW Initial Power)

Recriticality time @ 9 hrs 42 min, peak power time @ 10 hrs 50 min. This is ~3h later than measured experimental peak power.

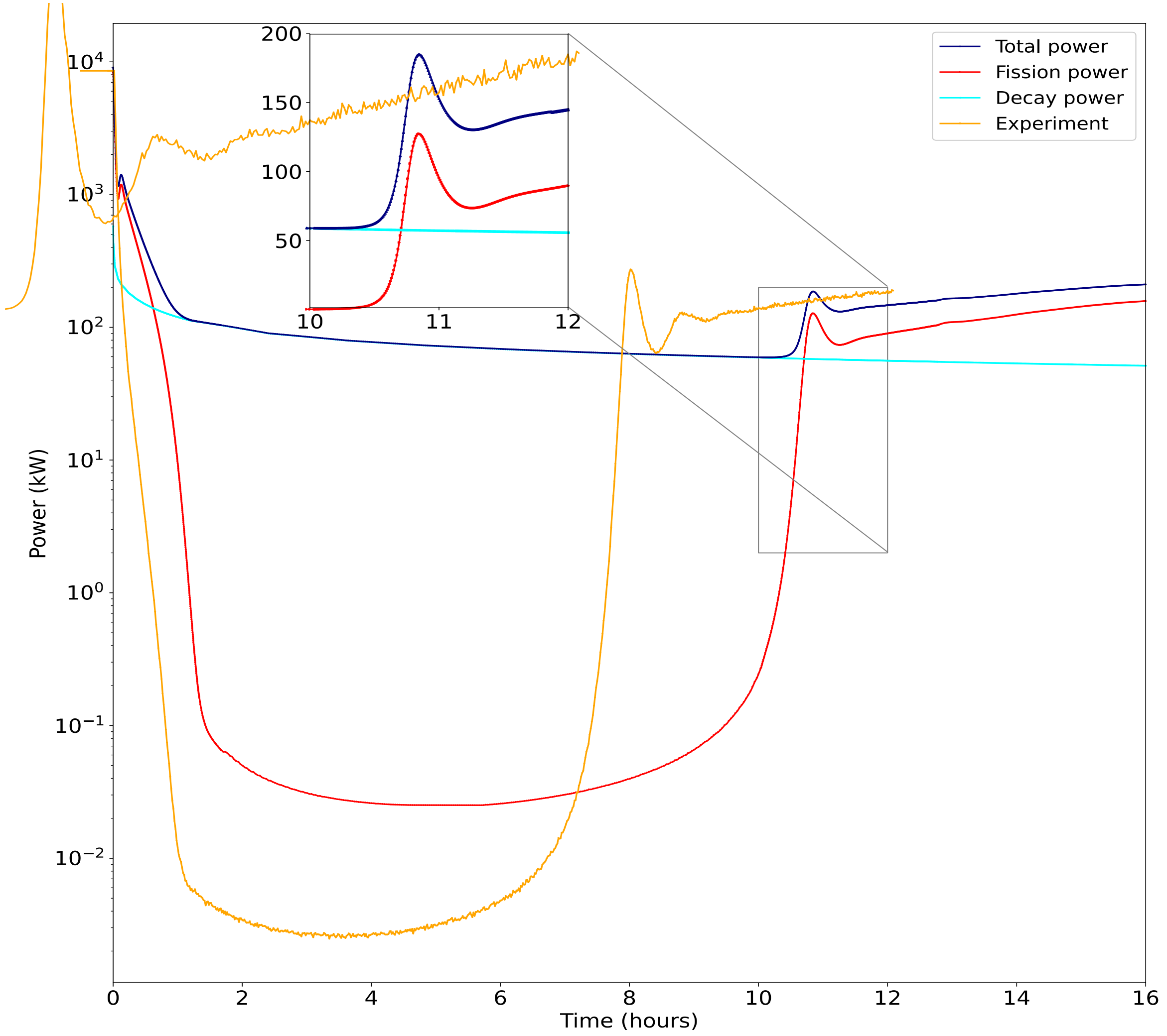
Peak power after recriticality: 185 kW (including 57 kW from decay heat). Compares reasonably well with measured power.

Future focus areas of improvement:

1. More sophisticated VCS model
2. Improved decay heat model
3. More accurate neutron source (additional data recently provided by JAEA)
4. Xe-135 initial worth currently about 60% overestimated
5. More accurate power history in Serpent depletion model (additional data provided by JAEA)

Promising results but will likely still change significantly

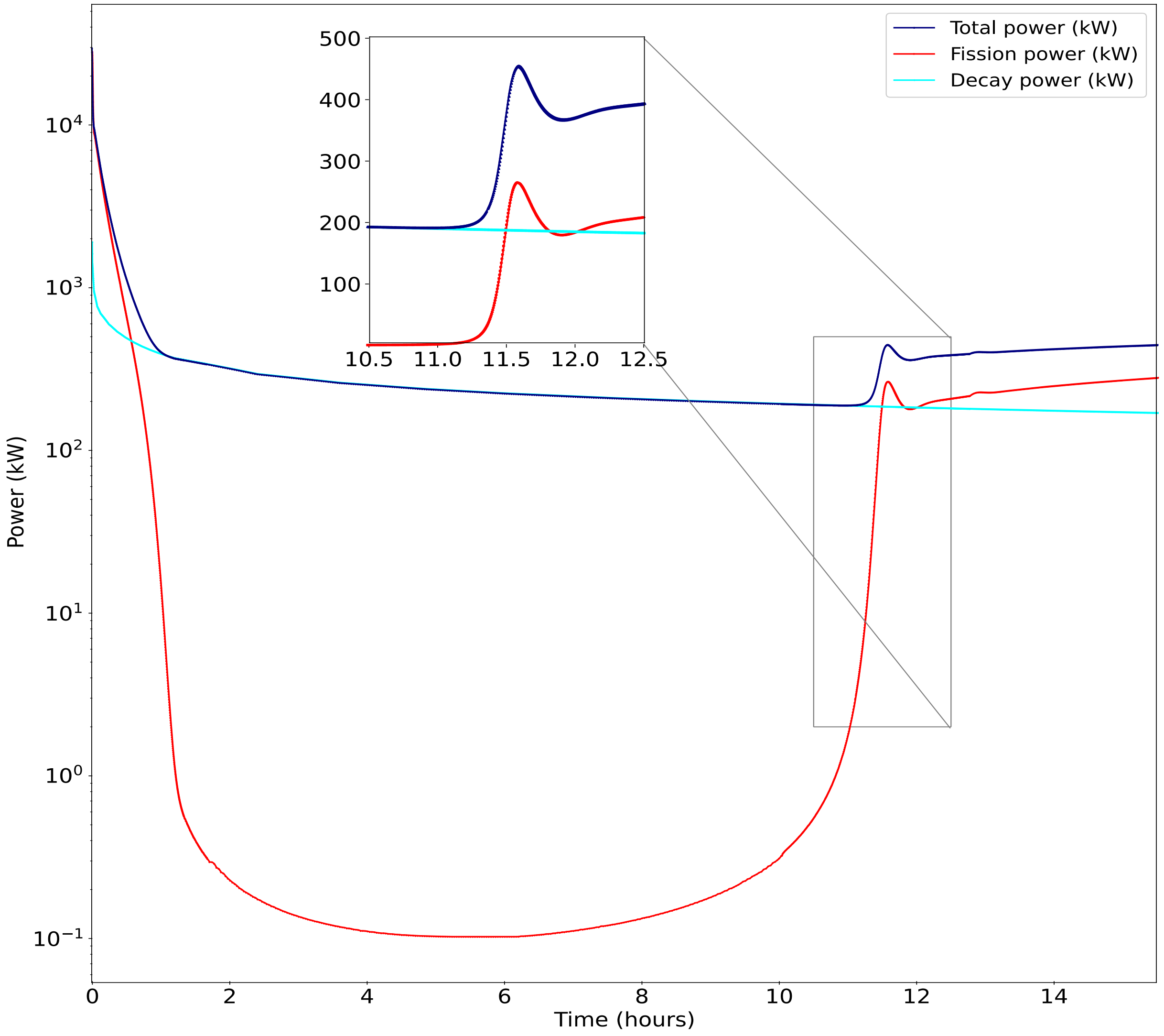
ALL RESULTS ARE PRELIMINARY AND SUBJECT TO CHANGE



Prediction of LOFC #2 (30 MW Initial Power)

ALL RESULTS ARE PRELIMINARY AND SUBJECT TO CHANGE

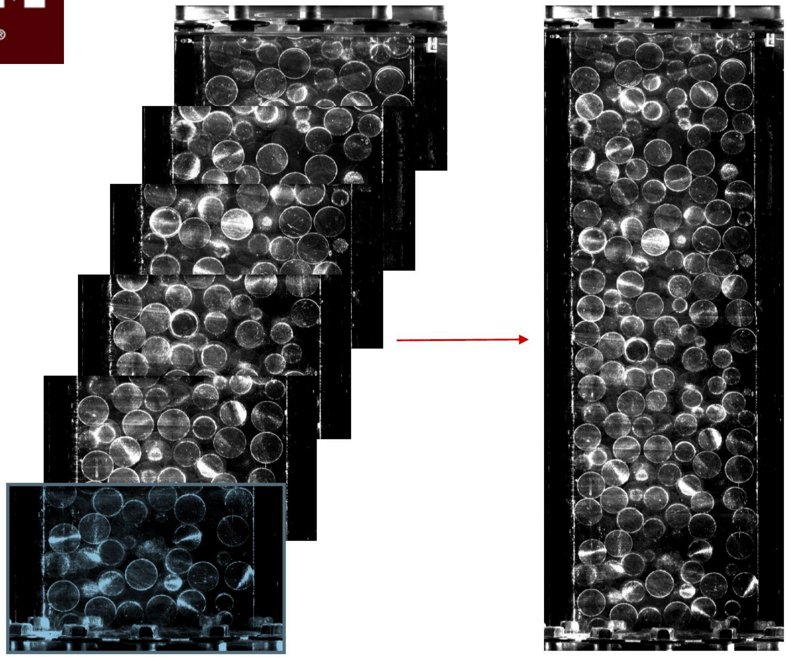
- Recriticality time @ 10 hrs 20 min; peak power time @ 11 hrs 35 min (45 min later compared to 9 MW LOFC#1 case).
- Peak power after recriticality: 450 kW (including 190 kW from decay heat).
- Results will be reported in September.

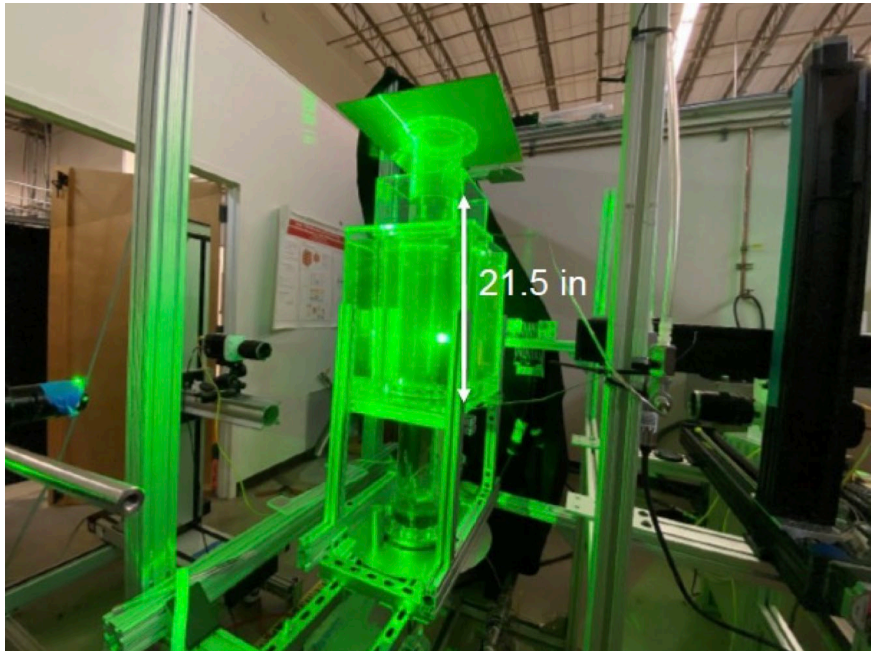


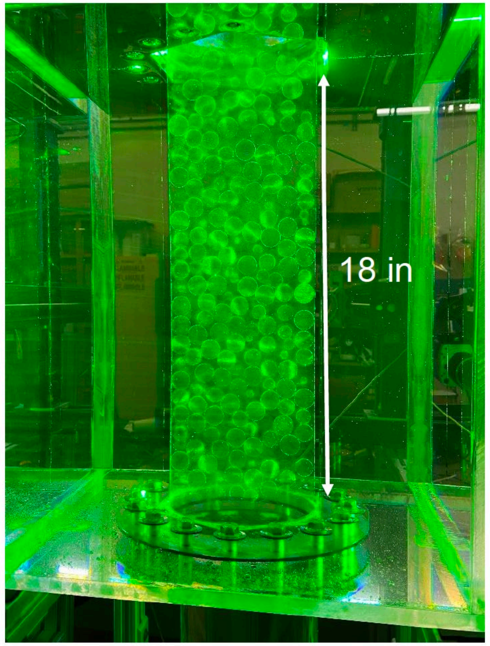
Random Pebble Bed Reconstruction

- **TAMU Isothermal Versatile Experiments III**
  - 35 images were taken of various cross-sections of a pebble bed at a spacing distance of 0.16 inches.
  - Pipe inner diameter 5.50 inches, pebble diameter 0.75 inches.
  - 1350 pebbles filled to 21.5-inch, reconstruction up to 18 inches.

Why and how do we reconstruct a digital version of the pebble bed?



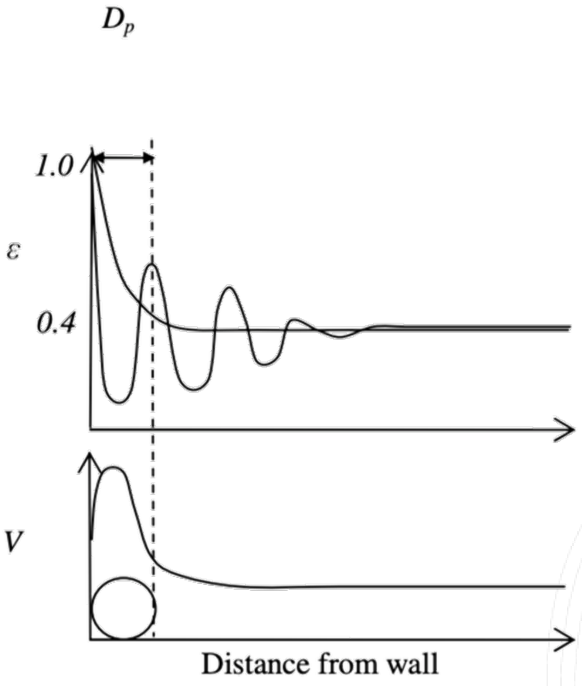




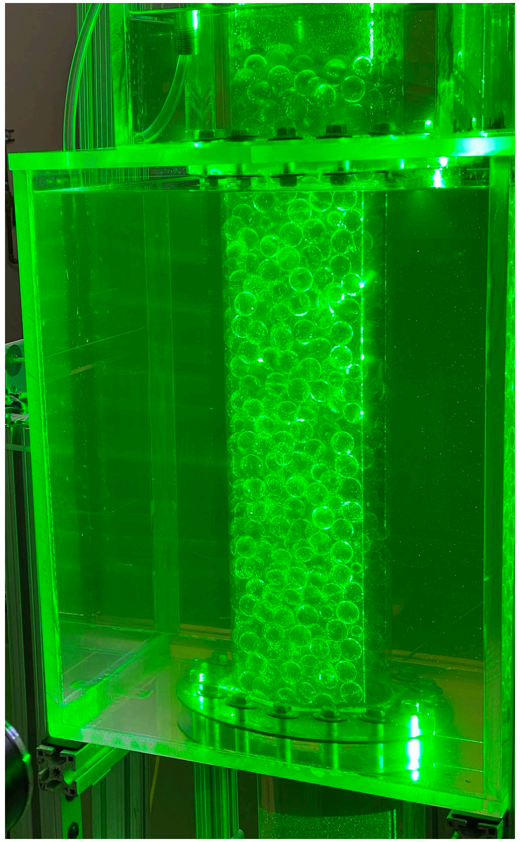
Random Pebble Bed Reconstruction

VGSTUDIO MAX
High-End Industrial CT Software

- **Why?**
  - New high fidelity CFD simulations (NEK5000,STARCC+) require high fidelity data for validation and high-fidelity modeling.
  - Wall channeling helium flow effects (caused by different packing fraction of the pebbles close to the bed wall) require validation:
    - Intermediate fidelity tools use porosity distribution functions (right).
    - High fidelity tools use molecular dynamics simulators (e.g., LANL LAMMPS) to reconstruct pebble distribution in the core.
- **How?**
  - Codes like VGSTUDIO can reconstruct a digital copy of a pebble bed based on laser pictures of the experiment.
  - This provides validation data for porosity function distributions, and molecular dynamics simulators used to create random pebble distributions for high fidelity codes.

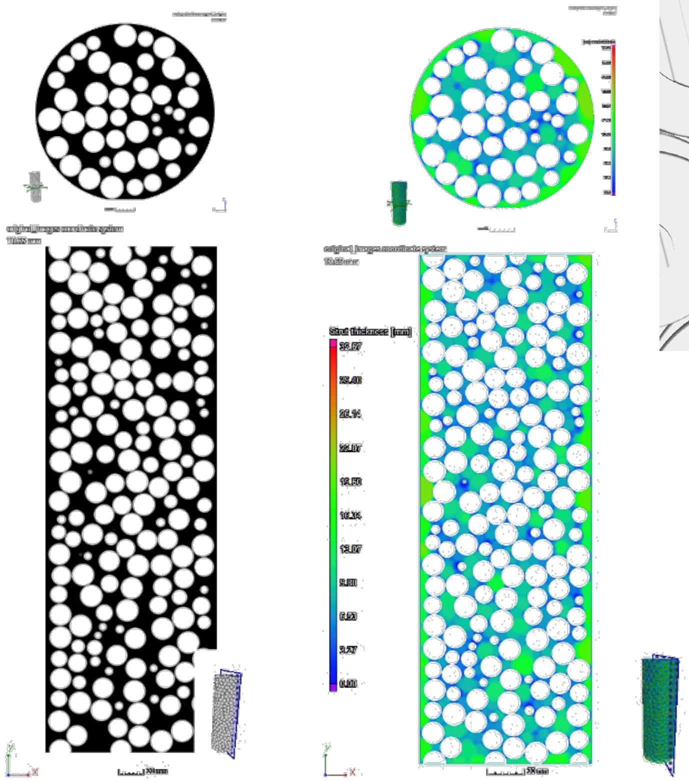


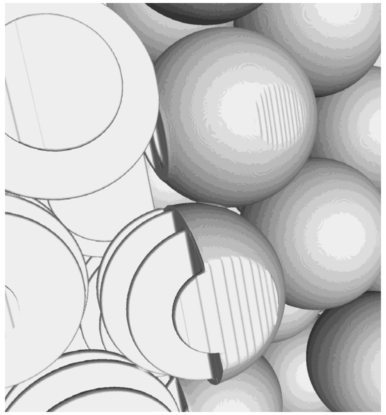
Random Pebble Bed Reconstruction Process



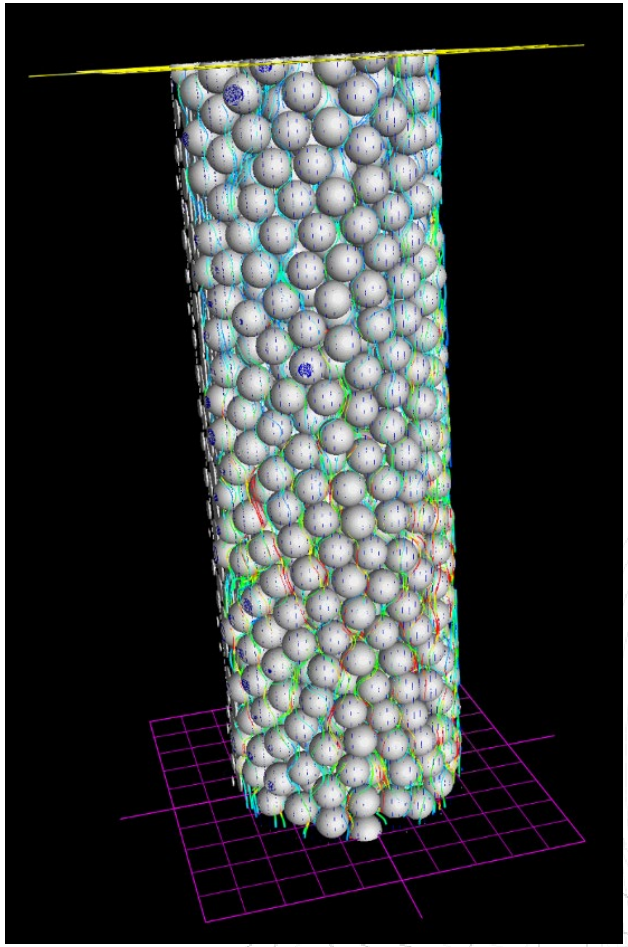
1. Laser pictures of facility at different depths

2. Picture analysis





3. 3D model of pebble bed

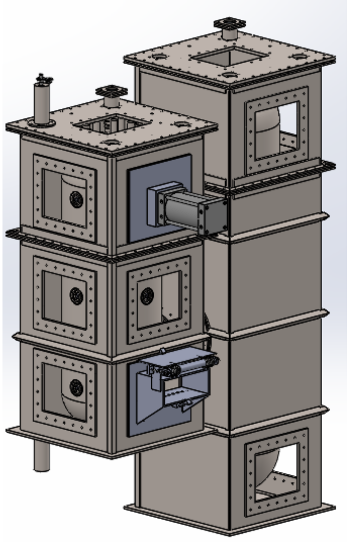


VGSTUDIO MAX
High-End Industrial CT Software

Validation of NEAMS Tools for Natural Circulation in the Reactor Cavity in Accident Conditions

University of Idaho
College of Engineering

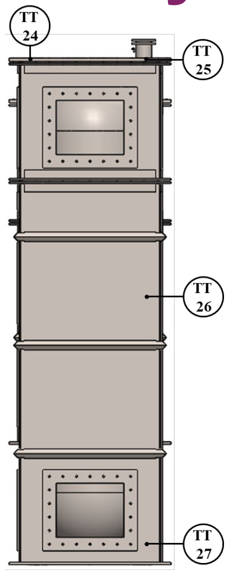
- **1/20th Scaled-down VHTR @ UI**
  - The containment of the RPV and power conversion unit (PCU) have 10 exhaust ports for optimization of containment ventilation and to detect air ingress into the RPV.
  - To mimic a point of break, the RPV has six vent locations on the side, and 9 penetrations at the top of the RPV.
  - A cross vessel connects the RPV to a dummy power conversion unit (PCU) vessel.
  - The system is equipped with 32 thermocouples, 10 oxygen sensors and 10 hot wire anemometers.



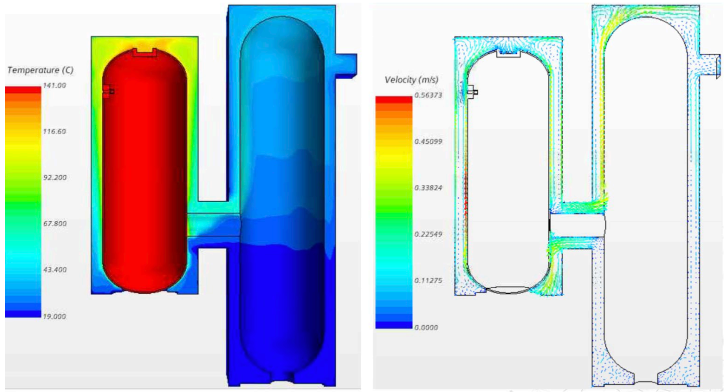
Validation for NEAMS Tools for Natural Circulation in the Reactor Cavity in Accident Conditions

- **Why?**
  - CFD codes, and even more so intermediate and low fidelity models, need to be validated to assess how well they simulate natural circulation in complex geometries such as a HTGR reactor cavity.
  - Different mixtures of air and helium could be present in the reactor cavity during a break event, depending on the position and the size of the break.
  - The codes must be therefore be validated for different fluid conditions, pressure and temperatures in order to correctly assess the amount of heat that is removed by convection during a LOFC event.
- **How?**
  - Temperature measurements provided by the UI facility can be used to validate natural circulation model in the reactor cavity.
  - CFD analysis has been already carried out to better understand the main phenomena during the experiment.
  - NEAMS/ART supported Pronghorn model development is underway as part of a summer internship at INL. The model results will be compared with measurements and CFD to check if the approximations made in the lower fidelity models are acceptable.

Validation for NEAMS Tools for Natural Circulation in the Reactor Cavity in Accident Conditions

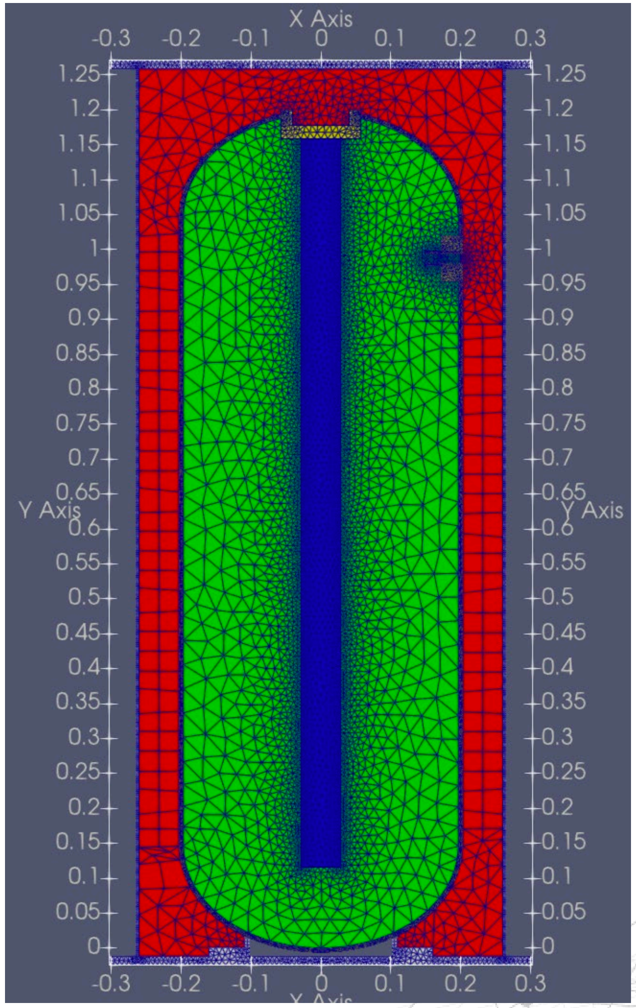


Measurements



CFD Results

Simplified Pronghorn Model



ART-GCR Methods International Collaborations

- GEN-IV VHTR Computational Methods Validation and Benchmark (CMVB)
  - *New Project Arrangement currently in DOE signature process!* (Japan and Korea already signed). CMVB activities expected to start late in 2021.
  - Paolo Balestra (INL) and Rui Hu (ANL) were nominated by DOE as new US CMVB representatives.
  - *Primary Objective*: Validation of computational tools and benchmarking of new methods.
  - Addresses lack of operating HTGR performance data for validation of NEAMS codes
    - Old German data for Pebble Bed type HTGR is not publicly available (Proteus, ANABEK and NACOK experiments) – will be shared under CMVB.
    - Chinese pebble flow experiments, HTR-PM first-core criticality and HTR-10 Melt-wire experimental data will be shared when performed.
  - Also addresses lack of scaled integrated experiments for HTGRs and of use of CFD in licensing and design.
- Civil Nuclear Working Group (CNWG) bi-lateral agreement with Japan (JAEA)
  - HTTR LOFC validation of NEAMS codes (as presented earlier)
  - Gas-turbine system work - INL/JAEA are jointly improving the secondary side modeling and started hydrogen and electricity market analysis (Shannon Bragg-Sitton).

Idaho National Laboratory