INL/CON-23-70740-Revision-0

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June 2023

Changing the World's Energy Future

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

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INTRODUCTION

The high-temperature gas-cooled reactor (HTGR) is an advanced reactor concept that has received considerable attention over the last 60 years. HTGRs boast high coolant outlet temperatures, passive safety, and large margins to fuel failure. Recent years have seen increasing interest in HTGRs, whether large-scale HTGRs for electricity or process heat applications or as microreactors serving remote communities. HTGRs have considerable potential to fulfill these applications, but modeling and simulation tools typically used for reactor safety analysis have not been validated for HTGR modeling. The High-Temperature Test Facility (HTTF) was constructed at Oregon State University (OSU) to provide validation data for HTGR modeling [1]. Recently, Idaho National Laboratory, OSU, Argonne National Laboratory, Canadian Nuclear Laboratories, and the University of Tennessee Knoxville have collaborated to develop an HTGR thermal hydraulics benchmark based on HTTF experiments [2]. That benchmark has been accepted by the Organization for Economic Cooperation and Development – Nuclear Energy Agency (OECD-NEA). This summary presents results from a portion of that benchmark using RELAP5-3D [3]. The RELAP5-3D models used in this work are based on the model developed by Paul Bayless presented in ref. [4]. The work contained in this summary represents preliminary results based on draft benchmark specifications. This work was performed in parallel with the development of the specifications and is intended to provide some indication of results from the benchmark using RELAP5-3D, but final benchmark results may differ. Nevertheless, this summary provides representative results from RELAP5-3D based on draft benchmark specifications.

The High-Temperature Test Facility

The HTTF is a 2.2 MW, electrically heated integral-effects thermal hydraulics test facility at OSU designed to represent a preconceptual HTGR design called the modular high-temperature gas-cooled reactor (MHTGR). HTTF is a quarter-length-scale representation of the MHTGR with a few key differences. Firstly, rather than using nuclear fuel, the HTTF is heated through a series of 210 resistive graphite heater rods. Secondly, rather than using graphite for the core blocks, HTTF uses an aluminum-oxide ceramic with a thermal conductivity ranging from approximately 2–5 W/m-K. This allows the HTTF blocks to achieve temperatures comparable to the MHTGR despite the much lower power. Thirdly, the HTTF is rated for a pressure of about 0.7 MPa, as opposed to 6.39 MPa for the MHTGR. Most of the coolant channels in HTTF are full-sized relative to those in the MHTGR [1].

In 2019, several experiments were conducted at HTTF that serve as the basis for the upcoming HTGR thermal hydraulics benchmark. These include PG-27, an experiment intended to provide conditions representative of a pressurized conduction cooldown (PCC) transient, PG-29, an experiment intended to provide conditions representative of a depressurized conduction cooldown (DCC) transient, and PG-28, an experiment for investigating lower plenum mixing. HTTF contains over 500 instruments, the vast majority of which are thermocouples for measuring the temperature of the core blocks or helium at several radial and axial positions. This vast array of instrumentation provides time-dependent data for temperatures, power, and pressure at many locations in the core.

The heat sink in the HTTF transients is the reactor cavity cooling system (RCCS), which is a set of stainless-steel plates with a water flow channel between them. Heat radiates from the reactor vessel to the RCCS plates, where the RCCS cooling water removes the heat from the system. The cavity between the reactor vessel and RCCS is not airtight, and a small air flow rate may have been present during the experiments.

The OECD-NEA HTTF Benchmark

The HTTF benchmark provides an opportunity for code-to-code and code-to-data comparisons for systems codes, computational fluid dynamics (CFD) codes, and coupled systems code to CFD applications. The benchmark consists of three problems, each of which has multiple exercises [5]. Problem 1 is based on HTTF Experiment PG-28 and captures the lower plenum mixing phenomenon. This problem is intended for CFD modeling and coupled system code to CFD modeling [5]. Problem 2 is based on the HTTF Experiment PG-29 and represents a DCC. This problem is intended for system codes modeling and coupled system code to CFD modeling [5]. Problem 3 is based on HTTF Experiment PG-27 and represents a PCC. This problem is intended for system codes modeling and coupled system code to CFD modeling [5]. A summary of the problems and their exercises can be found in Table I.

The benchmark problems can be further broken down into exercises. Exercise 1 is a fixed boundary condition exercise. This exercise is intended to provide an opportunity for code-to-code comparison [5]. Exercise 2 is a best-estimate exercise. Benchmark participants can develop models using their own assumptions of initial and boundary conditions to validate their codes against HTTF data [5]. Exercise 3 is an error scaling exercise aimed at evaluating the validation extrapolation between HTTF and MHTGR. Problem 1 consists only of Exercises 1 and 2. Exercise 3 is intended only for systems code models [5]. This summary presents preliminary results for Exercise 1 in Problems 2 and 3 using RELAP5-3D Version 4.4.2 [3].

TABLE I. Problems, their exercises, and relevant code types, where SYS means systems codes, COU means coupled system codes and CFD.

Problem (Experiment)	Code-to-Code (Ex. 1)	Best Estimate (Ex. 2)	Error Scaling (Ex. 3)
1 (PG-28)	CFD/COU	CFD/COU	N/A
2 (PG-29)	SYS/COU	SYS/COU	SYS
3 (PG-27)	SYS/COU	SYS/COU	SYS

EXERCISE 1 MODELS

Exercise 1 for both Problems 2 and 3 consists of multiple sub-exercises. Problem 2 consists of Exercises 1A, 1B, and 1C. Problem 3 consists of Exercises 1A, 1B, 1C, and 1D. The definition of Exercise 1A is the same for both Problems 2 and 3. Exercises 1B and 1C are different for Problems 2 and 3, and only Problem 3 contains an Exercise 1D. Exercise 1A represents a full-power steady state. The conditions for Exercise 1A can be seen in Table II. For material thermophysical properties, readers are directed to the HTTF benchmark specifications [5]. HTTF was never operated in a full-power steady state, but these conditions provide an opportunity for code-to-code comparison without the need for detailed initial temperature, pressure, and flow distributions. For the third (and fourth) part of Exercise 1, the goal for both problems is to use fixed boundary conditions to define a sub-exercise that is somewhat representative of HTTF conditions during the corresponding experiment.

Problem 2

Exercise 1B of Problem 2 represents a DCC from full-power steady-state. The initial conditions for Exercise 1B are the results from Exercise 1A. In this sub-exercise, the coolant flow rate coasts down linearly from 1.0 to 0.0 kg/s over 1 second, and the pressure drops from 0.7 to 0.1 MPa linearly over 20 seconds. Flow rates in the cavity and RCCS are held constant. SCRAM occurs at 0.0 seconds. This problem uses the 1994 American Nuclear Society decay heat standard following SCRAM [5].

Problem 2, Exercise 1C uses initial conditions (block and helium temperatures and pressure measurements) from HTTF taken shortly before the start of Experiment PG-29 and provides power and flow curves over time based on PG-29 data [5]. In Problem 2 Exercise 1C, the thermal conductivity of the core blocks is replaced with an effective thermal conductivity. For the full set of initial and boundary conditions plus the effective thermal conductivity, readers are directed to the benchmark specifications [5]. The goal of Exercise 1C is to provide a simplified set of conditions that are somewhat representative of PG-29 for code-to-code comparisons.

TABLE II. Exercise 1A boundary conditions

Parameter	Value
Helium Inlet Temperature (K)	500.0
Helium Pressure (MPa)	0.7
Helium Flow Rate (kg/s)	1.0
RCCS Inlet Temperature (K)	313.2
RCCS Water Pressure (MPa)	0.1
RCCS Flow Rate (kg/s)	1.0
RCCS Cavity Temperature (K)	300.0
RCCS Cavity Air Flow Rate (g/s)	25
Power (MW)	2.2

Problem 3

Exercise 1B of Problem 3 represents a PCC from full-power steady state. Once again, the helium flow rate drops linearly from 1.0 to 0.0 kg/s over 1.0 seconds. The 1994 American Nuclear Society decay heat standard is used for decay heat in this exercise. The only differences between Problem 2 Exercise 1B and Problem 3 Exercise 1B is the depressurization in Problem 2. In all other respects, these problems are defined identically.

Exercise 1C of Problem 3 represents a low-power steady state based on PG-27 conditions. Problem 3 Exercise 1C uses the same thermophysical properties as Exercise 1A. The conditions for Problem 3 Exercise 1C can be seen in Table III.

TABLE III. Problem 3 Exercise 1C boundary conditions

Parameter	Value
Helium Inlet Temperature (K)	380.0
Helium Pressure (MPa)	0.13
Helium Flow Rate (kg/s)	0.1
RCCS Inlet Temperature (K)	313.2
RCCS Water Pressure (MPa)	0.1
RCCS Flow Rate (kg/s)	0.33
RCCS Cavity Temperature (K)	300.0
RCCS Cavity Air Flow Rate (g/s)	25
Power (kW)	86.0

Problem 3 Exercise 1D represents the PCC portion of PG-27. The initial conditions of Exercise 1D are the results from Exercise 1C. In Exercise 1D, power is briefly ramped up from 86 kW to approximately 115 kW over a period of 2 minutes before ramping down over a period of approximately 4 hours. The RCCS conditions are left unchanged from Exercise 1C. For the full definition of Problem 3 Exercise 1D, the reader is referred to the benchmark specifications [5].

RESULTS

The Exercise 1A definitions of Problems 2 and 3 were identical, and the Exercise 1B definitions were identical aside from the depressurization in Problem 2. A sample of the results from Problem 3 Exercise 1B can be seen in Fig. 1. The results from Exercise 1B are similar for Problems 2 and 3. At the core midplane, the temperatures are higher in the DCC (Problem 2) than the PCC (Problem 3), but only by a small amount. The largest temperature difference at the core midplane is 9 K over the entire 40 hours shown in Fig. 1. The DCC is hotter than the PCC because the PCC includes a natural circulation flow rate of about 0.32 g/s within the core. This flow rate is calculated by RELAP5-3D and is not a specified boundary condition. Coolant flows upwards in the inner and middle portions of the core and flows downward in the outer core and outer reflector. This natural circulation transports heat from the inner regions of the core to the outer regions, reducing the core thermal resistance. These results show the expected behavior for a PCC or DCC. Heat is redistributed from the heated rings of the core towards the central reflector for the first few hours. After approximately 5 hours, the entire core cools down through conduction and radiation, leading to a slow heating of the core barrel and vessel. The vessel is ultimately cooled by radiation to the RCCS, which serves as the ultimate heat sink.

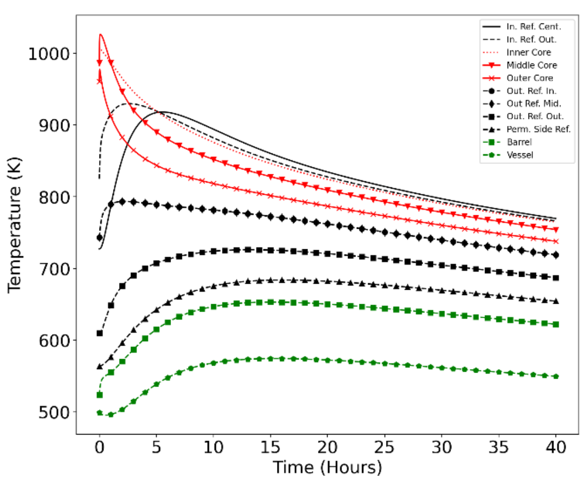

Fig. 1. Solid structure temperatures in HTTF at the core midplane during a PCC from full-power steady state (Problem 3 Exercise 1B).

Problem 2 – Exercise 1C

Problem 2 Exercise 1C uses measured HTTF data that have been smoothed and sampled to be used as boundary conditions as described in ref. [6]. The goal of Exercise 1C was to capture the general behavior of PG-29 for code-to-code comparison, not to provide a best-estimate solution.

Results from Problem 2 Exercise 1C can be seen in Fig. 2. The first 8 hours of the problem represent heating prior to the DCC onset. At Hour 8, the DCC is initiated. At approximately Hour 15, the heaters are shut off and the facility is allowed to cool down. The problem was run for approximately 22 hours; the end time of the problem represents the end of PG-29 data collection. The results in Fig. 2 show the major trends of PG-29. The middle core ring is hotter than the inner core ring for most of the transient because the heaters in the inner core were not used in this exercise, but heaters in the middle and outer parts of the core were. After the heaters are shut down and the facility enters cooldown mode, the inner core ring becomes hotter than the middle one.

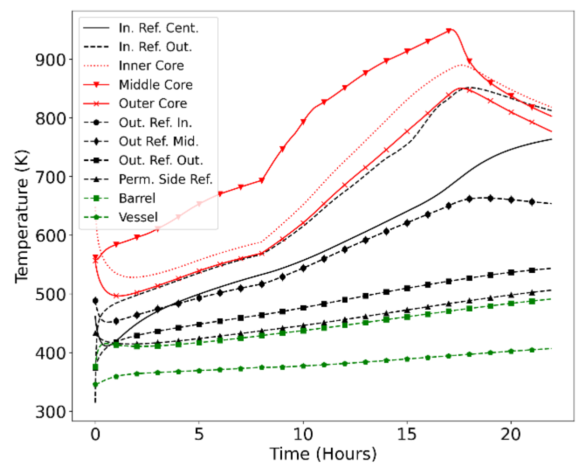

Fig. 2. Solid structure temperatures at the core midplane from Problem 2 Exercise 1C.

Problem 3 – Exercises 1C and 1D

Problem 3 Exercise 1C uses simplified PG-27 data to provide a low-power steady state that is representative of the state of the facility prior to the onset of the PCC. Problem 3 Exercise 1D uses simplified PG-27 data to provide a PCC transient that is representative of the PCC portion of the experiment.

Results from Problem 3 Exercise 1D can be seen in Fig. 3. After approximately 4 hours, the heaters are turned off, leading to the gradual cooldown from Hours 4–48. In this problem, the power is generated almost entirely in the outer core. This gives rise to the outer core ring being the hottest part of the system until after the heaters are turned off. The general behavior is similar to what is seen in Problem 3 Exercise 1B, but with lower temperatures due to the lower power and a different temperature distribution while the heaters are running.

The temperature increase during the first 4 hours in Fig. 3 arises due to the combination of a decrease in flow and increase in power for the first 2 minutes of the transient. For the first 90 minutes of Exercise 1D, the power is higher than the steady-state power from Exercise 1C. This differs from Exercise 1B where the power is always lower than the steady-state power from Exercise 1A. The power increasing while flow decreases explains why the temperature rise in the heated rings of the core is about 200 K for Exercise 1D as opposed to 50 K or less in Exercise 1B.

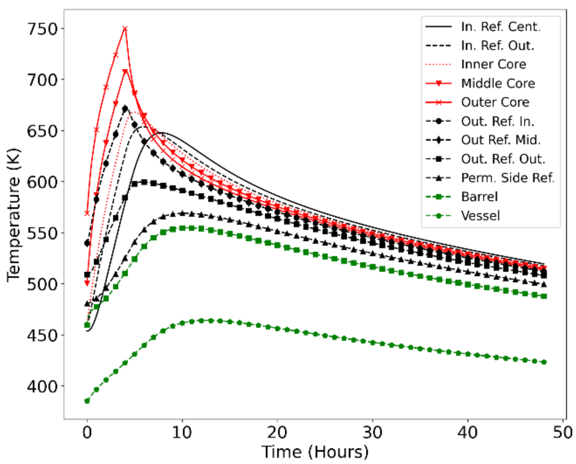

Fig. 3. Solid structure temperatures at the core midplane from Problem 3 Exercise 1D.

CONCLUSIONS

This summary has presented RELAP5-3D results for Exercise 1 of Problems 2 and 3 of the OECD-NEA HTTF benchmark. We found that, for Exercise 1B of Problems 2 and 3, the results were very similar. The temperatures in Problem 2 Exercise 1B were within 10 K of those in Problem 3 Exercise 1B, indicating that the natural circulation in Problem 3 Exercise 1B provides a relatively small contribution to cooldown over 40 hours. The Problem 2 Exercise 1C results showed that RELAP5-3D model captures the same general behavior of HTTF during the DCC transient. Results from Problem 3 Exercises 1C and 1D as expected showed similar behavior to Problem 3 Exercises 1A and 1B, but with lower temperatures due to the lower power. The temperature rise in Problem 3 Exercise 1D was larger than in Problem 3 Exercise 1B due to the initial increase in power from Exercise 1D as opposed to the drop in power from Exercise 1B.

The purpose of Exercise 1 is a code-to-code comparison, and the results presented here provide some points of comparison from RELAP5-3D for the HTTF benchmark. Benchmark specifications are being finalized and should be published in the summer of 2023. The final benchmark report will include comparisons between RELAP5-3D and other systems codes. Work is ongoing to develop best-estimate solutions for Problems 2 and 3 using RELAP5-3D.

ACKNOWLEDGEMENTS

This work was funded by the United States Department of Energy's Advanced Reactor Technologies Gas Cooled Reactor Program.

This research made use of Idaho National Laboratory computing resources which are supported by the Office of Nuclear Energy of the U.S. Department of Energy and the Nuclear Science User Facilities under Contract DE-AC07-05ID14517. This manuscript has been authored by Battelle Energy Alliance, LLC under Contract No. DE-AC07-05ID14517 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for U.S. Government purposes.

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