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Modeling of HTTF test PG-26 using RELAP5-3D and SAM

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INTRODUCTION

The High Temperature Test Facility (HTTF) at Oregon State University (OSU) is a scaled integral effects experiment designed to investigate transient behavior in high-temperature gas-cooled nuclear reactors (HTGR) with prismatic fuel and reflector blocks [1]. Several tests have been completed at the HTTF including depressurized conduction cooldown (DCC) and pressurized conduction cooldown (PCC) transients.

This summary reports on the analysis of test PG-26 using the INL system code REALP5-3D [2] as well as the ANL system code SAM [3]. Test PG-26 is a progression of the Double Ended Inlet-Outlet Crossover Duct Break transient that is referred to as a DCC [4]. Core initial conditions (i.e., before the DCC started) have been met using low power (<100 kW) and two of ten available electric heater banks. The DCC transient was initiated during the 50th hour of the test. The break valves were opened, and hot helium from the core and cold helium from the reactor cavity simulation tank (RCST) started mixing. The gases flowed in a countercurrent fashion, where the top half of the hot duct contained hot helium that flowed in one direction and cold helium that flowed in the other direction in the bottom half of the duct. After the pressure and density reached equilibrium, the event entered a diffusion mode. The onset of a reverse natural circulation was not observed during the DCC period of the test.

Test PG-26 poses several modeling challenges:

- **No helium mass flow measurements**: The HTTF facility is not equipped to directly measure the helium flow rate in the Primary Coolant System (PCS). However, to get the right energy balance and core conditions before the DCC transient, knowledge of the helium mass flow rate is needed.
- **No steady state**: HTTF did not reach a fully developed steady state (temperature distribution) during PG-26. On the one hand, the ceramic core blocks take a long time to completely cool down to room temperature. To avoid having to wait unreasonably long times between tests, a new test can be started before the core blocks are completely cooled down. At the start of PG-26, the core ceramics were at around 400 K. On the other hand, temperatures were still moving before the DCC transient was initiated. Looking at the test data in particular, the steam generator behavior did not reach a true steady state during the test.
- **Limited knowledge of heat flow**: The Reactor Cavity Colling System (RCCS) was activated during the test. The water temperature difference over the RCCS is very small during the whole test, indicating that nearly no heat is evacuated by it. However, the natural convection inside the cavity between the vessel and the RCCS panels is probably a large contributor to heat removal off the vessel wall (not measured), and air inside that cavity can escape since it is not airtight.

Also, the core ceramic temperatures go down during the core heat-up from ~120,000 s to 150,000 s (See Fig. 1). This is due to the steam generator behavior and heater power. The steam generator started producing steam around 80,000 s and pressurized up to about 110,000 s. At that time, the steam generator pressure was manually reduced, and the inventory was refilled with cold city water. This reduced the steam generator temperature, which affected the core inlet gas temperature.

Another phenomenon that happened during the PG-26 test was thermal stratification. For example, helium temperatures measured in the lower (outlet) plenum of the vessel show a strongly non-uniform temperature distribution. Thermal stratification plays an important role in determining the temperatures for helium flows leaving the plenum as well as for determining the structure temperatures encompassing the helium plenum.

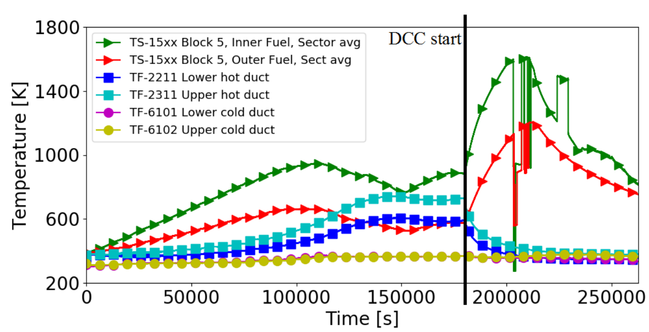

Fig. 1. Measured core ceramic (midcore around the inner and outer fuel rings) and helium (in the upper and lower part of the hot and cold ducts) temperatures.

- **Complex manual operator actions during transient**: There was a small helium leak from the PCS into the RCST during the heat-up phase of the test (see the rise of RCST pressure during heat-up in Fig. 2). To keep the pressure in the PCS somewhat constant, cold helium from helium bottles was periodically injected by the operators (see the sawtooth behavior of PCS pressure during heat-up). While attempting to reseal the leaking valve between the PCS and RCST, the operators overpressured the primary loop during the transient for a short period of time and subsequently blew down the overpressure into the RCST manually. In addition, before the DCC starts (i.e., before the break valves are opened that connect the primary pressure vessel with the RCST), pressure in the PCS and RCST have been manually blown down to about 1 bar. The slow pressure swing of the helium during the DCC is due to the heat up from the simulated decay heat and then, after the heaters have been shut off, it is due to the slow cooldown of the gas.

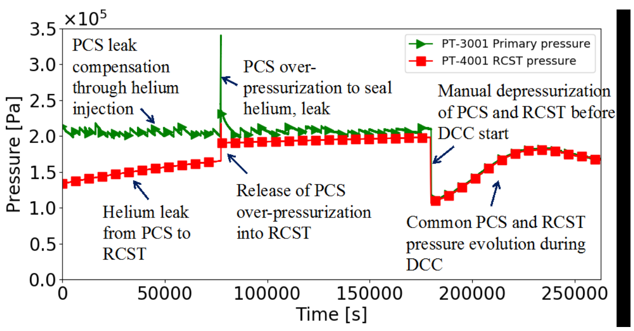

Fig. 2. Measured PCS and RCST helium pressure evolution.

RELAP5-3D MODEL AND RESULTS

The U.S. Department of Energy's (DOE) Advanced Reactor Development (ARD) program sponsored a project modeling PG-26 using INL's system code RELAP5-3D. Version 4.4.2ie of the RELAP5-3D computer code has been used to model the HTTF PG-26 test, and results have been compared to available high-quality measured data [5].

A RELAP5-3D input model has been developed for the HTTF (See Fig. 3). To capture the phenomena happening during the DCC portion of the transient, the core state (stored energy, temperature distribution, etc.) at the beginning of the transient must be known. To get initial conditions before the DCC start, different approaches can be considered, e.g. in a 'traditional' REALP5-3D analysis, the facility state right before the DCC starts would be modeled as steady-state, and only the DCC itself would be modeled as transient. However, as mentioned, HTTF did not reach a true steady state before the transient. Therefore, the presented results include running the whole test (i.e., the heat-up as well as the DCC) as a RELAP5-3D transient. As mentioned, HTTF is not equipped to measure helium mass flows. Using the circulator performance curves and measured pressure drops in the system, the helium mass flow rate was estimated to be 15 g/s. However, a calorimetric calculation across the core indicates a mass flow rate that is lower than the estimated 15 g/s from the circulator curve. Uncertainty on the helium mass flow rate must be considered large.

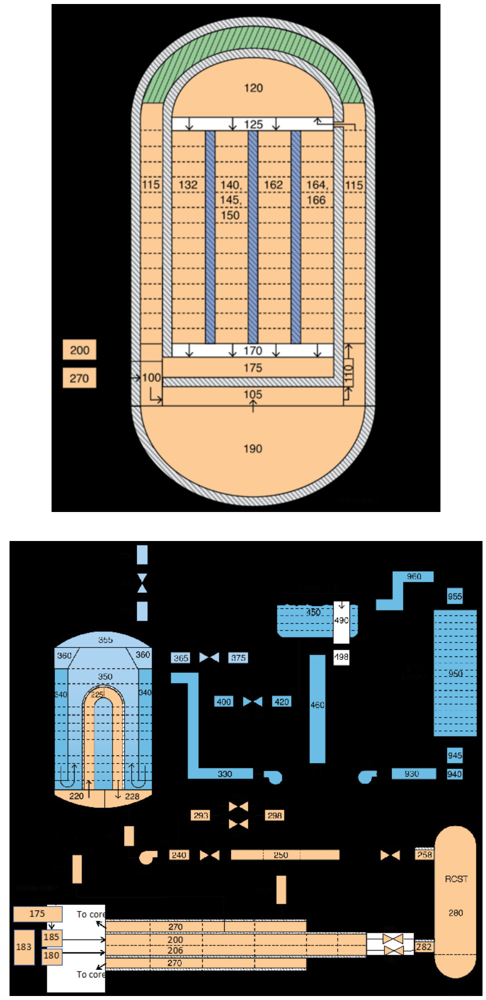

Fig. 3. Primary pressure vessel (top) and components outside the primary pressure vessel (bottom) nodalisations.

Fig. 4 shows a selected result of the RELAP5-3D calculations. Colored lines represent measured data while black lines are RELAP5-3D calculation results. Solid temperatures before the DCC starts are generally underpredicted. In addition, peak ceramic solid temperatures and temperature reduction rates are slower in the RELAP5-3D calculation compared to the measured data.

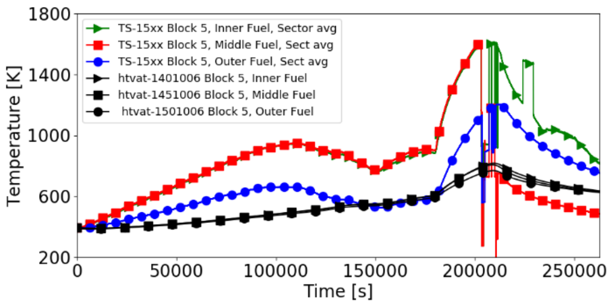

Fig. 4. Middle of the core (block 5) ceramic temperatures in the fuel region.

It has been speculated that both the specific heat capacity (c_p) as well as the thermal conductivity (λ) of the core ceramic might be overestimated in the calculations. Fig. 5 shows the same selected result as above, but c_p and λ have been lowered. One can see that peak ceramic solid temperatures are better captured.

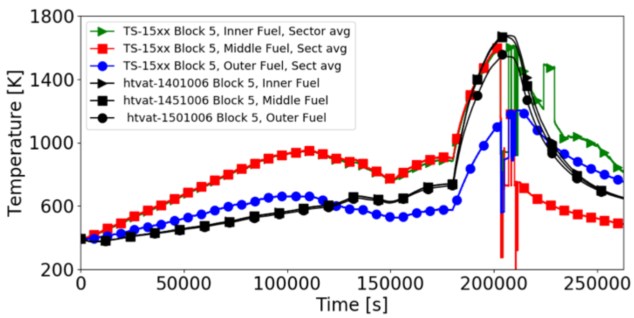

Fig. 5. Middle of the core (block 5) ceramic temperatures in the fuel region: 1/10 c_p and 1/5 λ.

In addition, it was suspected that the friction in the primary loop might be underestimated, since two natural convection flow path are established in the RELAP5-3D simulations (a) lower (outlet) plenum → upper hot duct → RCST → lower hot duct → lower outlet plenum and b) a reverse natural convection through the core (i.e., RCST → Cold duct → Core → Hot duct → RCST) that has not been observed during the test. The pressure drop in the core was measured during the test, but, since the flow rate is unknown, the friction factors that would lead to the measured pressure drop are unknown. While increasing friction in the loop eliminates the establishment of natural circulation in the simulation, helium temperatures in the core do not change noticeably between the base cases and the added friction cases. Natural convection and heat loss through the vessel walls are not a major contributor to the core temperature distribution during the investigated phase of the DCC transient.

SAM MODEL AND RESULTS

The System Analysis Module (SAM) [3] computer code has been developed under the NEAMS campaign and in April of 2019, the US NRC has formally stated its intent to use the SAM code for advanced non-LWR design basis event analysis [6]. The test campaign at HTTF provides a valuable opportunity to utilize SAM to model an integral effect facility and to assess and improve its modeling approach – the ring model – of a prismatic block core MHTGR design.

The SAM input model for the HTTF is based on the ring model approach [7]. In this approach, all components including the ceramic, heater, coolant channels, core barrel, pressure vessel, and RCCS are modeled as concentric cylindrical rings. A primary advantage of the ring model is in its ability to model radial heat transport (conduction and thermal radiation) which is the dominant heat transfer mode in key HTGR transient scenarios. The core is modeled using 47 rings as shown in Fig. 6. The coolant channels are modeled as 1-D fluid component. The ceramic and heater heat structure are modeled as 2-D components. Above the upper reflector is the inlet plenum and below the lower reflector is the outlet plenum. Each plenum is modeled as one-dimensional volume branch.

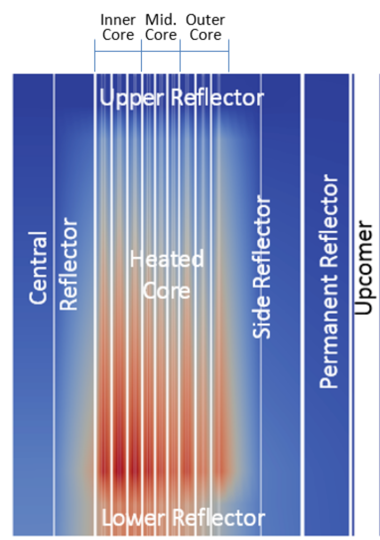

Fig. 6. Ring model of the HTTF core.

Because of the modeling challenges that are specific to this test as described earlier, it is not feasible to benchmark SAM with test data. Rather, the modeling activity and comparison with experimental data trend serves two main purposes: (1) to improve the prediction of heat transfer process and temperature distribution in HTGR prismatic fuel block, and (2) to lay the groundwork for familiarity with instrument placement, data collection and processing that will facilitate future HTTF benchmarking activities.

Fig. 7 compares the SAM predictions with the measured helium temperatures at the midplane in the inner, middle, and outer core regions prior to DCC. The observed radial temperature drop from inner to outer core is substantially higher than predicted. One of the main reasons for the difference in the trend is likely due to the input value of ceramic thermal conductivity which is obtained from material datasheet. However, radial heat flow in the ceramic blocks is complicated by the hundreds of cylindrical coolant channels and heater rods embedded in them as well as moisture retained in the blocks. As such, it is necessary to deduce an effective thermal conductivity (ETC) for the ceramic to analyze the core thermal behavior, particularly during DCC and PCC transients when decay heat is removed mainly by radial thermal conduction through the fuel blocks. A lower value for the ETC is expected to give larger radial temperature gradient and higher peak temperatures in the core.

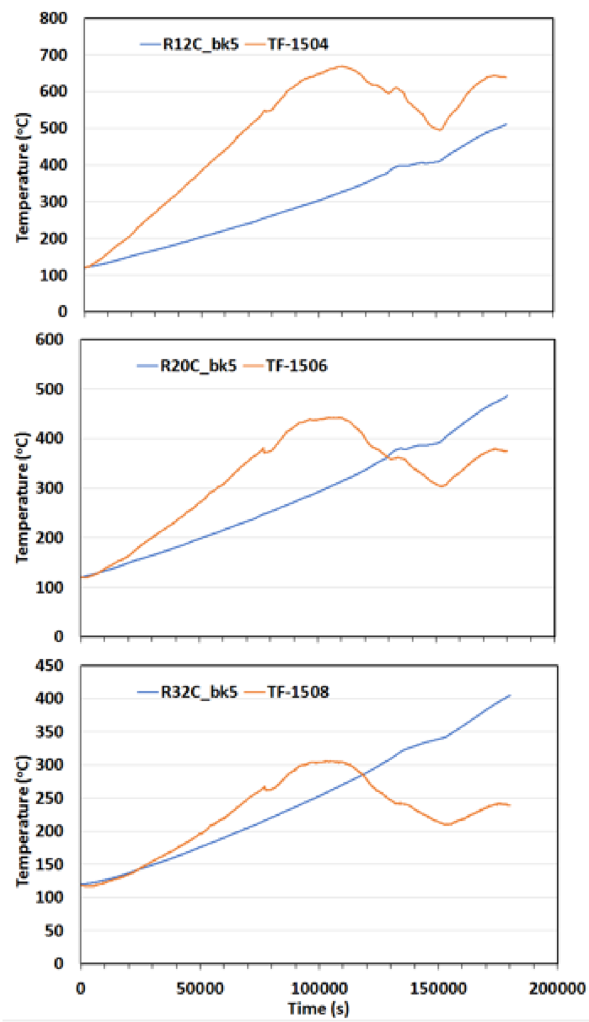

Fig. 7. Comparison of SAM simulations in blue with test data in orange for axial midplane coolant temperature taken at inner core (top), middle core (middle), and outer core (bottom).

CONCLUSIONS

The two system codes RELAP5-3D and SAM have successfully been used to model the HTTF test PG-26.

Using the base RELAP5-3D model predicts a countercurrent helium flow in the hot duct as observed at the beginning of the DCC, but instead of going into a molecular diffusion mode, the model predicts the onset of natural convection. Increasing friction in the core and hot duct prevents the natural convection from happening. Although some temperatures are well predicted (and even overpredicted), the general tendency is to underpredict the ceramic and helium temperatures and heat removal rates during the DCC, resulting in many of the assessment findings being in minimal or insufficient agreement with the data. It is worth noting that these discrepancies between measured data and RELAP5-3D predictions are not RELAP5-3D code limitations. More so, they reflect limitations in boundary condition and thermal property knowledge.

The comparison between SAM prediction and test data reveals a large difference in the radial temperature drop in the core. This phenomenon is believed to be caused by the complexities of radial heat transport in the solid blocks that contain hundreds of coolant channels and heater rods. This finding suggests that it is necessary to utilize an effective thermal conductivity for modeling the HTTF core in particular and HTGR fuel blocks in general when using reactor system analysis codes like SAM.

While the RELAP5-3D and SAM calculations of the test provide some insights into what happens during the transient, and point to missing or potentially uncertain data to which the experimenters can direct their attention, the principal conclusion is that the PG-26 test data are insufficient for a system code assessment.

ACKNOWLEDGEMENTS

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