July 27, 2023

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Idaho National Laboratory

GCR Methods Area Overview & International Collaborations

Experimental Validation, Reactor analysis & International Collaborations

DOE ART Gas-Cooled Reactor (GCR) Review Meeting
Virtual Meeting
July 25 – 27, 2023

ART
Advanced Reactor Technologies

Contributors

- **INL**
  - Ryan H. Stewart, Zachary M. Prince, Vincent M. Laboure, Gerhard Strydom, Javier Ortensi, Sebastian Schunert, Aaron S. Epiney, Sunming Qin
- **ANL**
  - Darius D. Lisowski, Qiuping Lv, Matt Jasica, Mitch Farmer, Art Vik, John Woodford
- **Universities**
  - Robert Kile, Adam Mafi

Content

Methods Experimental Validation - Support experiments such as HTTF tests, NSTF campaign and HTGR related NEUPs to fill the gaps of the validation matrix for High Temperature Gas Cooled reactors M&S tools.

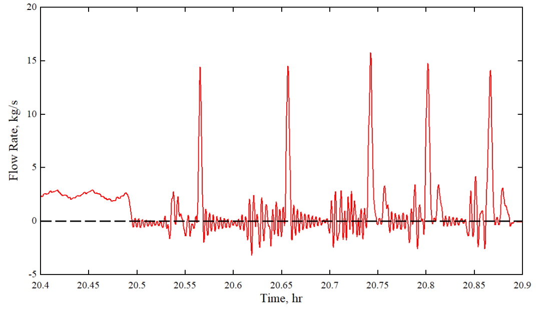
Reactor analysis - Development of integrated methodologies to test tools capabilities for High Temperature Gas Cooled reactors modeling and test new approaches that increase fidelity or simplify the analyst workflow. An example of that are the testing on the engineering scale of start-up, run-in and equilibrium core calculation capabilities.

International collaborations - Leveraging international collaborations to exchange data for validation of High Temperature Gas Cooled Reactors M&S tools. Operational reactor data such as the HTTR LOFC tests are extremely rare but really useful to prove the validity of the results obtained with the tools.

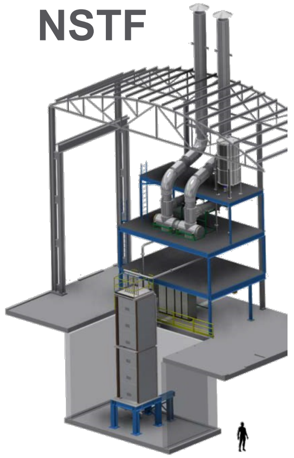
Methods Experimental Validation

- **Natural Convection Shutdown Heat Removal Test Facility (NSTF) experiments:**
  - **½ scale axial height of Framatome 625 MWt** Steam Cycle High-Temperature Gas-Cooled Reactor RCCS.
  - **Top level objectives** of NSTF program: Confirm the performance of the next generation nuclear plant reactor cavity cooling systems (RCCS) based on passive safety; Generate NQA-1 standard data; Provide benchmark data for code V&V.
  - **FY23**, tested accident scenarios and off-normal events.
    - Blocked flow channels in heated core and isothermal piping
    - Operation past inventory depletion and into "dry-out"
    - Refill procedure for replenishment of lost inventory post-accident
  - **FY24**, will perform major modification on network piping, changing the elevation of the chimney into the primary tank
    - Area of specific interest based on industry feedback
  - **Future planning** to identify future roles, purpose, and needs of the NSTF program at Argonne
    - Industry outreach to 19 US vendors on their passive decay heat removal gaps and needs
- **High Temperature Test Facility (HTTF) Benchmark:**
  - **¼ scale of General Atomics' modular high-temperature gas-cooled reactor.** Helium cooled, electrically heated, prismatic blocks made of Alumina, Over 500 instruments, designed primarily to investigate phenomena occurring during depressurized (DCC) and pressurized (PCC) conduction cooldown transients
  - **OECD-NEA** High Temperature Gas-Cooled Reactor Thermal Hydraulics Code Validation Benchmark Based on HTTF Data **has begun** – participation from industry, academia, and labs around the world.
  - **RELAP5-3D validation** activities based on HTTF have shown an ability to reproduce trends in the HTTF data.
  - This work will accelerate the **deployment of prismatic HTGR microreactors** by providing an opportunity for designers to assess their codes against experimental data and solutions from other codes.

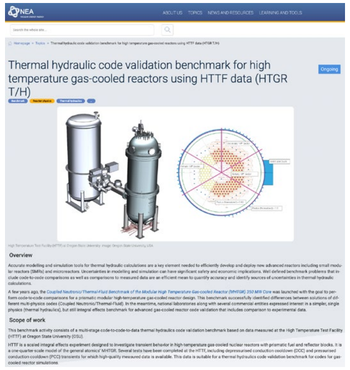
Violent geysering inventory depletion



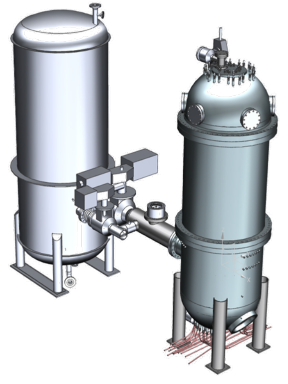
NSTF



NEA-Benchmark



HTTF

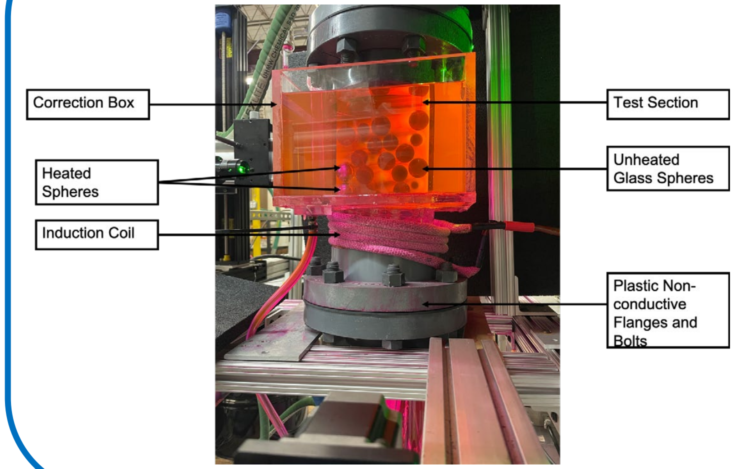


Task	FY23		FY24		FY25		FY26	
NSTF Experiments								
HTTF Benchmark								

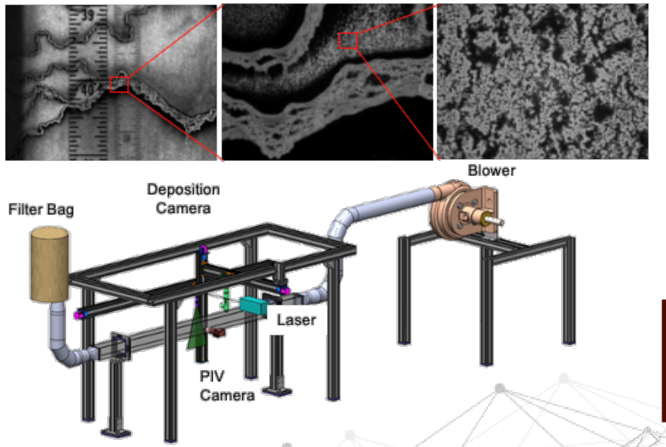
Methods Experimental Validation

- NEUP1 - **Experimental Investigations and Numerical Modeling of Near-wall and Core Bypass Flows in Pebble Bed Reactors**
  - Multiple experimental facilities employed for pressure drop and flow visualization testing for validation of simulation
  - Advanced experimental techniques include three-dimensional reconstruction for direct experiment-simulation comparison
- NEUP2 - **Experimental Investigations of HTGR Fission Product Transport in Separate-effect Test Facilities Under Prototypical Conditions for Depressurization and Water-ingress Accidents**
  - Analytical deposition, resuspension model development, numerical validation, scaling, nondimensionalization, and sensitivity study.
  - Plateout, Liftoff, Washoff Experiments under atmospheric and prototypical conditions

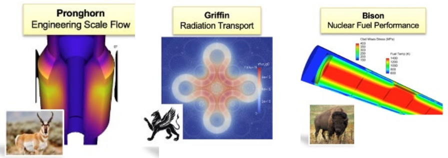
Pebbles heated with magnetic induction



Graphite deposition tests



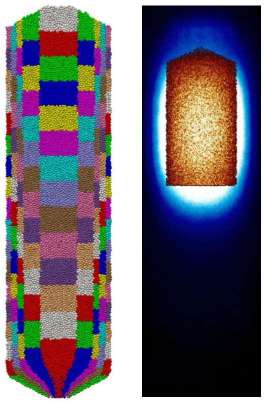
Methods Reactor Analysis



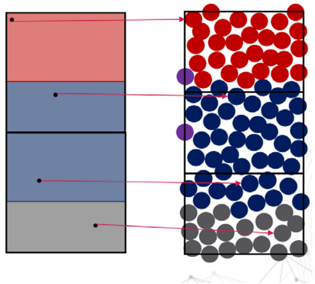
- **Monte Carlo based Multiphysics running in methodology integration:**
  - This approach use **existing Monte Carlo codes** and **avoid the difficult cross-section generation** task for pebble bed reactor micro depletion calculations.
  - The pebbles can be modeled explicitly defining and random distribution with **real local packing fractions**
  - FY22 prototype has been developed assuming simplified temperature profiles and criticality search procedures; FY23 Coupling with Griffin/Pronghorn for accurate temperature profile calculations.
- **Reduced order model development for optimization studies and uncertainty propagation:**
  - **Optimizing** Equilibrium core design and running in procedures is currently **challenging** using **conventional tools**.
  - Training **Reduced Order Models** (e.g. Neural Networks, Polynomials) selected based on the results behavior will provide a **fast running and accurate** tool for optimization studies and uncertainty quantifications.
  - During FY22 the methodology to generate ROMs has been applied to equilibrium core calculations, studying economics and performance of the reactor, FY23 safety related parameters has been added to the study simulating a DLOFC accident.
- **TRISO fuel performance study during Control Rod Withdrawal accidents:**
  - Two pebble bed reactor designs using TRISO fuel → GPBR200 and GFHR representative models available.
  - Realistic withdrawal from critical position at full power for both the reactors.
  - Estimation of TRISO failure probability coupling with BISON
- **Pronghorn Tutorials Development:**
  - 12 interactive steps (primer) on how to model a pebble bed reactor using Pronghorn from a simple heated pebble bed to a model with cavity, gaps bypasses.
  - Accessible by anyone trough the Virtual Test Bed repository supported by NRIC.

NRIC National Reactor Innovation Center

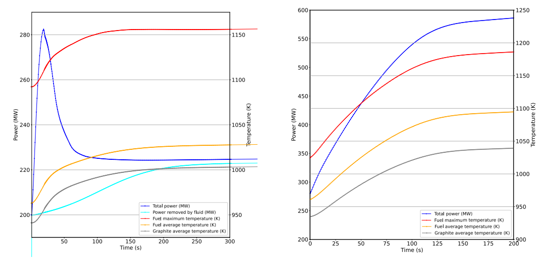
MC MP Run-In



Serpent Griffin Information exchange

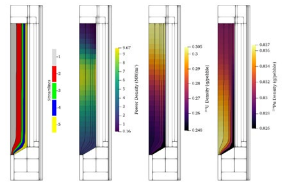


CRW transients

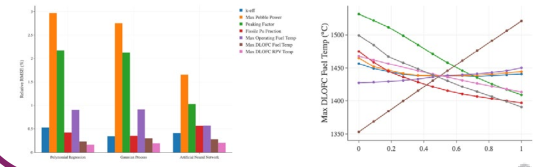


GPBR200 GFHR

GPBR200 equilibrium core



ROMs Gen and sensitivity analysis



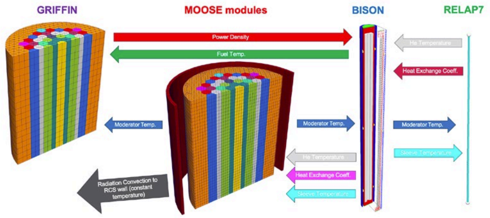
Task	FY23		FY24		FY25		FY26	
Running in, Equilibrium core capabilities								
ROMs generation for Optimization studies								
CRW TRISO fuel performance studies								

International collaborations

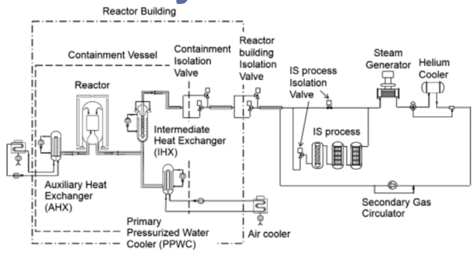
- **High Temperature Test Reactor (HTTR) Loss of Forced Cooling (LOFC) Benchmark:**
  - **30MW Gas cooled prismatic reactor** capable of reaching **950℃ (Max.)** of helium outlet temperature at 4.0MPa.
  - The experimental campaign was **interrupted in the 2011**, the only test performed so far was a **9MW LOFC** scenario with the Vessel Cooling System (VCS) activated.
  - The data have been collected in an **NEA international benchmark** HTTR LOFC benchmark.
  - The reactor **restarted operation in the FY22** and a **new test** has been performed **30MW LOFC** scenario with the Vessel Cooling System (VCS) activated.
  - The LOFC Test#3 data have just been shared, Test#2 (LOFC full power VCS on) planned for the end of CY23.
- **Civil Nuclear Energy Research and Development Working Group (CNWG) US and Japan bilateral agreement:**
  - From January 5 to March 21, 2010, JAEA operated the HTTR ramping the reactor power from zero to full power and back to zero in 1800h.
  - Although the focus of the experiment was tritium measurement other reactor parameters such as fluid temperatures and Control Rod (CR)s positions were recorded.
  - The model developed using NEAMS tools for the LOFC experiment will be modified adding CR explicit modelling and used to simulate the power ramps
  - A MELCOR model of HTTR will be developed to simulate production and transport of TRITIUM within the reactor.
  - #1 Extension of the multiphysics NEAMS model validation range to startup and shutdown conditions.
  - #2 Validation of TRITIUM production and transport modelling in MELCOR for high temperature reactors.

Task	FY23		FY24		FY25		FY26	
HTTR LOFC Benchmark								
US/Japan - CNWG								?

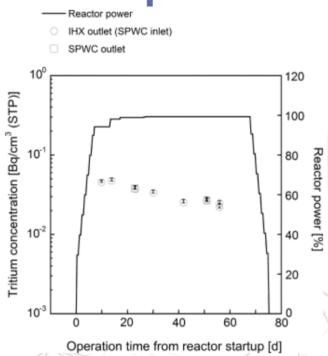
NEAMS tools (GRIFFIN, BISON, RELAP7) Model



HTTR systems



Power ramp transient



MELCOR NEAMS NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

Dipu, Arnoldus Lambertus, et al. "Assessment of amount and concentration of tritium in HTTR-IS system based on tritium behavior during high-temperature continuous operation of HTTR." Annals of Nuclear Energy 88 (2016): 126-134.

International collaborations

GIF Very High Temperature Reactor – Computation Methods Validation and Benchmark (VHTR-CMVB):

- **Several participants** including the following signatories: Korea Atomic Energy Research Institute (KAERI) for the Republic of Korea, Institute of Nuclear and New Energy Technology of Tsinghua University (INET) for China, U.S. Department of Energy (DOE) for the United States (U.S.), Joint Research Centre (JRC) for EURATOM, Japan Atomic Energy Agency (JAEA) for Japan.
- **U.S. is leading 3 out of the 5 WPs** and oversees subtask in all the WPs for a total of 7y
- U.S. signed the agreement end of FY22, activities **started on FY23**
- First year, data has been collected to create the benchmark specifications.

Task	FY23	FY24	FY25	FY26
GIF VHTR-CMVB				

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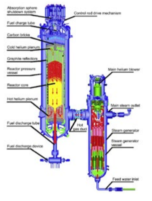
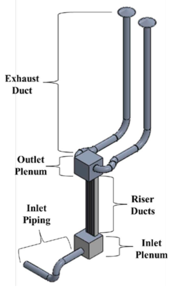
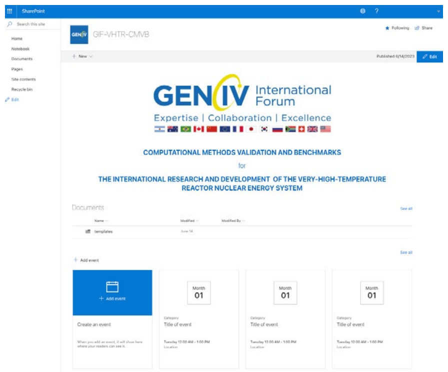
Activities





SharePoint



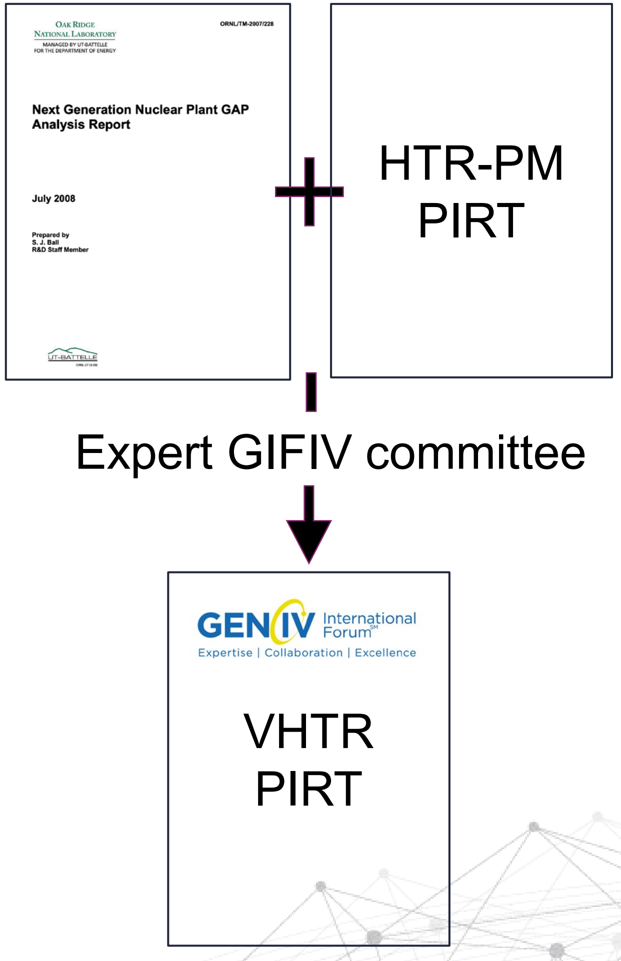
CMVB PA	EU	JP	CN	KR	US	UK	CA
	P	P	P	P	P	O	O

Date	Event
2018.10.05	• The Project Plan has been approved by all SSC.
End of 2020	• The confirmation of CMVB PA has been received from each signatory, comments have been received from the signatories: EU, Japan, China, Korea, and US.
2021.05.14	• The SSC members approved the updated project plan concerning the subject of signatories
2021.09.01-02	• Signatory from KAERI (05/21/2021), JAEA (06/17/2021), JRC (07/15/2021), and INET (08/31/2021).
2022.09.19-20	• At the 25th CMVB pPMB Meeting Canada joined as observer and signatory from the DoE was announced by the end of the 2022.

WP1 - Phenomena Identification and Ranking Table (PIRT) Comparison, Evaluation, and Update

Consolidation of the knowledge about VHTRs important phenomena

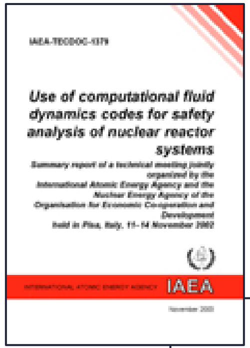
- **Task 1.1:** The Task Leader (DOE) shall construct a template of PIRT values and populated with values from the Task Leader's PIRT. Update members' knowledge of important or poorly understood thermo-fluid and core safety phenomena
- **Task 1.2:** Consolidation of PIRTs on Chemistry and Transport (including Water Ingress)
- **Task 1.3:** Construction of a Validation Matrix (Experiments being available and being needed)



WP2 - Computational Fluid Dynamics

Validation of CFD tools for VHTR analysis

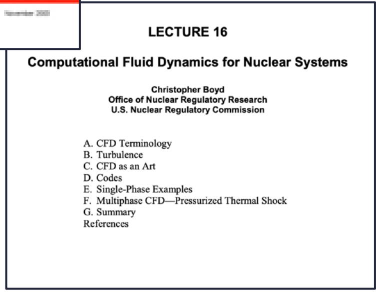
- **Task 2.1:** Review the existing guidance reports from OECD/NEA, US NRC, IAEA, etc. and summarize general and specific guidance of using CFD tools in HTGR applications.
- **Task 2.2:** Thermal mixing effect and pressure drop in the scaled structure of bottom reflectors and hot gas chamber of the HTR-PM blind calculations. INET will provide the description of the test facility, structure geometry, and experimental data in various test conditions
- **Task 2.3:** Validate CFD numerical models and measure the capability of CFD numerical models to calculate the radiation and convective heat transfer in the air-cooled RCCS. Texas A&M Air-cooled RCCS experimental facility produced particle image velocimetry that will be used for validating CFD models.
- **Task 2.4:** Perform CFD validation studies related to the prismatic core bypass flow. Air experiments performed by Seoul National University (SNU) and the MIR experiments performed by INL will be used for validating CFD models.


IAEA-TECDOC-1379

Use of computational fluid dynamics codes for safety analysis of nuclear reactor systems

Summary report of a technical meeting jointly organized by the International Atomic Energy Agency and the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development held in Pisa, Italy, 11-14 November 2002

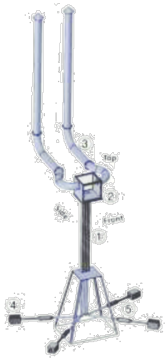
IAEA


LECTURE 16

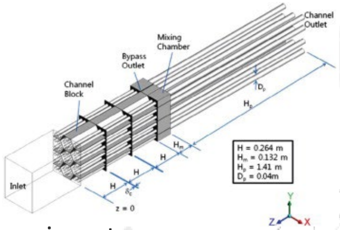
Computational Fluid Dynamics for Nuclear Systems

Christopher Boyd
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission

A. CFD Terminology
B. Turbulence
C. CFD as an Art
D. Codes
E. Single-Phase Examples
F. Multiphase CFD—Pressurized Thermal Shock
G. Summary
References



TAMU air-cooled reactor cavity cooling system for the VHTR



Air experiments performed at Seoul National University (SNU)

GEN IV International Forum
Expertise | Collaboration | Excellence

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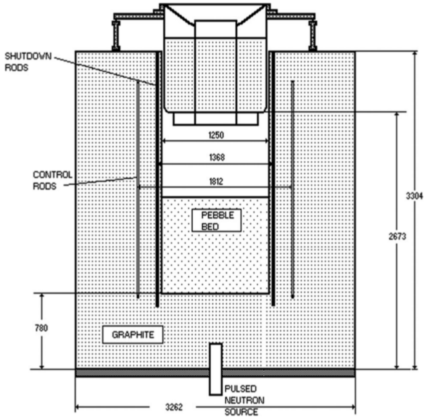
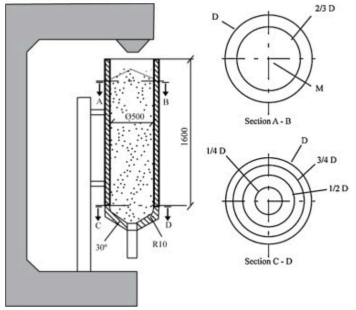
WP3 Reactor Core Physics and Nuclear Data

Validation of Burnup and Reactor physics codes

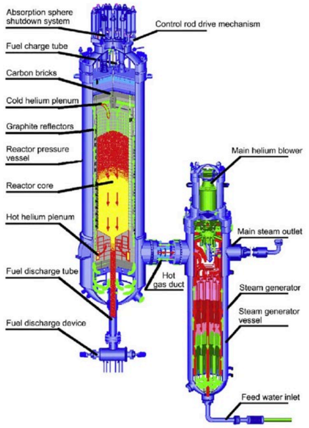
- **Task 3.1:** Validate burnup analysis using isotopic data from AGR and HFR-Petten fuel irradiations - compare models for computing decay heat generation rates and source term for accident analyses.
- **Task 3.2**: Quantify the uncertainty in key safety parameters due to the random distribution of particles and pebbles in a pebble bed reactor - validation against HTR Proteus experiments - then modified to reflect different packing assumptions.
- **Task 3.3:** Pebble flow characterization - ANABEK experimental data and more recent INET pebble flow experiments.
- **Task 3.4:** Effect of neutron damage and annealing on thermal and neutronics properties of graphite and matrix carbon - explore models for the determination of the extent of the damage-recovery effects and their impact on static and dynamic neutronic behavior
- **Task 3.5:** Predict the startup critical configuration of HTR-PM - participants will predict the number of pebbles required for the HTR-PM reactors to achieve criticality under the conditions specified for the startup physics experiments



HTR Proteus experiments



ANABEK experiment



HTR-PM

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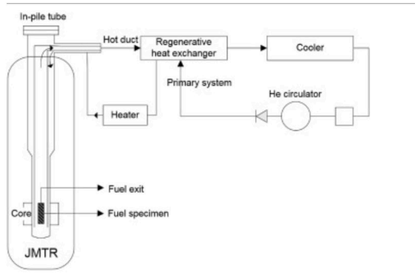
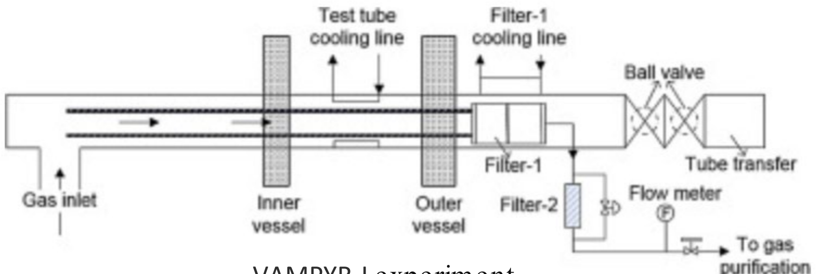
WP4 Chemistry and Transport

Identify the chemistry and transport scenarios of important radionuclides

- **Task 4.1:** Radionuclide and dust transport and plate-out in the Primary Loop - Reactor Operating Experience and measurements (AVR, Fort St. Vrain, etc.), DEACO dust activity measurements, Limited additional data (Peach Bottom, Storm experiments, HTR-10), Plate-out test facilities(VAMPYR-I, OGL-1 experiment)
- **Task 4.2:** Radionuclide and dust transport in the reactor building after a break
- **Task 4.3:** Tritium Transport Models and code verification
- **Task 4.4:** C-14 Transport Models and code verification



OGL-1 experiment

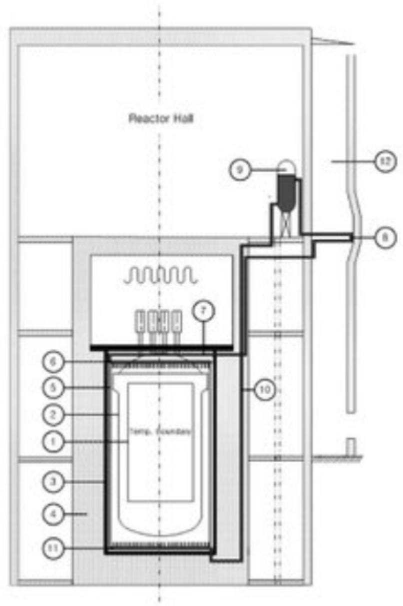


VAMPYR-I experiment

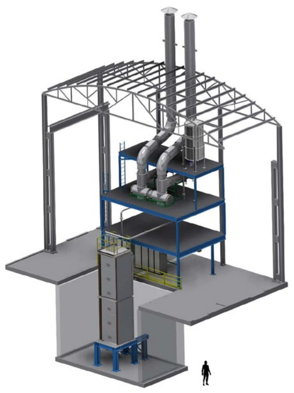
WP5 Reactor and Plant Dynamics

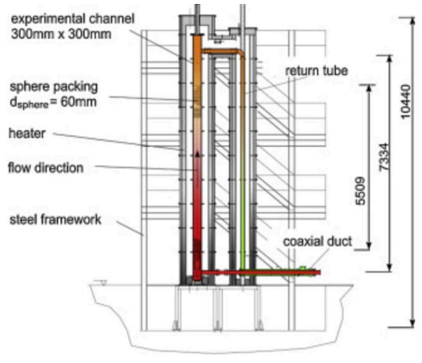
Establish guidelines for the validation of system models

- **Task 5.1**: Oregon State University (OSU) High Temperature Test Facility (HTTF)
- **Task 5.2**: Argonne National Laboratory (ANL) Natural Circulation Shutdown Heat Removal System (NSTF) Experiments in Air-Cooled Reactor Cavity Cooling Systems (RCCS)
- **Task 5.3**: System Studies of the HTR-10 RCCS Experiments
- **Task 5.4**: System Studies of the ANL Water-cooled NSTF Experiment
- **Task 5.5**: KOREA Hybrid RCCS Experiment
- **Task 5.6**: NACOK II Experiments – Air ingress
- **Task 5.7**: Code-to-Code Comparisons of operational transients
- **Task 5.8**: Guidelines for Validation and Application of Systems Analysis Numerical Models



HTR-10 RCCS


NSTF test facility



NACOK test facility

FY23 External Collaborations and Editorial Production

NEUPs

- TAMU - High-fidelity, data science-informed pebble-bed reactor simulator
- OSU - Progression of High-Resolution SET and IET Benchmarks on PCC and DCC events in HTGRs
- UW-Madison - Telescopic Control Rod for Significant Reduction in HTR Height and therefore Cost

ARDPs, iFOA, Other Programs

- iFoa X-energy Neutronics Support Analyses for the Xe-100. Licensing Baseline – **finalized FY22**
- ARDP PTS1 - NQA1 MCNP Xe-100 modeling
- ARDP PTS2 - Fine temperature grid NQA1 NJOY cross section generation
- ARDP PTS3 - Xe-100 MELCOR modeling and BISON training.
- NEAMS HTGRs Multiphysics – verification of multiphysics equilibrium core calculations capabilities
- NRIC – Virtual Test Bed models uploading
- ASME – **VVUQ** for nuclear engineering applications recommendations.

LDRDs

- **New approach** for code **validation** demonstration using HTGRs experimental data FY23-24
- Long term **pebble storage** studies using NEAMS tools FY23-25

PhDs and Articles

- **Two** Ph.D. students currently working in the methods area.
- **More than 10** conference papers (NURETH, PHYSOR, ASME, ANS Annual & Winter meeting)
- **More than 5** journal papers on the way by the end of the FY.

Thanks for your attention…
Questions?