INL/CON-23-73441-Revision-0

Release of a High Temperature Engineering Test Reactor (HTTR) Steady State Multiphysics Model to the Virtual Test Bed

November 2023

Changing the World's Energy Future

Kylee Rachel Swanson, Guillaume Louis Giudicelli

Idaho National Laboratory

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http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Release of a High Temperature Engineering Test Reactor (HTTR) Steady State Multiphysics Model to the Virtual Test Bed

Kylee Swanson°† and Guillaume Giudicelli°

°*Computational Frameworks, Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415*
†*Howard R. Hughes College of Engineering, University of Nevada, Las Vegas, 4505 S Maryland Pkwy, Las Vegas, NV 89154*

INTRODUCTION

In response to climate change, global governments and private industry have established a common goal of achieving net-zero emissions by 2050 [1]. This goal requires a reassessment of current energy demands and production methods. Reducing emissions at an affordable cost while maintaining grid reliability requires a nationwide collaborative effort among government and industry in the United States. Nuclear power is the leading low-carbon electricity generation method. In the past 50 years, the use of nuclear power has reduced carbon dioxide emissions by over 60 gigatons and has played a crucial role in the security of energy supply [2]. In the U.S., nuclear power accounts for 20% of the electrical supply and provides energy reliably. Advanced reactors will operate at higher temperatures, operate more efficiently, utilize more energy stored within fuel, and reduce the amount of waste produced [3].

To face these challenges and goals, the U.S. Department of Energy has created an initiative to focus on the modeling and simulation tools to support future nuclear power plant design, licensing, and operations. The Virtual Test Bed (VTB) [4] was launched by the National Reactor Innovation Center (NRIC) in collaboration with the Nuclear Energy Advanced Modeling and Simulation (NEAMS) program to support the advanced nuclear reactor community. The VTB involves teams from both Idaho National Laboratory and Argonne National Laboratory and aims to provide example models for a broad range of both current and future advanced reactor designs. A feature of the VTB is the automatic testing of these models to ensure continued functionality as simulation tools are further developed. The VTB and the advanced reactor models documented there are important resources for this initiative. This work describes the inclusion of a new model on the VTB—a High Temperature Engineering Test Reactor (HTTR) steady state model [5].

REACTOR DESCRIPTION

The HTTR is a graphite-moderated and helium-cooled prismatic reactor developed and operated by the Japan Atomic Energy Agency (JAEA). It was designed to test the safety of high-temperature gas-cooled reactors (HTGRs). The HTTR is the first and only HTGR in Japan; it first reached criticality in 1998 and was used to conduct safety analyses and performance tests until 2011 when it was shut down following the Fukushima accident.

After a safety review by the Nuclear Regulation Authority in 2021, the HTTR was restarted as a cooperative effort between the United States and Japan under the Civil Nuclear Energy Research and Development Working Group (CNWG) in collaboration with the Advanced Reactor Technologies (ART) program at Idaho National Laboratory (INL) and JAEA [6, 5].

MODEL DESCRIPTION

The INL-developed steady state HTTR model [7, 5] has been uploaded to the VTB, a library of reference reactor models using NEAMS tools [4]. The general radial layout of the HTTR core, shown in Figure 1, follows a hexagonal lattice containing 30 fuel columns, 16 control rods, 12 replaceable reflectors, and three instrumentation columns surrounded by a permanent reflector [8].

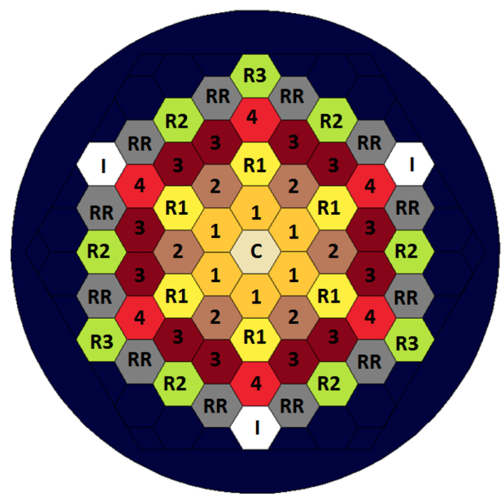

Fig. 1. HTTR core layout with fuel (columns 1–4), control rods (C, R1, R2, R3), replaceable reflectors (RR), and instrumentation (I), from [8].

Each fuel column is composed of nine blocks: five fuel pins fitted between two top and two bottom axial reflectors, represented in Figure 2. Each block, both fuel pin and axial reflectors, measures 58 cm in height. The burnable poison and fuel enrichment inside the fuel pins vary both radially and axially. Cold helium flows upward between the permanent reflectors and the reactor pressure vessel (RPV), and flows downward through the cooling channels inside the core. The general HTTR design and fuel specifications are summarized in Table I I.

Neutronics

The neutronics calculation utilizes the NEAMS code Griffin [9]. The calculations rely on a two-step approach in which cross sections are generated for a multitude of core conditions that form a grid covering the conditions present in the steady state configuration. A 10-energy-group macroscopic cross-

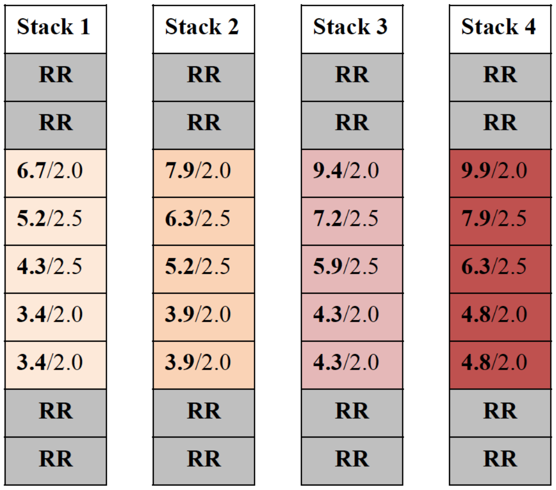

Fig. 2. Description of the four different HTTR fuel columns (UO_2 wt% fuel enrichment/burnable poison wt% enrichment), from [8].

TABLE I. HTTR specifications and operating parameters, from [8].

Design Specifications	Value	Unit
Thermal Power	9	MW
Outlet Coolant Temperature	320	°C
Inlet Coolant Temperature	180	°C
Primary Coolant Pressure	2.77	MPa
Core Structure	Graphite	
Equivalent Core Diameter	2.3	m
Effective Core Height	2.9	m
Average Power Density	2.5	W/cm^3
Fuel/Enrichment	UO_2/ 3-10wt.%	
Fuel Type	Pin in Block	
Burnup Period	660	EFPD
Coolant Material/Flow	Helium Gas/Downward	
Reflector Thickness: Top/Side/Bottom	1.16/0.99/1.16	m
Number of Fuel Assemblies	150	
Number of Fuel Columns	30	
Number of Control Rod Pairs: In Core/In Reflector	7	

section library is created based on the average moderator and fuel temperatures, assuming representative axial temperature profiles. A continuous finite element super homogenization (SPH)-correct diffusion transport solver is used [6].

Heat Transfer

Heat transfer simulations utilize the NEAMS code BISON [10] as well as the heat conduction module in MOOSE. The model includes a macroscale 3-D full core homogenized heat transfer and 2-D axisymmetric pin-scale fuel rod heat transfer. The macroscale 3-D full core homogenized heat transfer model simulates the thermal behavior of the homogenized blocks.

The local heat flux in the homogenized calculation is not directly relied upon to couple to the distributed thermal-hydraulics channel simulations and 2-D axisymmetric pin-scale fuel rod heat transfer. Instead, two volumetric heat transfer terms are applied at the homogenized full-core level:

$$q''' = \tilde{h}_{\text{gap}}(T - T_{\text{inner}}), \tag{1}$$

where $\tilde{h}_{\text{gap}}$ is the homogenized gap conductance (in W/K-m^3) and T_{inner} is the block-averaged temperature of the outer surface of the graphite sleeve (i.e., inner surface of the fuel cooling channels). Heat removal by convection is modeled by adding the following source to the homogenized fuel and CR columns [6]:

$$q''' = \tilde{h}_{\text{outer}}(T - T_{\text{fluid}}), \tag{2}$$

where $\tilde{h}_{\text{outer}}$ is the homogenized heat transfer coefficient of the outer wall and T_{fluid} is the block-averaged fluid temperature. [6].

Equation 1 relies on the thermal-hydraulics calculation to simulate heat removal by convection in the cooling channels. Equation 2 uses data from the pin-scale model to simulate heat transfer throughout the gaps between the graphite sleeve and moderator blocks by conduction and radiation [6, 7].

Thermal-Hydraulics

The thermal-hydraulics calculations in the coolant channels use the NEAMS code RELAP-7 [11].

One cooling flow channel is simulated for each of the 30 fuel columns. Another set of flow channel simulations is performed for each of the 16 control rod channels. The cooling flow simulation is represented in Figure 3 [6]; the cold helium flows downward from the top of the reactor core through the control rod channels and around the fuel rods to cool the fuel pins.

To simplify the coolant flow path of the HTTR, the flow in inter-column gaps is neglected and the bypass flow is set to a fixed value. Total flow is equally distributed among all cooling channels.

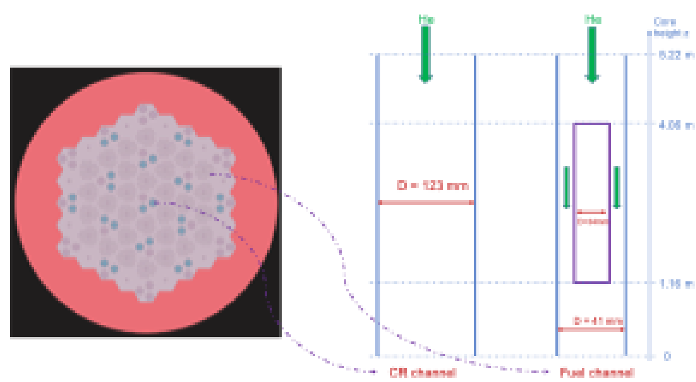

Fig. 3. Left: Radial cross-section of the Serpent model. Right: Description of the RELAP-7 models for fuel and CR channels, at the example locations shown in the core view, from [6].

Coupled multiphysics model

The HTTR model released is a multiphysics model that combines 3-D full core super homogenization-corrected neutronics, macroscale 3-D full core homogenized heat transfer, 2-D axisymmetric pin-scale fuel rod heat transfer, and distributed 1-D thermal-hydraulics channels [7].

The model utilizes the MOOSE framework's MultiApps system to couple the individual physics models, shown in

Figure 4. The neutronics data (local power) is sent to the pin-level heat transfer model, which then sends fuel temperature data back to the neutronics model. The thermal-hydraulics model sends fluid temperature and heat transfer coefficient data to the pin-level heat transfer and macroscale heat transfer models. The pin-level heat transfer model sends gap conductance information to the macroscale heat transfer model and sleeve temperature data to both the macroscale heat transfer model and the thermal-hydraulics model. The macroscale heat transfer model sends moderator temperature data to all of the models.

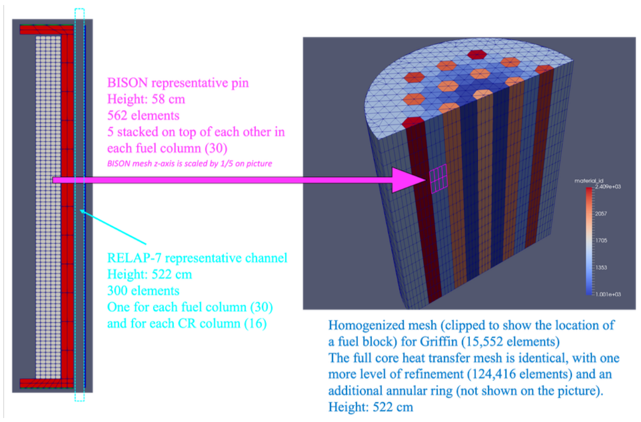

Fig. 4. Relationship between various sub-models, from [7].

RESULTS

The model, even with its modeling approximations, accurately simulates the behavior of the measured fission power and the average moderator and fuel temperatures in agreement with the original JAEA model [6]. The multiplication factor of this model was calculated to be 1.0123, which is satisfactory as the uncertainties in the graphite composition are very high [12].

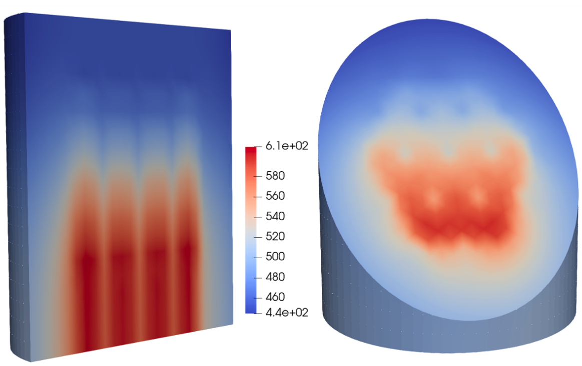

Fig. 5. Moderator temperature distribution of HTTR Steady State Model (K).

Figure 5 shows higher temperatures at the bottom of the core due to the cold helium flowing from the top of the reactor core through the cooling channels down to the bottom of the reactor core. The cold helium cools the graphite at the top, but the helium is no longer cool as it flows toward the bottom, leaving the graphite below much hotter.

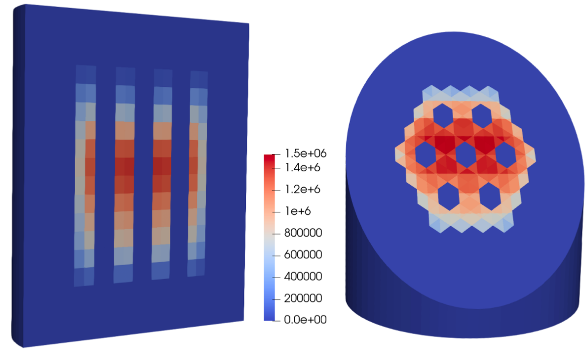

Fig. 6. Power Density distribution of HTTR Steady State Model (W/m^3).

Figure 6 shows peaks in power at the center of the core and dips in power at the front and back portions of the hexagonal core layout, specifically where several of the control rods are located. This alludes that the control rods are responsible for some neutron absorption, causing a lower fission power and more reactive fuel where the temperatures are lower, and less reactive fuel where temperatures are significantly raised.

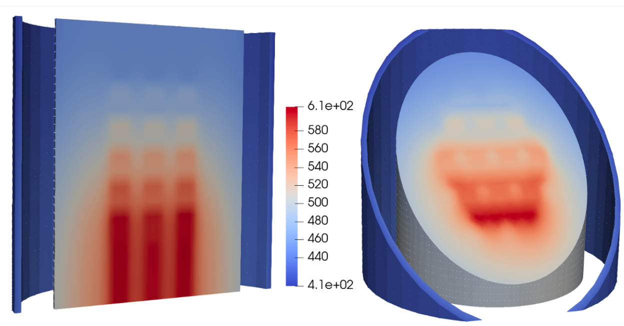

Fig. 7. Fuel blocks temperature distribution of HTTR Steady State Model (K).

Figure 7 shows a higher temperature at the bottom of the core than at the top. Again, this is due to the cold helium flow from the top of the core, through the cooling channels, to the bottom of the core. The five distinct squares seen in the left-hand section of the figure are the five fuel pins, varying from cooled to extremely hot as the helium flows through the fuel columns. The portion of the fuel columns that are traversed by the helium flow are effectively cooled. The fuel temperature field extends outside of the fueled portion of the core allowing evaluation of reflector cross sections that depend indirectly on the fuel temperature in the tabulation.

CONCLUSION

INL's HTTR steady state multiphysics model has been released to the Virtual Test Bed. This model is now available on the VTB open-source repository for industry and individuals to adapt for their own simulation test cases. The model features a homogenized heat transfer simulation, distributed cooling channel simulations, and neutronics calculations coupled together.

ACKNOWLEDGMENTS

The VTB model presented in this work comes from [5]. Any work making use of that model should cite that reference. The release of the model was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internships Program (SULI). This manuscript was authored by Battelle Energy Alliance LLC under contract no. DEAC07-05ID14517 with the U.S. Department of Energy (DOE). This work was prepared for the U.S. DOE through the National Reactor Innovation Center (NRIC). Analysis using this model made use of the resources of the High Performance Computing Center at Idaho National Laboratory, which is supported by the Office of Nuclear Energy of the U.S. Department of Energy and the Nuclear Science User Facilities under the same contract.

REFERENCES

1. S. M. BRAGG-SITTON, "The Essential Role of Nuclear Energy in Achieving Economy-wide Net-Zero Solutions," Tech. rep., Idaho National Laboratory (2022).
2. I. E. AGENCY, "Nuclear Power in a Clean Energy System," (2019).
3. K. BEIERSCHMITT, M. BUCHANAN, A. CLARK, I. ROBERTSON, P. BRITT, A. NAVROTSKY, P. BURNS, P. TORTORELLI, A. MISRA, J. WISHART, P. FENTER, A. GEWIRTH, B. WIRTH, B. MINCHER, I. SZLUFARSKA, J. BUSBY, L. HORTON, B. GARRETT, J. VETRANO, P. WILK, K. RUNKLES, S. KUNG, S. LESICA, B. WYATT, D. COUNCE, and K. JONES, "Basic Research Needs for Future Nuclear Energy: Report of the Basic Energy Sciences Workshop for Future Nuclear Energy, August 9-11, 2017," Tech. rep., USDOE Office of Science (2017).
4. G. L. GIUDICELLI, A. ABOU-JAOUDE, A. J. NOVAK, A. ABDELHAMEED, P. BALESTRA, L. CHARLOT, J. FANG, B. FENG, T. FOLK, R. FREILE, T. FREYMAN, D. GASTON, L. HARBOUR, T. HUA, W. JIANG, N. MARTIN, Y. MIAO, J. MILLER, I. NAUPA, D. O'GRADY, D. REGER, E. SHEMON, N. STAUFF, M. TANO, S. TERLIZZI, S. WALKER, and C. PERMANN, "The Virtual Test Bed (VTB) Repository: A Library of Reference Reactor Models Using NEAMS Tools," *Nuclear Science and Engineering*, pp. 1–17 (2023).
5. V. LABOURÉ, J. ORTENSI, N. MARTIN, P. BALESTRA, D. GASTON, Y. MIAO, and G. STRYDOM, "Improved Multiphysics Model of the High Temperature Engineering Test Reactor for the Simulation of Loss-of-Forced-Cooling Experiments," *Annals of Nuclear Energy*, **189**, 109838 (2023).
6. V. M. LABOURÉ, M. A. E. ÅBERG LINDELL, J. ORTENSI, G. STRYDOM, and P. BALESTRA, "FY22 Status Report on the ART-GCR CMVB and CNWG International Collaborations," Tech. rep., Idaho National Laboratory (2022).
7. V. LABOURE, J. ORTENSI, Y. WANG, S. SCHUNERT, F. GLEICHER, M. DEHART, and R. MARTINEAU, "Multiphysics Steady-State Simulation of the High Temperature Test Reactor with MAMMOTH, BISON and RELAP-7," Tech. rep., Idaho National Laboratory (2019).
8. V. M. LABOURE, J. ORTENSI, and A. HUMMEL, "HTTR 3 D Cross Section Generation with Serpent and MAMMOTH," Tech. rep., Idaho National Laboratory (2018).
9. M. DEHART, F. N. GLEICHER, V. LABOURE, J. ORTENSI, Z. PRINCE, S. SCHUNERT, and Y. WANG, "Griffin User Manual," Tech. Rep. INL/EXT-19-54247, Idaho National Laboratory (2020).
10. R. L. WILLIAMSON, J. D. HALES, S. R. NOVASCONE, G. PASTORE, K. A. GAMBLE, B. W. SPENCER, W. JIANG, S. A. PITTS, A. CASAGRANDA, D. SCHWEN, A. X. ZABRISKIE, A. TOPTAN, R. GARDNER, C. MATTHEWS, W. LIU, and H. CHEN, "BISON: A Flexible Code for Advanced Simulation of the Performance of Multiple Nuclear Fuel Forms," *Nuclear Technology*, **207**, *7*, 1–27 (2021).
11. R. BERRY, L. ZOU, H. ZHAO, H. ZHANG, J. PETERSON, R. MARTINEAU, S. KADIOGLU, and D. ANDRS, "RELAP-7 Theory Manual," Tech. Rep. INL/EXT-14-31366, Idaho National Laboratory (2014).
12. J. D. BESS and N. FUJIMOTO, "Benchmark Evaluation of Start-Up and Zero-Power Measurements at the High-Temperature Engineering Test Reactor," *Nuclear Science and Engineering*, **178**, *3*, 414–427 (2014).