July 13, 2022

HTTR LOFC experiment simulation using US DOE NEAMS tools

DOE-NE Advanced Reactor Technologies Gas-Cooled Reactor Program 2022 Annual Review Meeting

ART Advanced Reactor Technologies
GAS-COOLED REACTORS

Contributors

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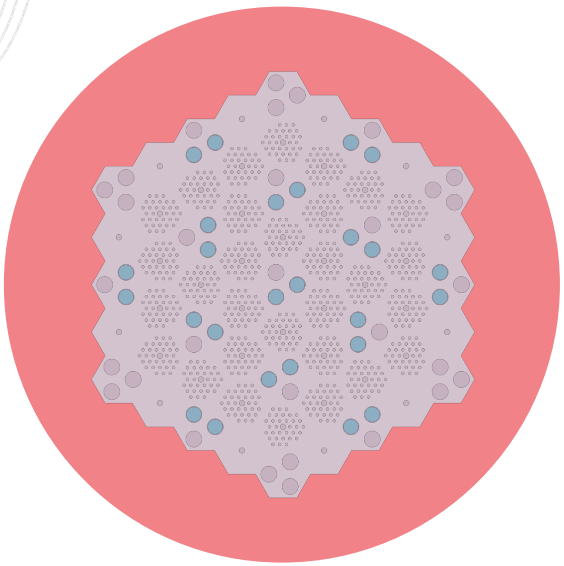
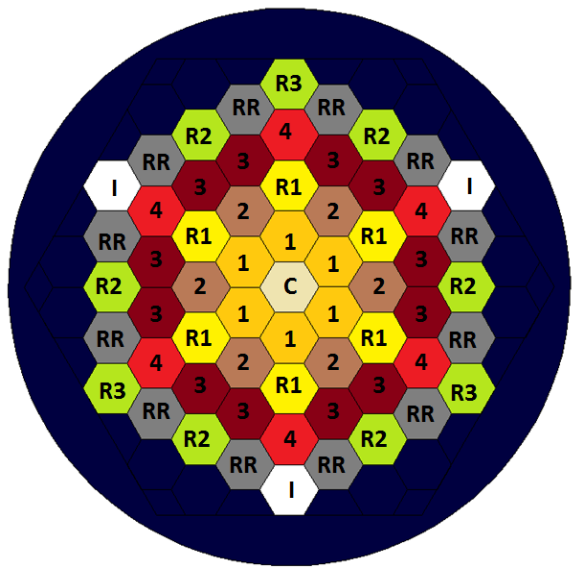
Content

- HTTR Model Overview.
- Cross Section Generation Procedure.
- Steady-State Results.
- 9MW LOFC Transient Results.
- 30 MW LOFC Transient Results.
- Validation of the Serpent Model
- Future Work

HTTR Overview

- Graphite moderated, helium cooled prismatic High Temperature Reactor
- Power: 9 or 30 MW
- Large axial thermal gradient (up to 600K from top to bottom)





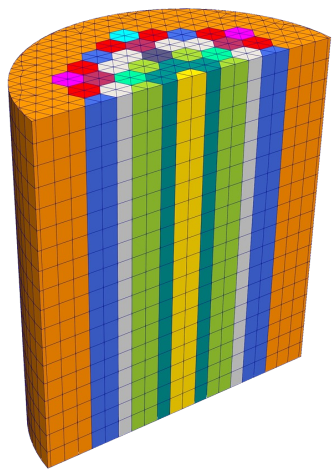
(a) HTTR core layout with fuel (columns 1-4), control rods (C, R1, R2, R3), replaceable reflectors (RR), and instrumentation (I).

Stack 1	Stack 2	Stack 3	Stack 4
RR	RR	RR	RR
RR	RR	RR	RR
6.7/2.0	7.9/2.0	9.4/2.0	9.9/2.0
5.2/2.5	6.3/2.5	7.2/2.5	7.9/2.5
4.3/2.5	5.2/2.5	5.9/2.5	6.3/2.5
3.4/2.0	3.9/2.0	4.3/2.0	4.8/2.0
3.4/2.0	3.9/2.0	4.3/2.0	4.8/2.0
RR	RR	RR	RR
RR	RR	RR	RR

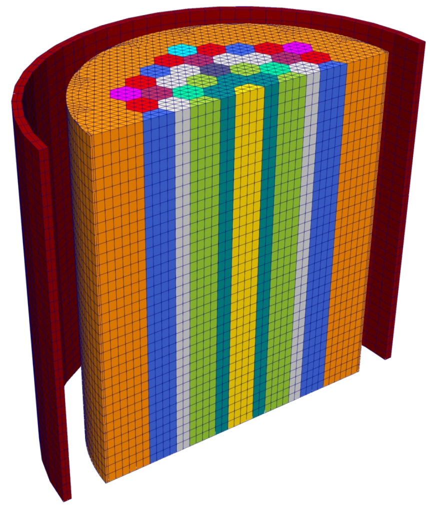
(b) Description of the four different HTTR fuel columns/stacks (UO_2 wt.% fuel enrichment / burnable poison wt.% enrichment).

Current INL HTTR Multiphysics Multiscale Model

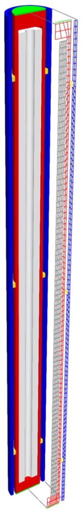
GRIFFIN
3D Full Core Neutronic Model SPH Diffusion 10 Groups



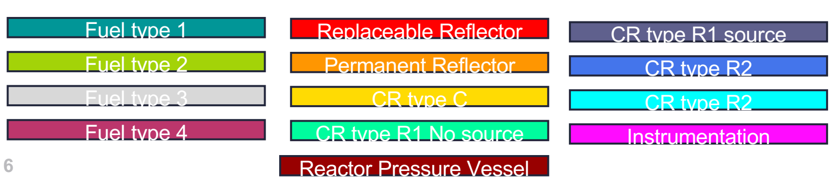
MOOSE modules
3D Full Core Thermal Conduction and Radiation

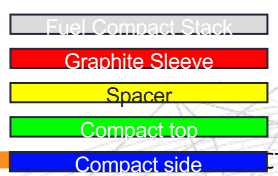


BISON
2D RZ Fuel Column Model
150 Multiapps

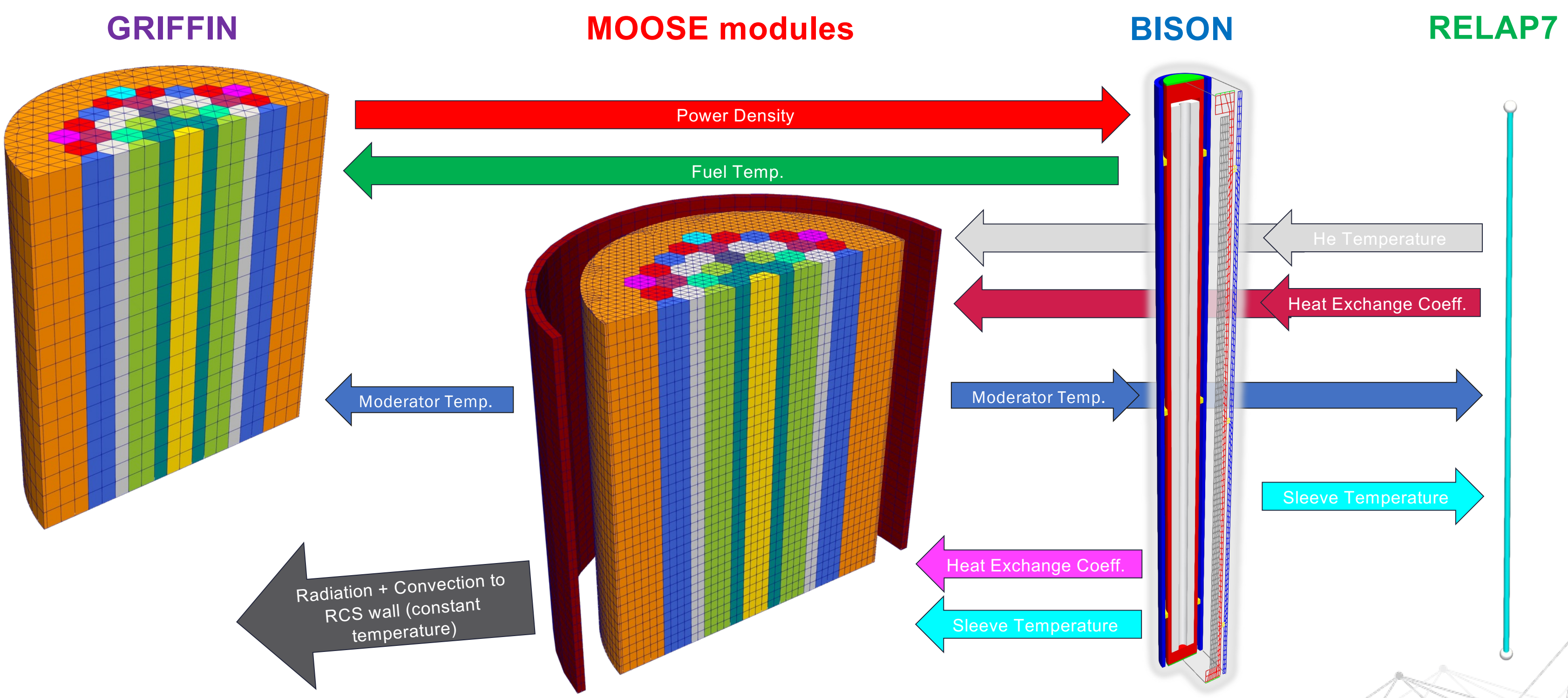


RELAP7
1D Helium Channels
30 Active channels, 16 CR cooling channels

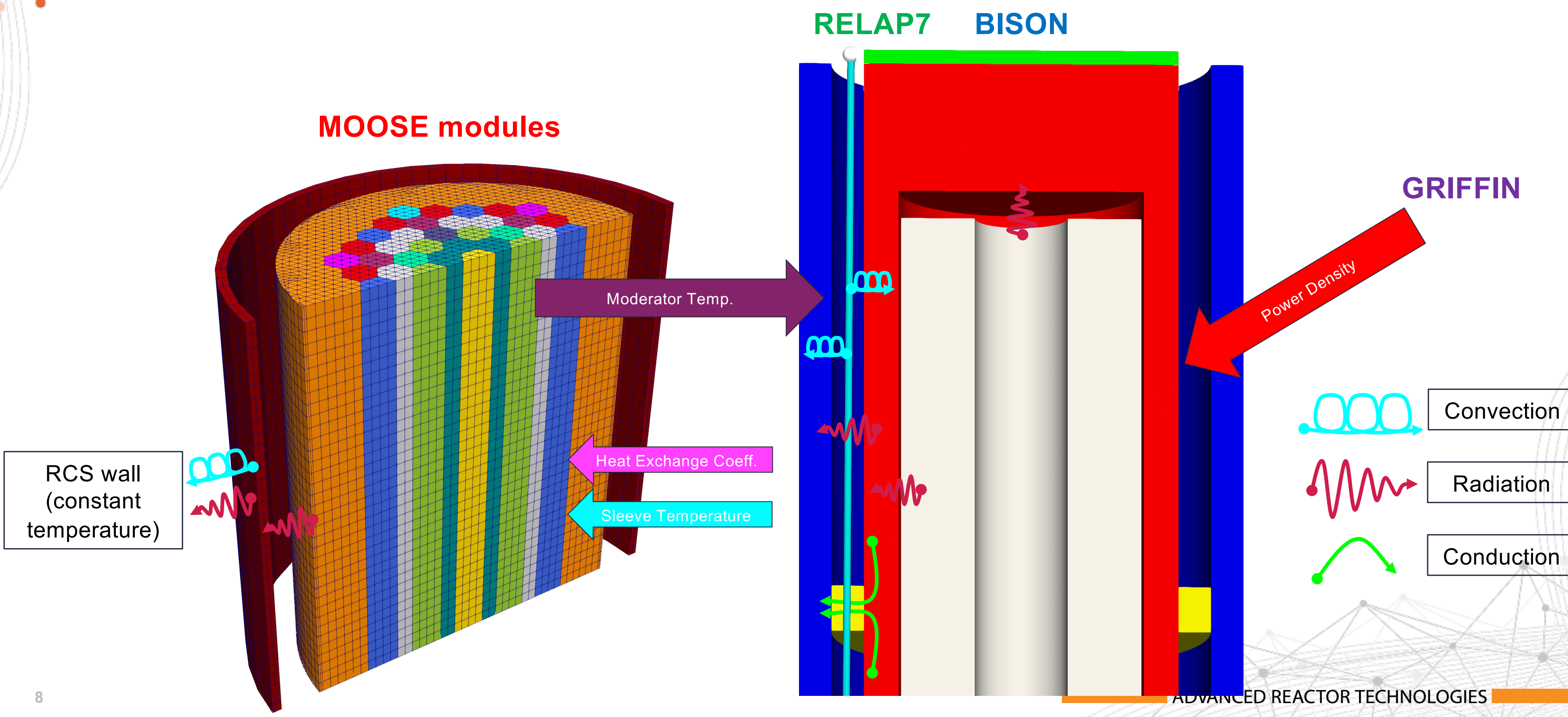




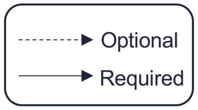
Current INL HTTR Multiphysics Multiscale Model



Current INL HTTR Multiphysics Multiscale Model

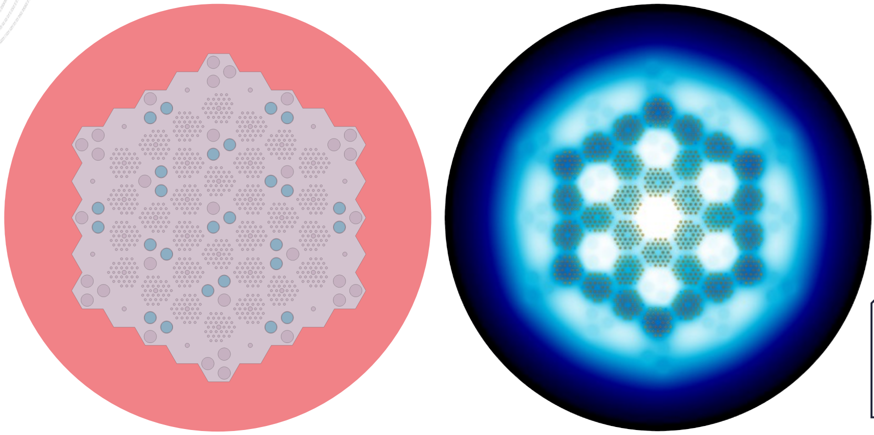


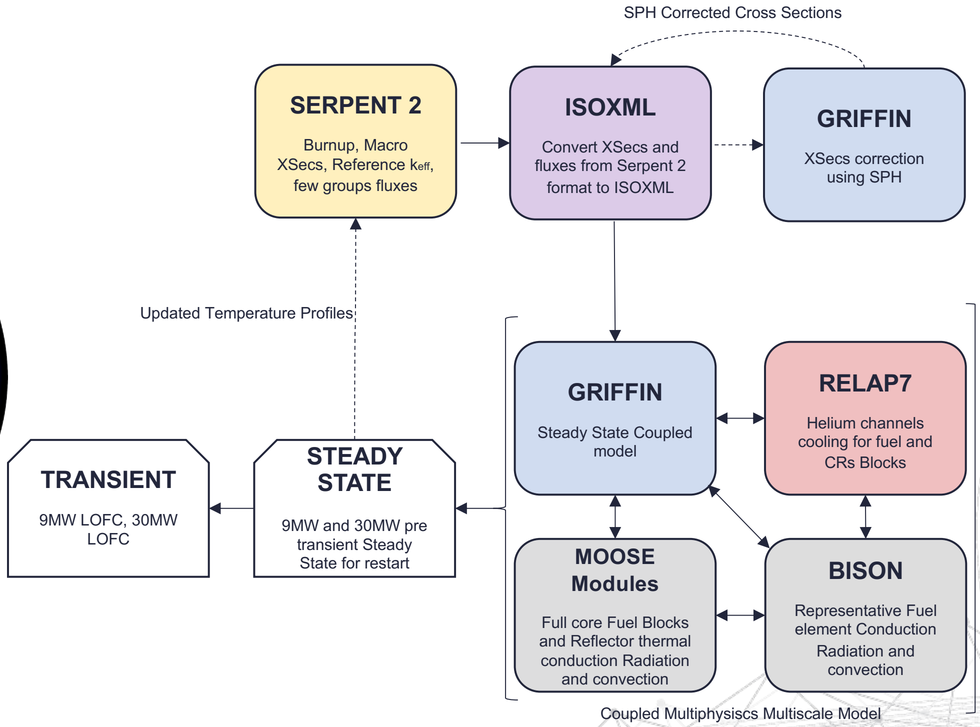
Cross section generation procedure



SERPENT 2

Full core Monte Carlo solution and Burnup calculation

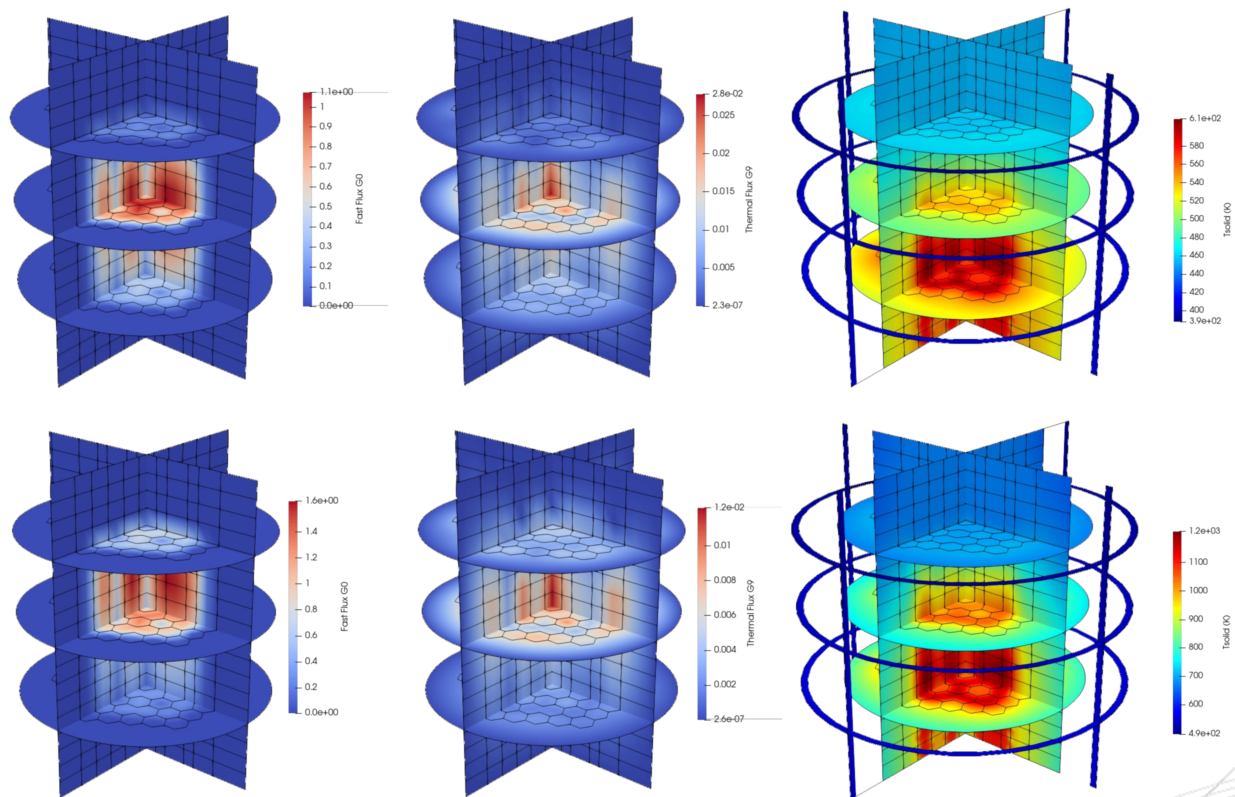




Steady State Analysis Results

9 MW

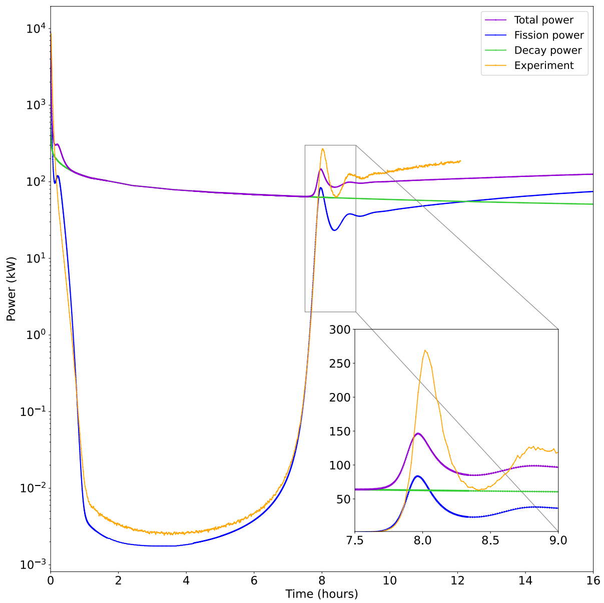
30 MW

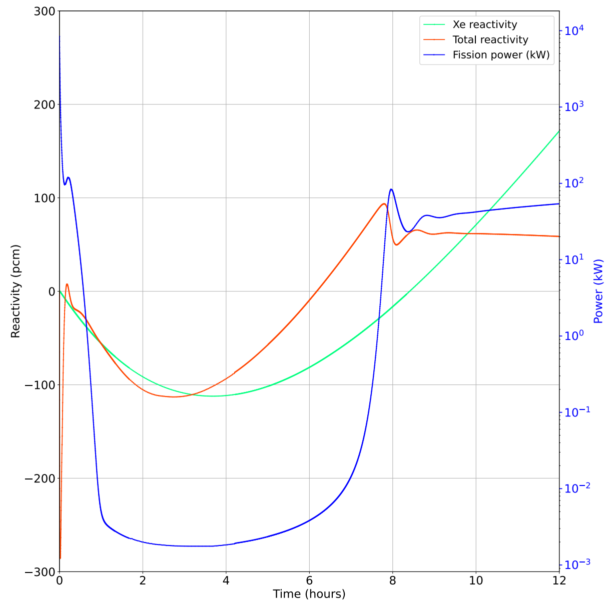


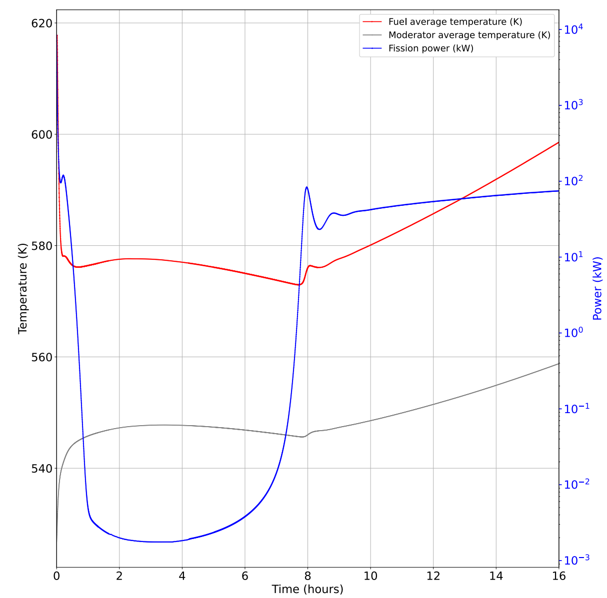
- **Latest improvements**
  - Runtime decreased from ~50 hrs to ~50 min (48 processors)
  - Global energy balance discrepancy reduced from 11% to <2%
  - High keff → ongoing validation of the Serpent model → need to further improve burnup and cross-section generation procedure

Power (MW)	k_{eff}
9	1.02946
30	1.02276

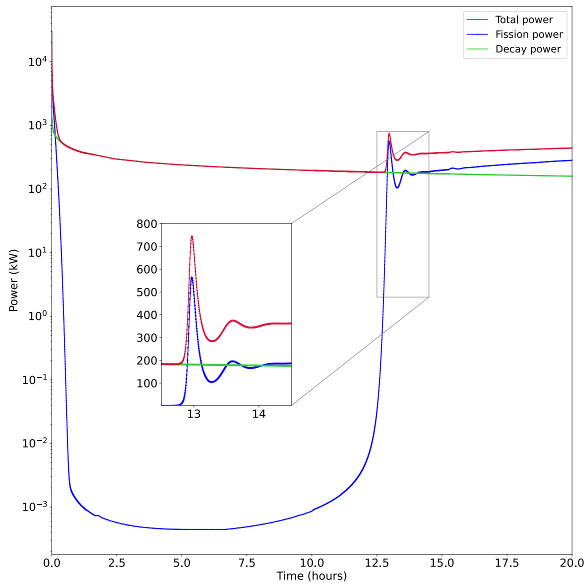
9MW LOFC Simulation

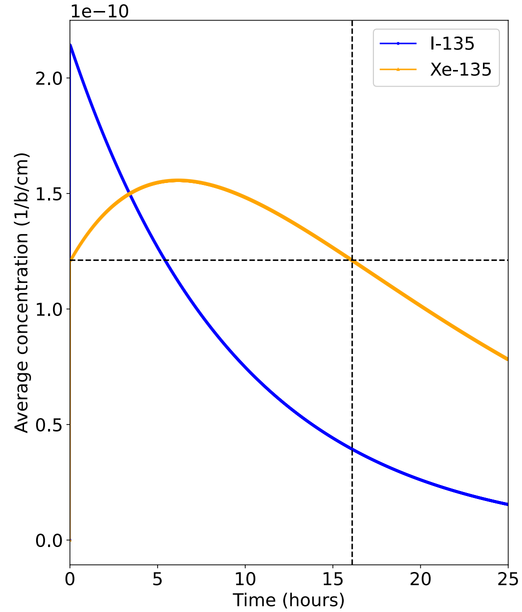


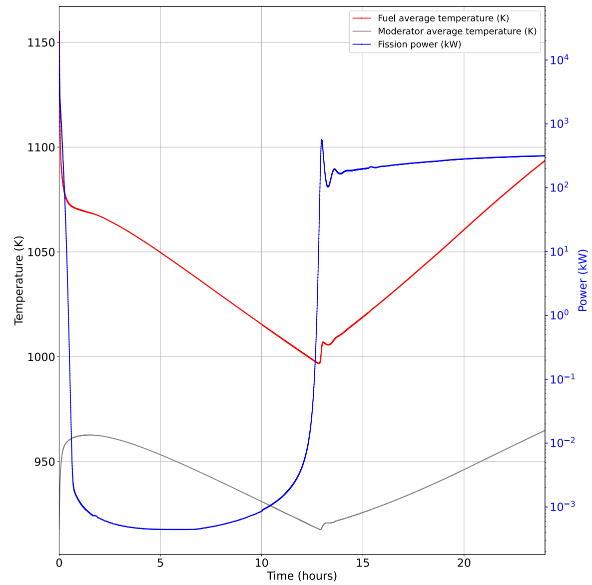




(FY21) 30MW LOFC Simulation

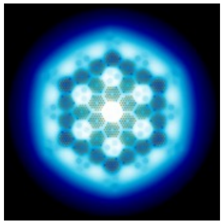




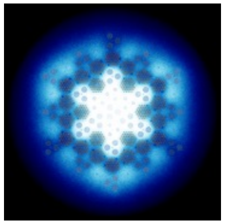


Benchmark calculation: excess reactivity

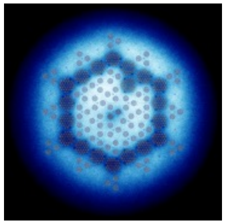
- Cold, zero-power operation.
- Matches JAERI results well and experimental data within 2-σ uncertainty.
- Large uncertainty, mostly due to graphite impurities.



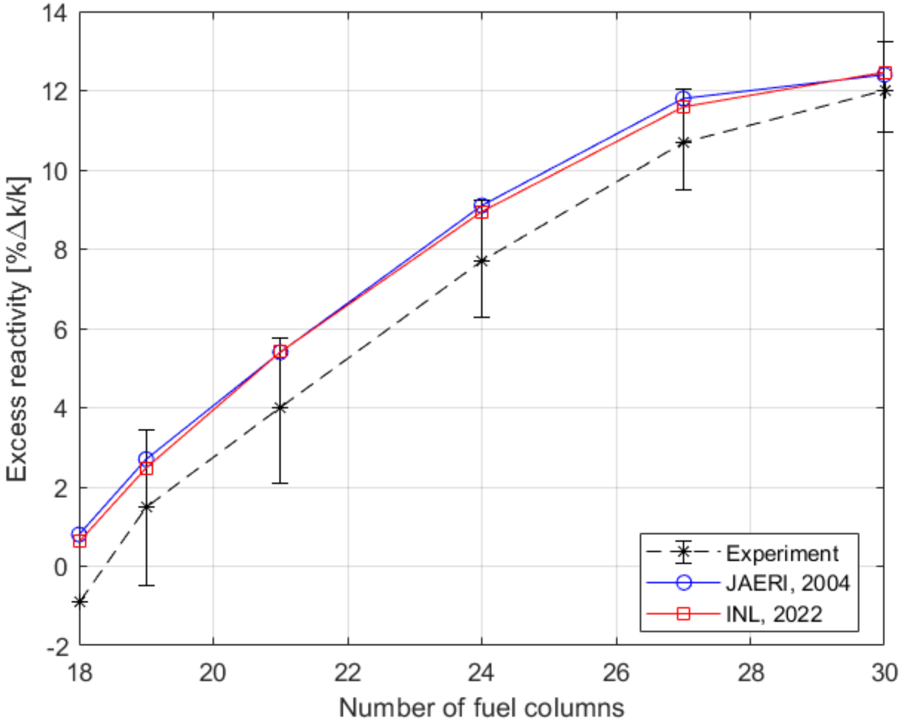
30 fuel columns



24 fuel columns



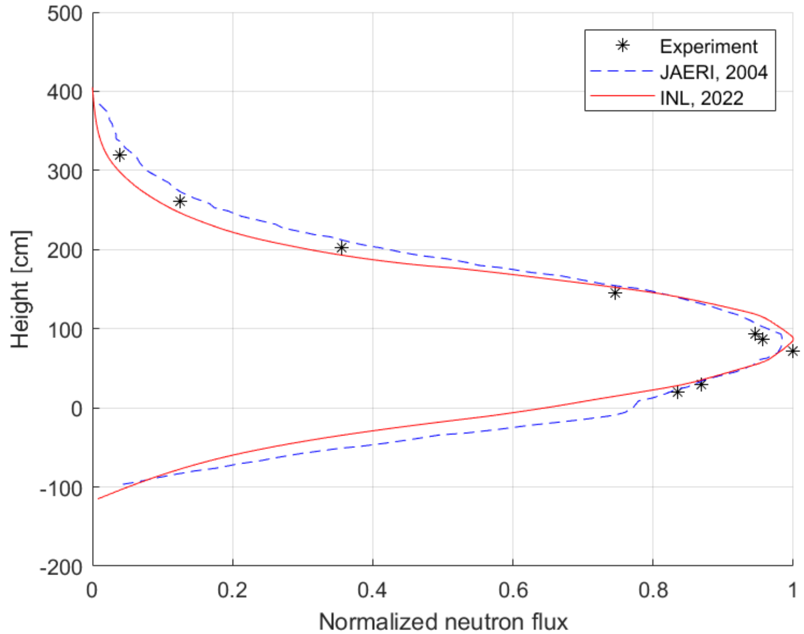
19 fuel columns



Naoki Nojiri et al., Characteristic test of initial HTTR core, Nuclear Engineering and Design 233 (2004) 283–290, doi:10.1016/j.nucengdes.2004.08.015

Benchmark calculation: axial neutron flux

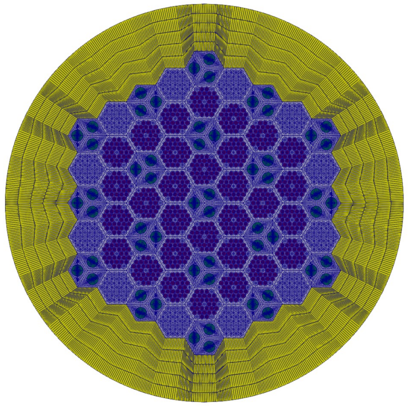
- Cold, zero-power operation
- Axial profile matches the experiment and JAERI data relatively well



Naoki Nojiri et al., Characteristic test of initial HTTR core, Nuclear Engineering and Design 233 (2004) 283–290, doi:10.1016/j.nucengdes.2004.08.015

Future Work

- Study in details the early recriticality for the 9MW LOFC. Probably due to an over estimation of the fuel feedback coefficient.
- Get a better understanding of the Helium flow during the transients to understand if and how natural circulation occurs.
- Model the gaps between blocks
- Use a semi-heterogeneous thermal mesh at the full-core level
- Further validate the Serpent model
- Perform sensitivity analysis to assess the effect of the parameters uncertainties on the results.



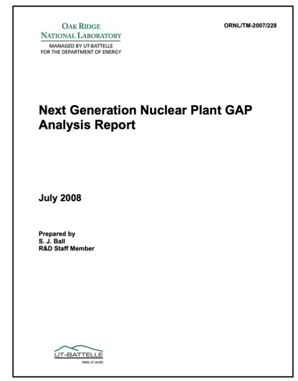
Created with MOOSE generators implemented by Yinbin Miao (ANL)

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

High Level Schedule of WP 1 Tasks

Task	Year 1		Year 2		Year 3		Year 4		Year 5		Year 6		Year 7	
1.1														
1.2														
1.3														

- Task 1.1 LEAD&LREV 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 SPECS&LREV Construction of a Validation Matrix (Experiments being available and being needed) NEUP report of last 10y coming soon.


OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

ORNL/TM-2007/228

Next Generation Nuclear Plant GAP Analysis Report

July 2008

Prepared by
S. J. Ball
R&D Staff Member

UT-BATTELLE
ORNL-27 (4-00)

NEUP Survey and data collection for the last 10y of activities.

SPECS=generate specifications, LREV=literature review, LEAD=Leading Task or WP, DATA=providing data, CALCS=perform calculations

WP2 Computational Fluid Dynamics

High Level Schedule of WP 2 Tasks

Task	Year 1		Year 2		Year 3		Year 4		Year 5		Year 6		Year 7	
2.1														
2.2														
2.3														
2.4														

- Task 2.1 LEAD&LREV&SPECS To 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 CALCS Thermal mixing effect and pressure drop in the scaled structure of bottom reflectors and hot gas chamber of the HTR-PM blind calculations
- Task 2.3 LEAD&DATA&CALCS To 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 and other available data
- Task 2.4 CALCS To perform CFD validation studies related to the prismatic core bypass flow

Follow similar strategy used to study HTTF lower plenum using NEK5000.

Collecting data and models from the facility operators.

Follow similar strategy used to study bypass flow for PBFHR using NEK5000.

WP3 LEAD Reactor Core Physics and Nuclear Data

Task	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
3.1								
3.2								
3.3								
3.4								
3.5								

- Task 3.1 LEAD&SPECS&LREV&CALCS Validate burnup analysis using isotopic data from AGR and HFR-Petten fuel irradiations.
- Task 3.2 LREV&SPECS&CALCS Quantify the uncertainty in key safety parameters due to the random distribution of particles and pebbles in a pebble bed reactor
- Task 3.3 LEAD&LREV&SPECS&CALCS Pebble flow characterization
- Task 3.4 LEAD&LREV&SPECS&CALCS Effect of neutron damage and annealing on thermal and neutronics properties of graphite and matrix carbon
- Task 3.5 LEAD&CALCS Criticality predictions

Collect and organize available post irradiation concentration data.

WP4 Chemistry and Transport

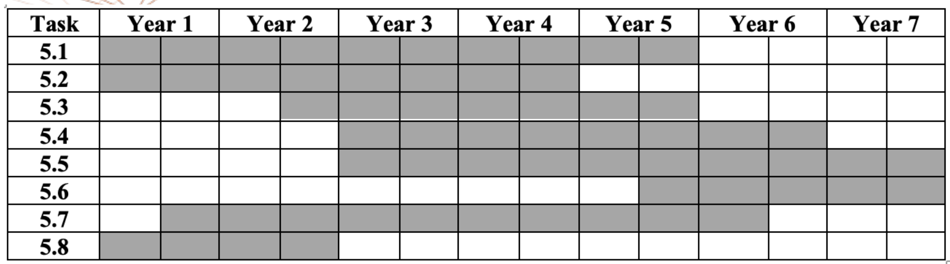
Task	Year 1		Year 2		Year 3		Year 4		Year 5		Year 6		Year 7	
4.1														
4.2														
4.3														
4.4														

- Task 4.1 LREV&CALCS Radionuclide and dust transport and plate-out in the Primary Loop
- Task 4.2 LEAD&LREV&CALCS Radionuclide and dust transport in the reactor building after a break
- Task 4.3 LREV&CALCS Tritium Transport Models and code
- Task 4.4 LREV&CALCS C-14 Transport Models and Code

Check efforts on MELCOR adaptations to HTGRs. And current capabilities available in RELAP5-3D

Check adaptability of methods developed in SAM for PB-FHR.

WP5 Reactor and Plant Dynamics



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

Collect and organize data and available models

GIFIV Forum Budget.

WP#	Contributors	Year 1 M(py)	Year 1 F(k$)	Year 2 M(py)	Year 2 F(k$)	Year 3 M(py)	Year 3 F(k$)	Year 4 M(py)	Year 4 F(k$)	Year 5 M(py)	Year 5 F(k$)	Year 6 M(py)	Year 6 F(k$)	Year 7 M(py)	Year 7 F(k$)	Total M(py)	Total F(k$)
WP1	DOE	0.2	30.0	0.6	90.0	0.1	15.0	0.1	15.0	0.0	0.0	0.0	0.0	0.0	0.0	**1.0**	**150**
	INET	0.2	30.0	1.0	150.0	0.2	30.0	0.5	75.0	0.0	0.0	0.0	0.0	0.0	0.0	**1.9**	**285**
	KAERI	0.0	0.0	0.0	0.0	0.2	30.0	0.1	15.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.3**	**45**
	JRC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0**	**0**
	JAEA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0**	**0**
	Subtotal	0.4	60	1.6	240	0.5	75	0.7	105	0	0	0	0	0	0	**3.2**	**480**
WP2	DOE	0.4	60.0	0.6	90.0	1.3	195.0	2.2	330.0	0.0	0.0	0.0	0.0	0.0	0.0	**4.5**	**675**
	INET	1.6	240.0	2.9	435.0	2.8	420.0	1.3	195.0	0.0	0.0	0.0	0.0	0.0	0.0	**8.6**	**1,290**
	KAERI	0.3	45.0	0.9	135.0	1.4	210.0	1.1	165.0	0.0	0.0	0.0	0.0	0.0	0.0	**3.7**	**555**
	JRC	0.2	30.0	0.3	45.0	0.5	75.0	0.2	30.0	0.0	0.0	0.0	0.0	0.0	0.0	**1.2**	**180**
	JAEA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0**	**0**
	Subtotal	2.5	375	4.7	705	6.0	900	4.8	720	0	0	0	0	0	0	**18.0**	**2,700**
WP3	DOE	0.1	15.0	0.5	75.0	0.7	105.0	0.4	60.0	0.5	75.0	0.3	45.0	0.0	0.0	**2.5**	**375**
	INET	0.2	30.0	0.5	75.0	1.2	180.0	1.1	165.0	0.7	105.0	0.6	90.0	0.0	0.0	**4.3**	**645**
	KAERI	0.2	30.0	0.5	75.0	0.5	75.0	0.2	30.0	0.2	30.0	0.2	30.0	0.0	0.0	**1.8**	**270**
	JRC	0.2	30.0	0.4	60.0	0.4	60.0	0.2	30.0	0.0	0.0	0.0	0.0	0.0	0.0	**1.2**	**180**
	JAEA	0.2	30.0	0.3	45.0	0.3	45.0	0.1	15.0	0.1	15.0	0.1	15.0	0.0	0.0	**1.1**	**165**
	Subtotal	0.9	135	2.2	330	3.1	465	2.0	300	1.5	225	1	180	0	0	**10.9**	**1,635**
WP4	DOE	0.2	30.0	0.5	75.0	2.5	375.0	2.5	375.0	1.7	255.0	0.5	75.0	0.5	75.0	**8.4**	**1,260**
	INET	0.5	75.0	0.6	90.0	2.0	300.0	2.5	375.0	2.2	330.0	1.7	255.0	1.4	210.0	**10.9**	**1,635**
	KAERI	0.5	75.0	0.7	105.0	1.1	165.0	1.3	195.0	1.3	195.0	1.2	180.0	1.2	180.0	**7.3**	**1,095**
	JRC	0.7	105.0	0.9	135.0	0.9	135.0	0.4	60.0	0.4	60.0	0.4	60.0	0.8	120.0	**4.5**	**675**
	JAEA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0**	**0**
	Subtotal	1.9	285	2.7	405	6.5	975	6.7	1,005	5.6	840	4	570	4	585	**31.1**	**4,665**
WP5	DOE	2.3	345	1.0	150	4.2	630	3.2	480	3.2	480	2	330	1	150	**17.1**	**2,565**
	INET	0.5	75	1.6	240	2.2	330	3.0	450	3.0	450	2	330	1	150	**13.5**	**2,025**
	KAERI	0.4	60	1.0	150	2.4	360	3.2	480	2.7	405	2	240	0	45	**11.6**	**1,740**
	JRC	0.3	45	0.6	90	0.7	105	1.0	150	1.5	225	1	180	1	75	**5.8**	**870**
	JAEA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	**0**
	Subtotal	3.5	525	4.2	630	9.5	1,425	10.4	1,560	10.4	1,560	7	1,080	3	420	**48.0**	[illegible]
Total	DOE	3.2	480	3.2	480	8.8	1,320	8.4	1,260	5.4	810	3	450	2	225	**33.**	**5,025**
	INET	3.0	450	6.6	990	8.4	1,260	8.4	1,260	5.9	885	5	675	2	360	**39.2**	[illegible]
	KAERI	1.4	210	3.1	465	5.6	840	5.9	885	4.2	630	3	450	2	225	**24.7**	**3,705**
	JRC	1.4	210	2.2	330	2.5	375	1.8	270	1.9	285	2	240	1	195	**12.7**	**1,905**
	JAEA	0.2	30	0.3	45	0.3	45	0.1	15	0.1	15	0	15	0	0	**1.1**	[illegible]
	Total	9.2	1,380	15.4	2,310	25.6	3,840	24.6	3,690	17.5	2,625	12	1,830	7	1,005	**111.**	**16,680**

- 2.5 FTEs per year, to manage the 5 work packages.
- The other Members accepted (and signed) the terms of the agreement
- Different professional figures are needed (from CFD to reactor physics and chemistry) - **INL/ANL joining** in a collaborative effort.
- Obtaining Data from the other members to validate DoE tools and saving **100s M$** (and time) of experiments (e.g. HTR-PM operation)

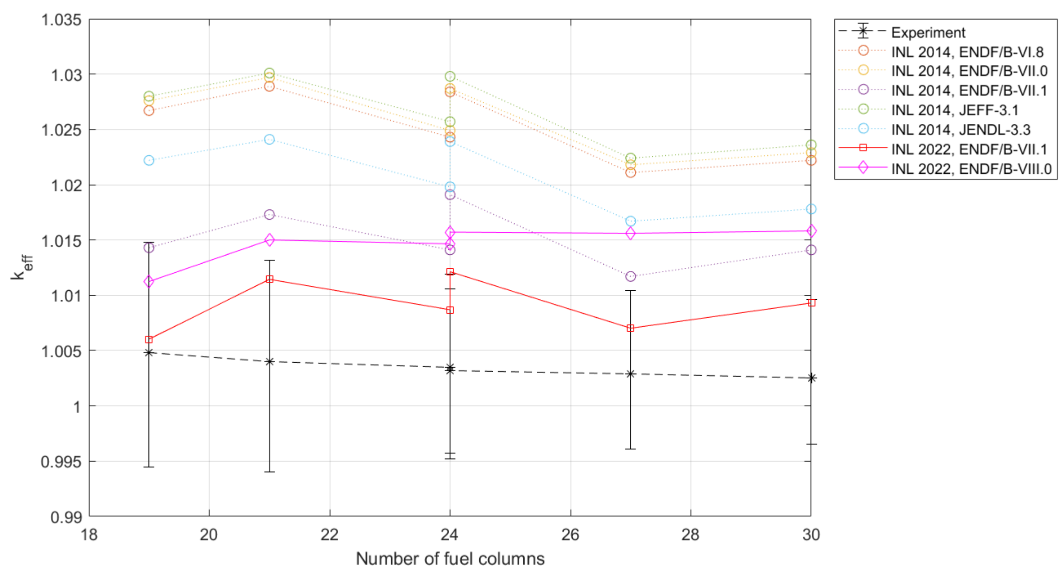
Questions?

Backup Slides

HTTR benchmark calculations with Serpent 2

Annular core with control rods inserted

- Cold start-up operation
- Too high reactivity in all calculated cases
- The newest library, ENDF/B-VIII.0, gives higher reactivity than ENDF/B-VII.1.

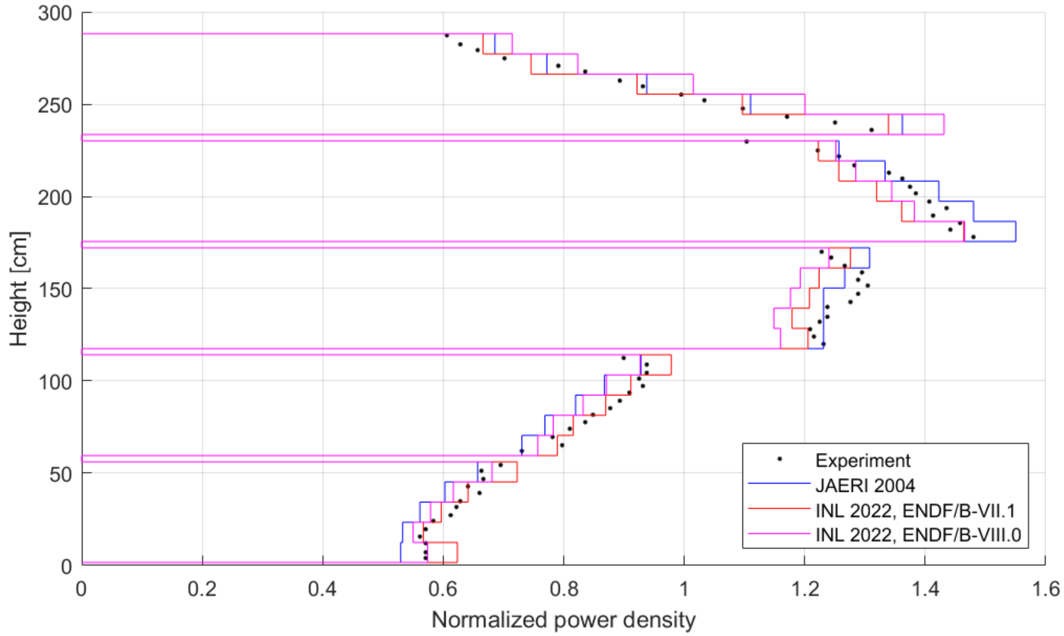


John D. Bess & Nozomu Fujimoto, Benchmark Evaluation of Start-Up and Zero-Power Measurements at the High-Temperature Engineering Test Reactor, Nuclear Science and Engineering (2014) 178:3, 414-427, DOI: 10.13182/NSE14-14

HTTR benchmark calculations with Serpent 2

Axial power distribution

- Averaged over 9 - 30 MW

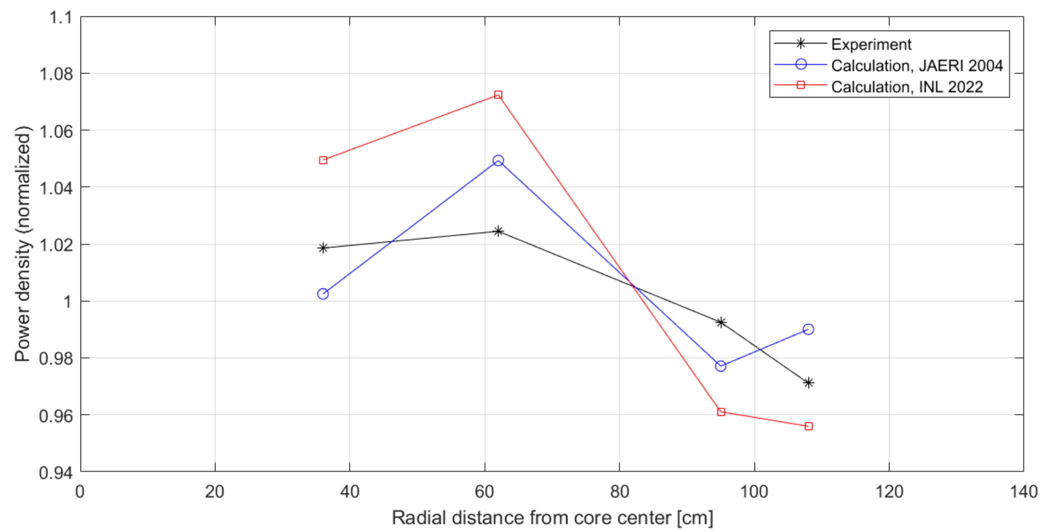


Naoki Nojiri et al., Characteristic test of initial HTTR core, Nuclear Engineering and Design 233 (2004) 283–290, doi:10.1016/j.nucengdes.2004.08.015

HTTR benchmark calculations with Serpent 2

Radial power distribution

- Power: 30 MW
- Average burnup: 4400 MWd/t



Naoki Nojiri et al., Characteristic test of initial HTTR core, Nuclear Engineering and Design 233 (2004) 283–290, doi:10.1016/j.nucengdes.2004.08.015