Integral System Testing for Prismatic Block Core Design HTGR

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Abstract

The High Temperature Test Facility (HTTF) at Oregon State University (OSU) is an integral system test facility scaled ¼ in length and diameter as compared against its reference design, the General Atomics Modular High Temperature Gas Reactor (MHTGR). The HTTF currently has over 400 data acquisition channels including thermocouples, pressure transducers, differential pressure transducers, flow meters, and gas sensors. It consists of of a primary loop containing the reactor vessel with an electrically heated ceramic core, a steam generator, gas circulator and associated piping. The maximum core power output at the HTTF in its current configuration is 880 kW. The primary loop is capable of operating at prototypical temperatures at a pressure of 8 bar. The steam generator discharges its steam to the atmosphere. A Reactor Cavity Cooling System (RCCS) is also present at the HTTF. This consists of forced water-cooled panels that surround the reactor vessel. This RCCS is not a scaled version of an actual HTGR design but rather is used to specify the boundary conditions to control radiation heat transfer from the vessel wall.

The purpose of this research project was to complete eight integral-level thermal-fluid tests at the HTTF in order to investigate the phenomenological behavior of these events at a system level. Although not part of the scope of this project, the data collected can also be used for code validation. The tests completed under this project include the following tests:

1. PG-28 Low Power (<350kW) Lower Plenum Mixing Test
2. PG-29 Low Power (<350kW) Double Ended Inlet-Outlet Crossover Duct Break, Hybrid Heater
3. PG-32 Low Power (<350kW) Asymmetric Core Heatup
4. PG-30 Low Power (<350kW) Lower Plenum Mixing, Constant Temperature Test
5. PG-31 Low Power (<350kW) Pressure Vessel Bottom Break with Restored Forced Convection Cooling Test
6. PG-33 Zero Power Long Term Cooldown Test
7. PG-34 Low Power (<350kW) Asymmetric Core Heatup Full Hybrid Heater
8. PG-35 Zero Power Crossover Duct Exchange Flow and Diffusion Test 1

In support of this test campaign, the HTTF Scaling Report was revised to include additional detail and analysis concerning the intracore natural circulation. The HTTF Instrumentation Plan was also revised under this project. Additionally, a computational fluid dynamics (CFD) scoping analysis that examined upper plenum mixing events was completed.

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Chapter 1. Introduction

The High Temperature Test Facility (HTTF) at Oregon State University (OSU) is an integral system test facility scaled ¼ in length and diameter as compared against its reference design, the General Atomics Modular High Temperature Gas Reactor (MHTGR). The HTTF currently has over 400 data acquisition channels including thermocouples, pressure transducers, differential pressure transducers, flow meters, and gas sensors. It consists of of a primary loop containing the reactor vessel with an electrically heated ceramic core, a steam generator, gas circulator and associated piping. The maximum core power output at the HTTF in its current configuration is 880 kW. The primary loop is capable of operating at prototypical temperatures at a pressure of 8 bar. The steam generator discharges its steam to the atmosphere. A Reactor Cavity Cooling System (RCCS) is also present at the HTTF. This consists of forced water-cooled panels that surround the reactor vessel. This RCCS is not a scaled version of an actual HTGR design but rather is used to specify the boundary conditions to control radiation heat transfer from the vessel wall.

The purpose of this research project was to complete eight integral-level thermal-fluid tests at the HTTF in order to investigate the phenomenological behavior of these events at a system level. Although not part of the scope of this project, the data collected can also be used for code validation. The tests completed under this project include two heat-up tests, one depressurized conduction cooldown (DCC) test, one DCC with restored cooling test, two outlet plenum mixing tests, one long-term cooldown test, and one exchange flow and diffusion test. Each of these tests will be discussed in detail in chapters 2 through 9 of this report.

In support of this test campaign, the HTTF Scaling Report was revised to include additional detail and analysis concerning the intracore natural circulation. The HTTF Instrumentation Plan was also revised under this project. Additionally, a computational fluid dynamics (CFD) scoping analysis that examined upper plenum mixing events was completed.

1.1. HTTF Scaling Report Revisions

The HTTF Scaling Analysis was revised in order to include a more rigorous scaling analysis for intracore natural circulation. This is expected to occur during the Pressurized Conduction Cooldown (PCC) event as well as during times in the DCC event. Revision 1 of the Scaling Report (OSU-HTTF-TECH-001-R1) was issued. The section revised under this project (section 6.3) has been included in Appendix A.

1.2. HTTF Instrumentation Plan Revisions

The HTTF Instrumentation Plan was revised to include a more detailed discussion on instrument uncertainty, a test acceptance philosophy and a revised naming convention. This included the issuance of revisions 3 and 4 of the Instrumentation Plan (OSU-HTTF-TECH-002-R3 and OSU-HTTF-TECH-002-R4). The sections revised under this project (chapters 5 and 6 and appendices A and B) have been included in Appendix B of this report.

1.3. CFD Scoping Analysis

A CFD analysis was conducted to examine the intracore natural circulation that will set up during a loss of flow accident simulation at the HTTF. The results of this analysis were published and presented at the 18th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-18) conference in 2019. The title of the paper was ”CFD Assessment of LOFA intra core natural circulation in the High Temperature Test Facility” by Izabela Gutowska and Brian Woods.

Chapter 2. PG-28 Low Power (<350kW) Lower Plenum Mixing Test

The purpose of this test is to investigate the impact on Lower Plenum thermal profiles and mixing due to changes in the system mass flow rate in an integral test facility scaled to General Atomics' Modular High Temperature Gas Reactor (MHTGR) design. This test is referred to as a Lower Plenum Mixing Test. Initial conditions will be met using a hybrid heater bank at low power (<350kW).

This test began on 7/24/2019 and was completed on 7/24/2019. Facility heatup started on 7/22/19 and went as expected. The Lower Plenum Mixing Test was initiated over 47 hours after heatup start. This test was started and completed in one session, and there is only one data file. In this report the data set, PG28_PG29_A_data, will be presented and discussed.

2.1. Initial Conditions

On July 24, 2019, the HTTF reached the initial conditions for the start of OSU-HTTF-TEST-028-R0 and test operators Brian Woods, Seth Cadell, and Tommy Moore began to follow the test procedure OSU-HTTF-TEST-028-R0. All members of the testing team were certified as HTTF Test Engineers and were briefed on the purpose of the test before they began operating the facility in support of OSU-HTTF-TEST-028-R0.

Conditioning of the facility started 7/19/2019 and was completed following OSU-HTTF-O&M-010-R0 and OSU-HTTF-O&M-011-R0. The facility conditions at the time of the start of the test are presented in Table 9.1. All pumps were secured and the flow rate was zero in each fluid carrying system at the start of the test.

Table 2.1: Initial conditions for the start of the test.

Primary Loop:	>200 kPa helium
RCSS:	>180 kPa <190kPa nitrogen
Cooling Water System:	filled with water and at operating conditions
Steam Generator:	60 to 80% water level and at operating conditions
RCCS Tank:	filled with water and at operating conditions
RCCS Panels:	filled with water and at operating conditions

2.2. Heater Operation

The heaters were operated during the entire test. Heater bank 104 was operated, where the power output was approximately 25kW.

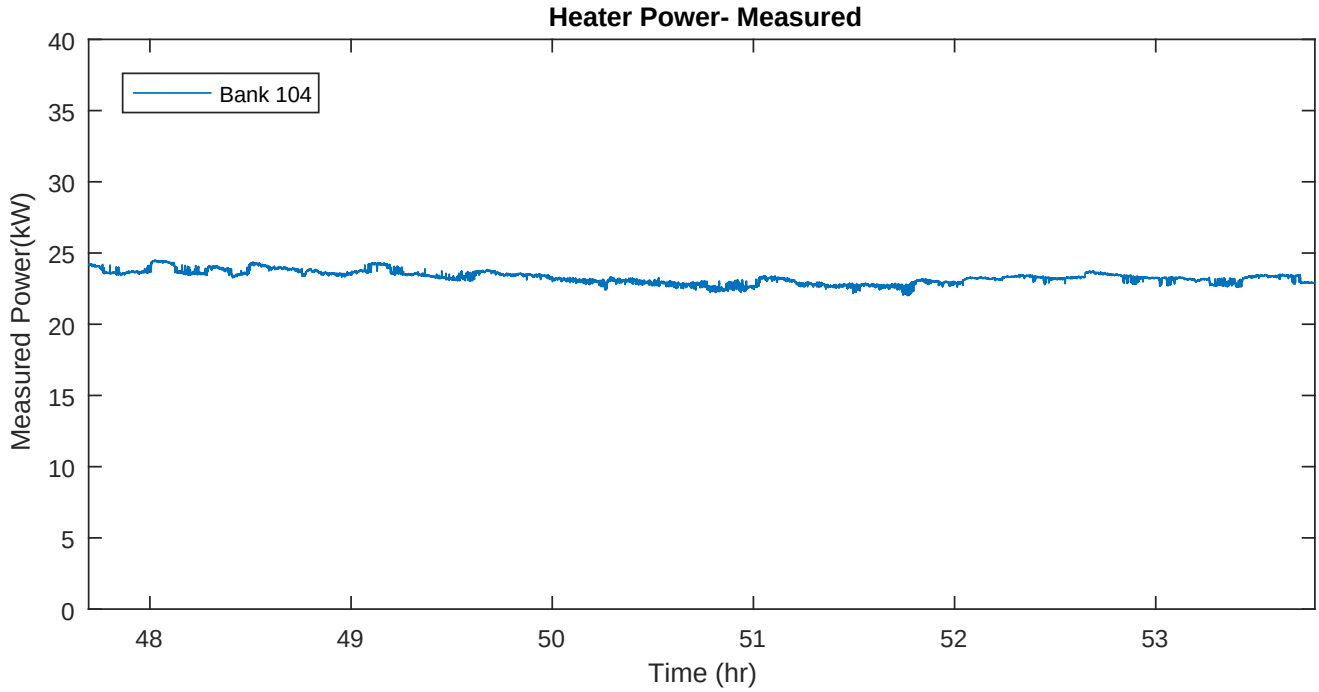

Figure 2.1: Measured heater power output on channel HO-103/104

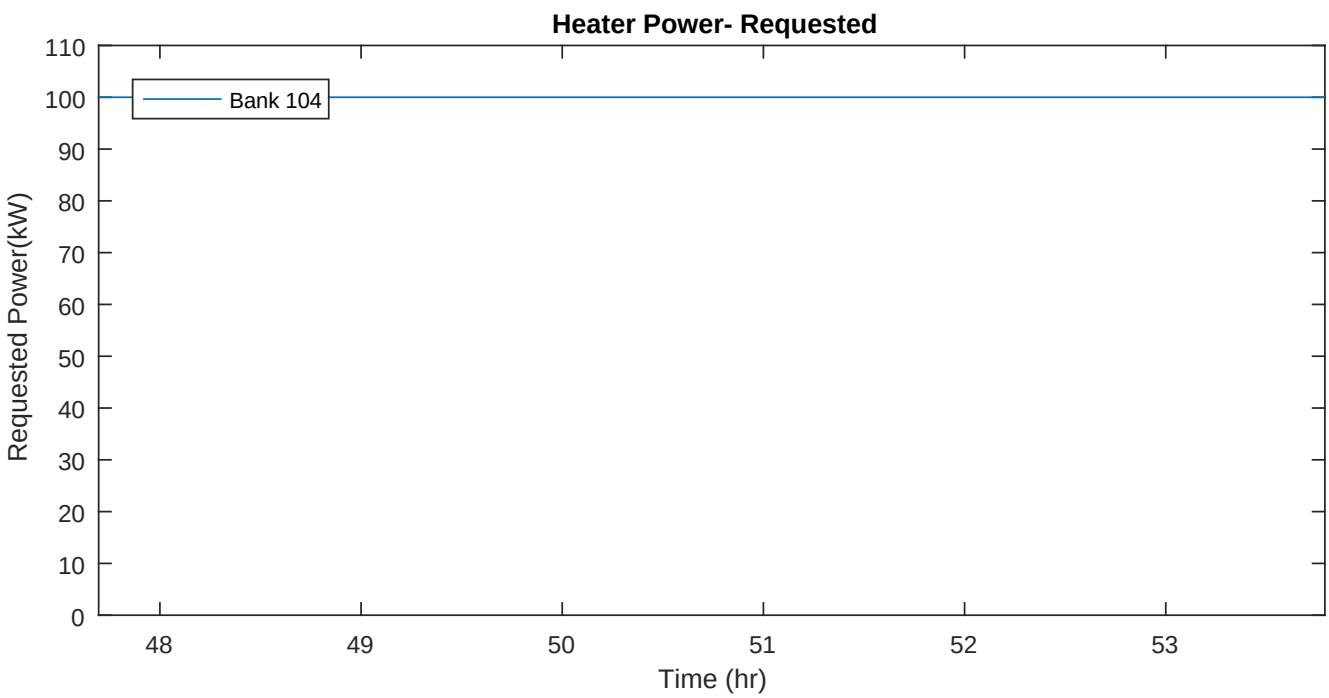

Figure 2.2: Requested heater power output on channel HO-103/104

2.3. Reactor Cavity Cooling System

The system was operated continuously with a motor speed of 30%

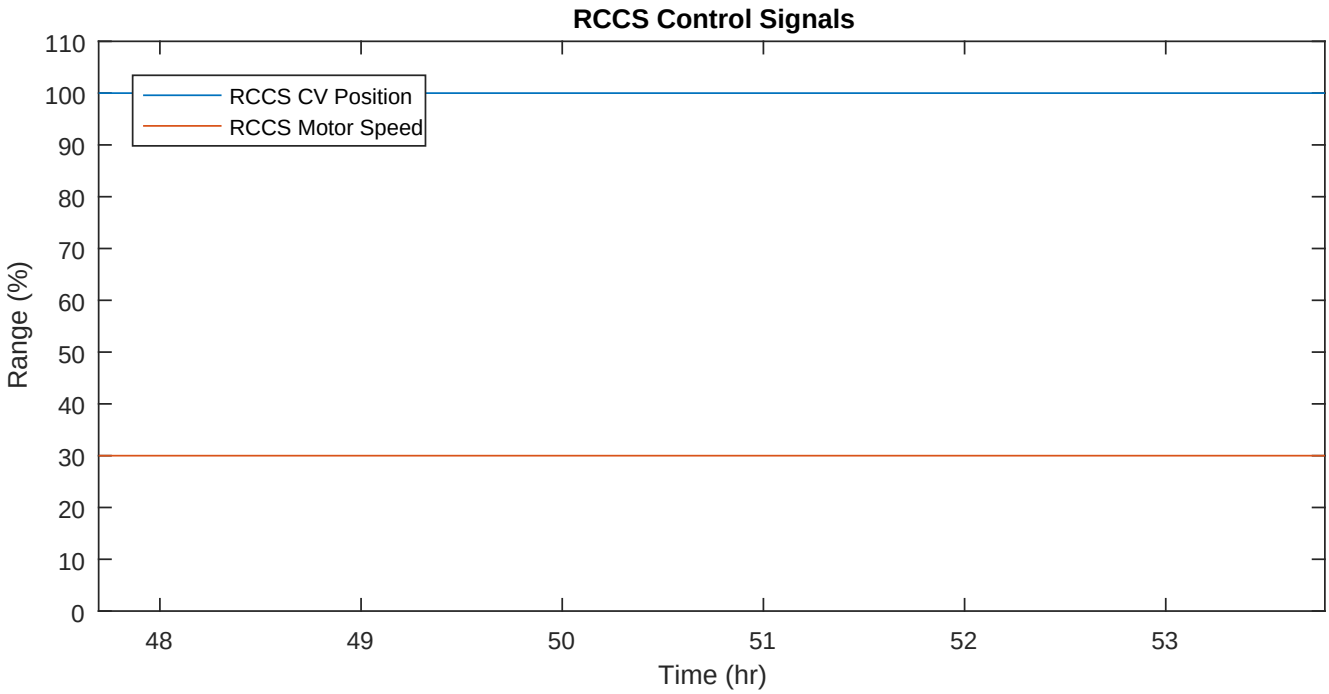

Figure 2.3: RCCS Control signals: MS-9001 and CV-9001

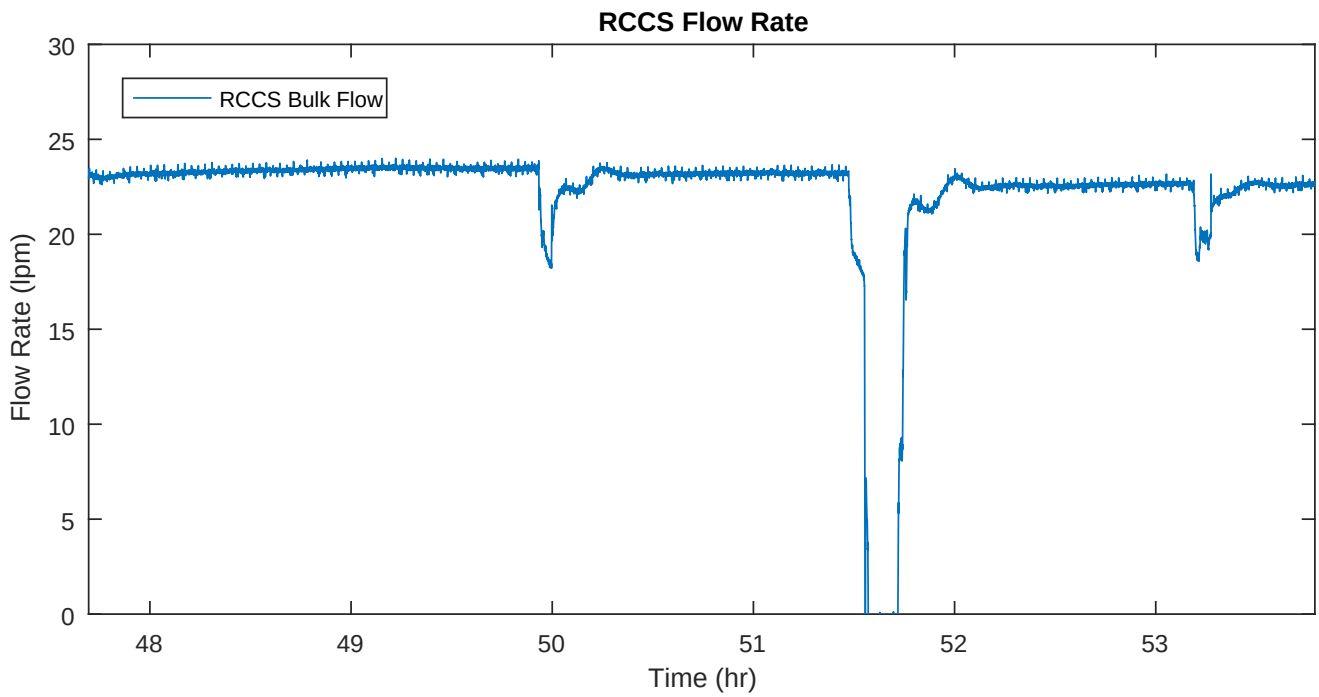

Figure 2.4: RCCS flow rate during the test.

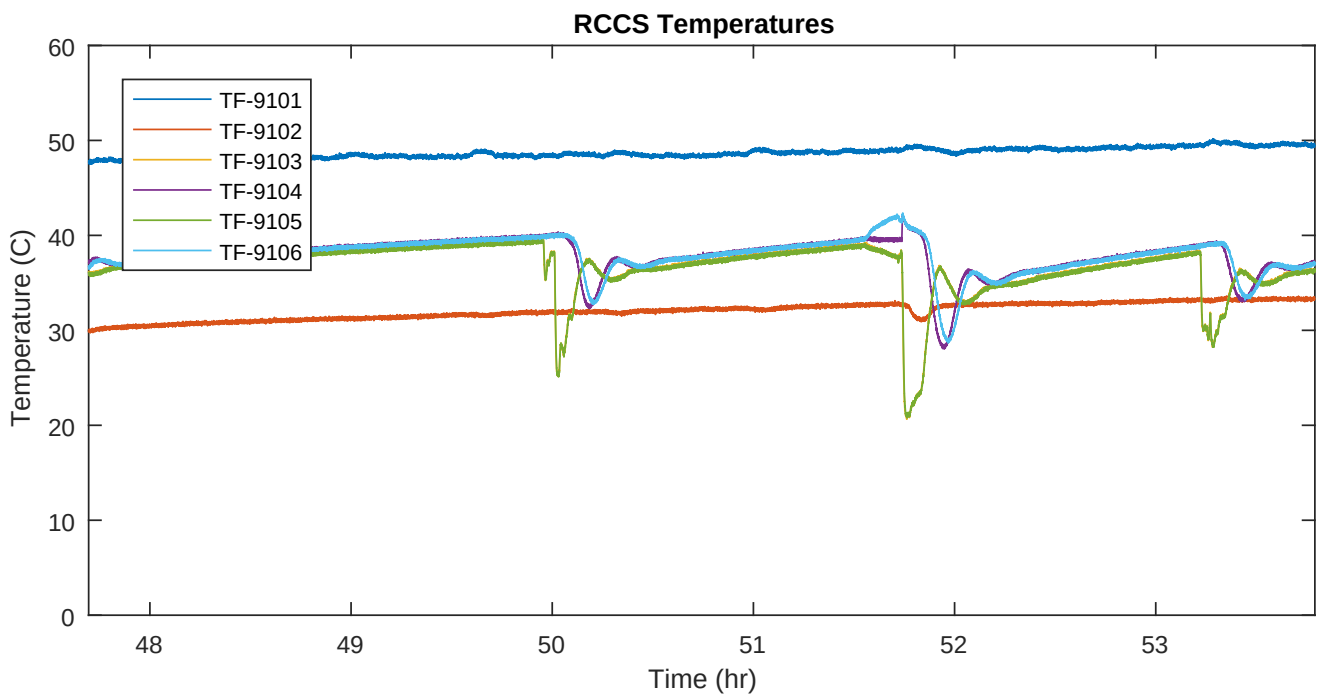

Figure 2.5: Temperatures on the Northeast corner of the RCCS. These are typical of the other three corners.

2.4. Steam Generator Performance

During this test, the steam generator was filled to 70% of its volume before the test. Water was added as needed to maintain the level between 60 and 80%. The control signals are shown in figure 2.6 and the level is shown in figure 2.8. The water inlet flow rate is measured and shown in figure 2.7.

During the test, the SG operated at a steady state pressure of about 170 kPa, see figure 2.9. This steady state pressure provided a SG fluid temperature of about 116 ℃ and the SG temperatures are shown in figure 2.10.

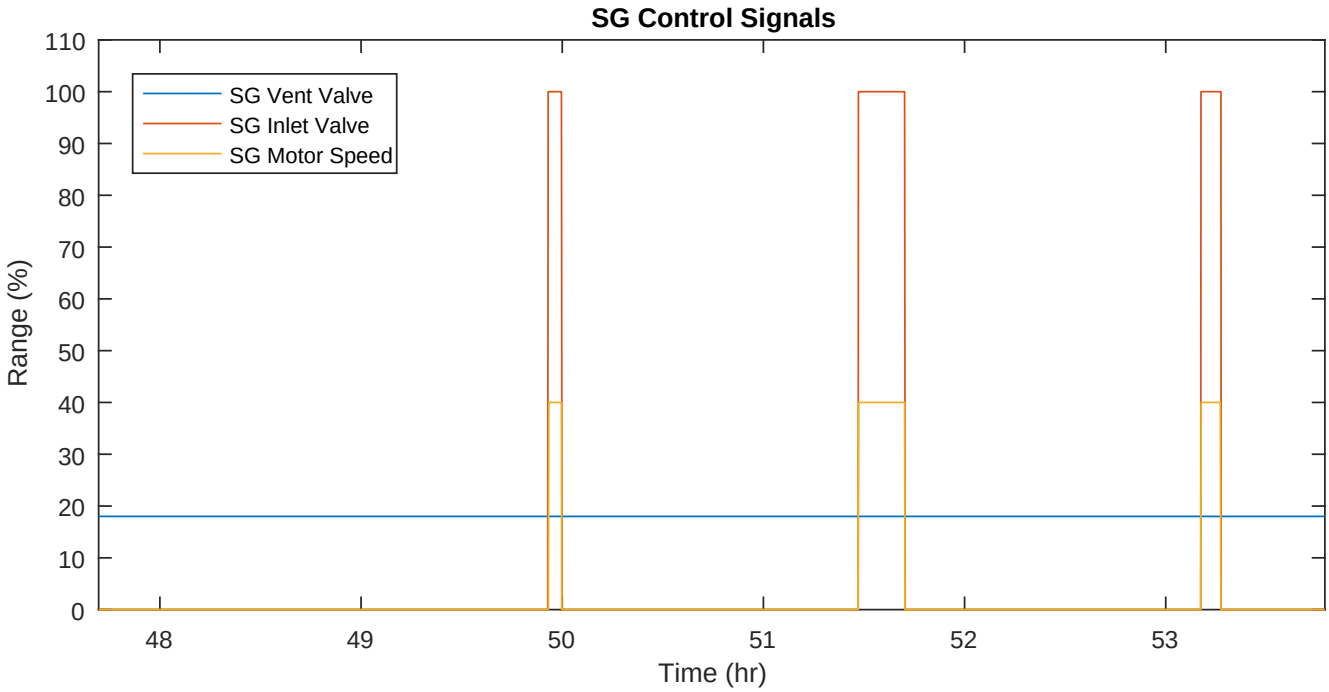

Figure 2.6: Steam Generator control signals: CV-5001 Vent valve position, CV-5002 water inlet valve position, and MS-9001 water inlet pump speed.

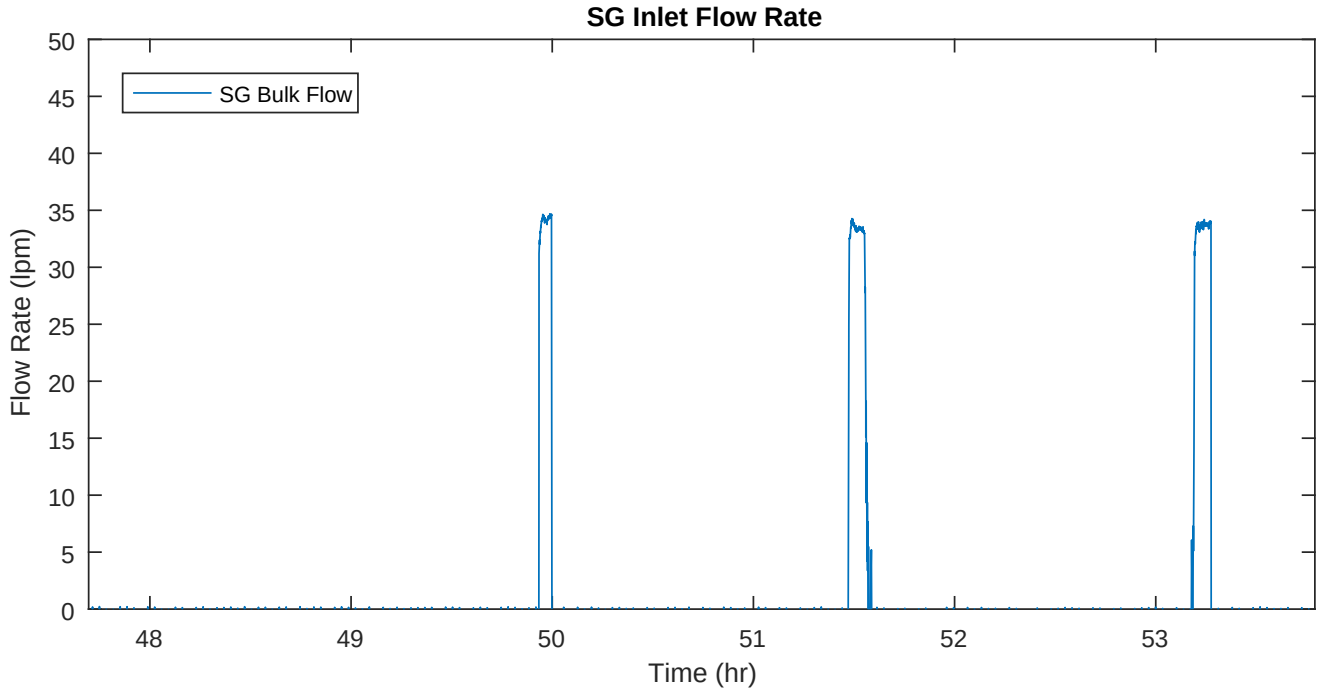

Figure 2.7: Steam Generator inlet flow rate, FT-5001

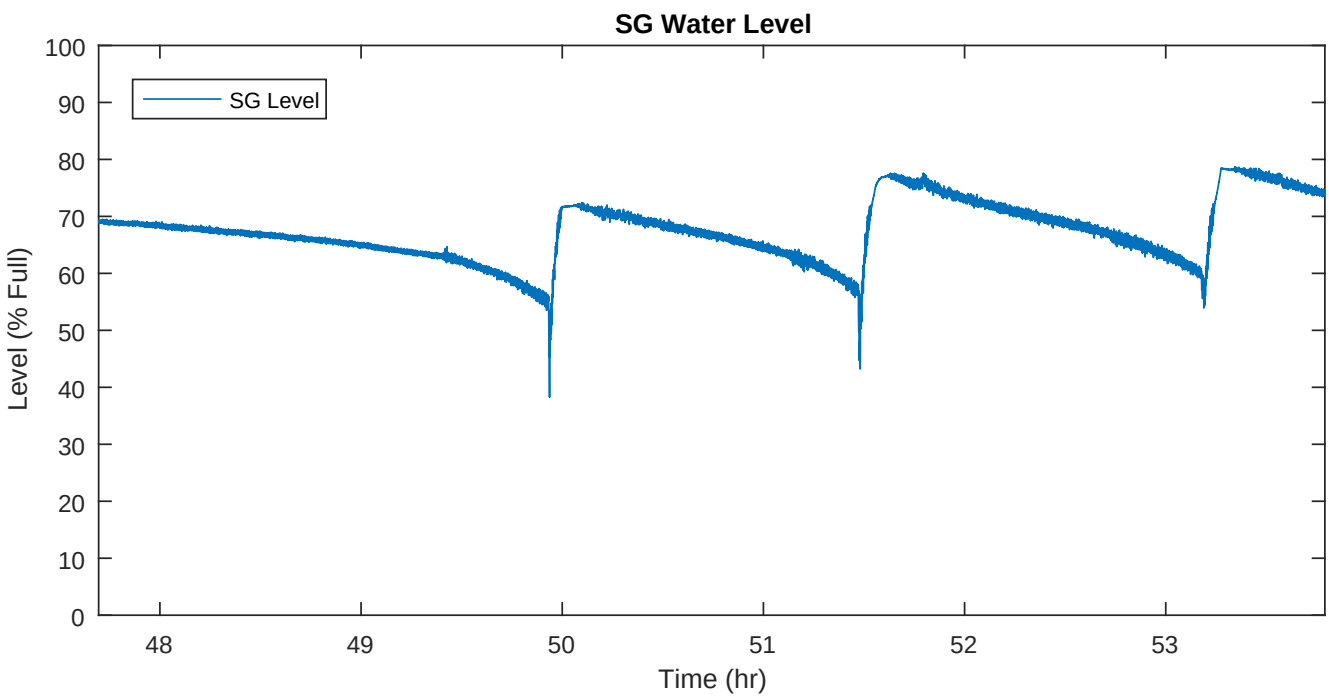

Figure 2.8: Steam Generator Water Level, LF-5002

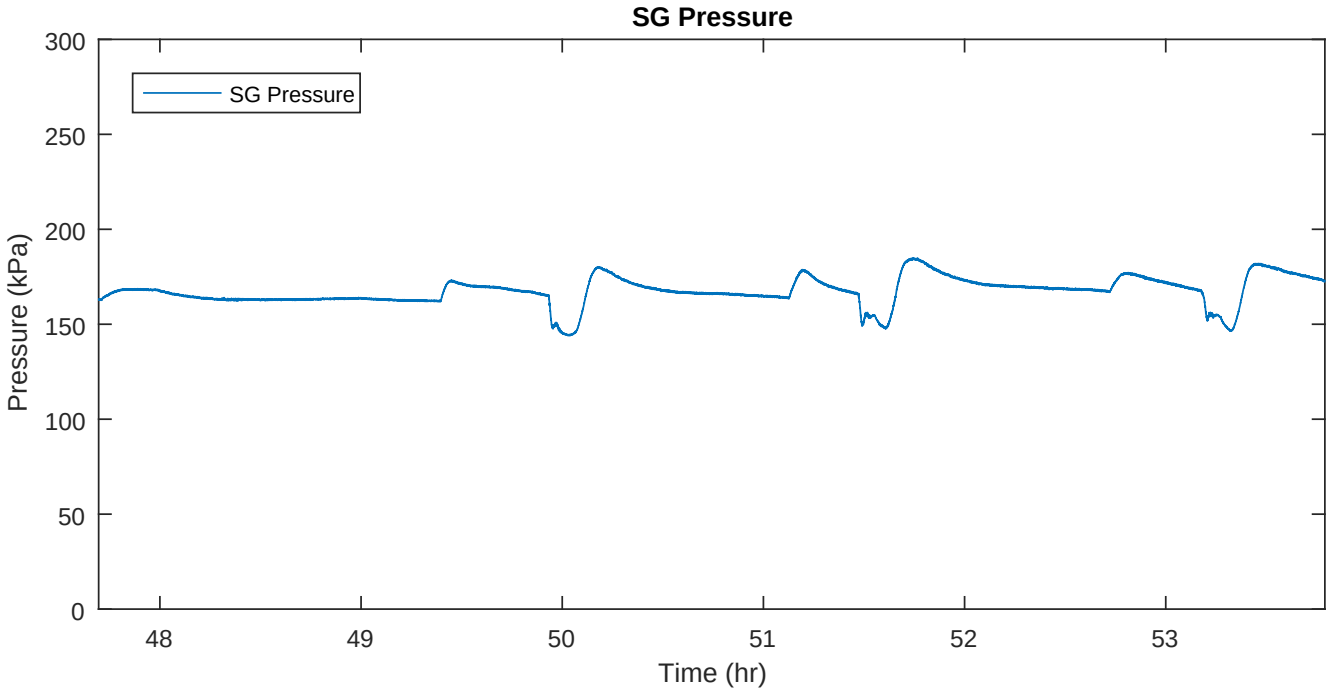

Figure 2.9: Steam Generator Pressure, PT-5001

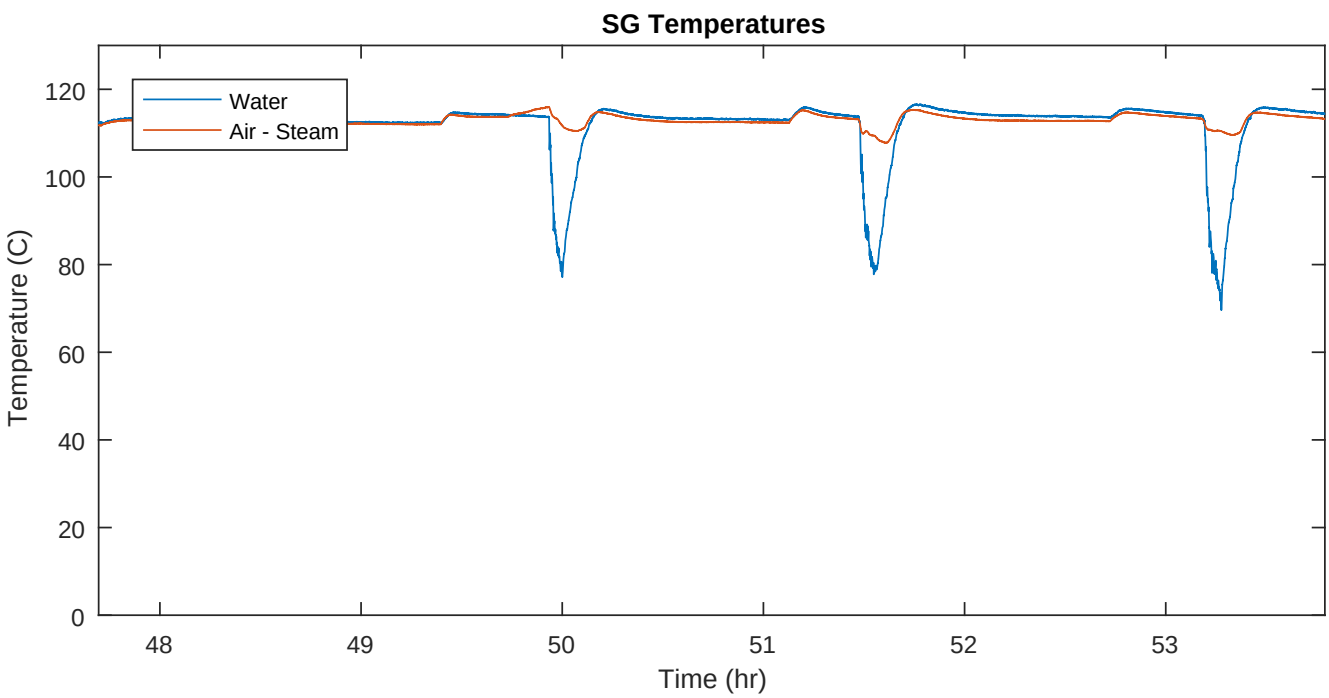

Figure 2.10: Steam Generator Fluid Temperatures, TF-5001 water temperature, TF-5002 air-steam temperature

2.5. Test Results

During the test flow rate was increased three times. The three changes in gas flow rate can be seen in 2.13 as the three sudden changes in differential pressure. With each change in flow there was a significant effect on the temperature of the lower plenum. The measurements from two sets of lower plenum post thermocouples shown in 2.11 and 2.12. In response to each gas flow rate change there was a small sudden change in temperature. From the start of the test until the first gas flow rate change, the lower plenum temperature is relatively stable, increasing only slightly in that time. With the first gas flow rate change, there is an increase both in temperature and the rate of heat increase, with the exception of TF-2411 and TF-2214. As gas flow rate increases, the cooling effect can be seen in the downward trend of the lower plenum temperatures, with higher flowrates correlating to faster cooling.

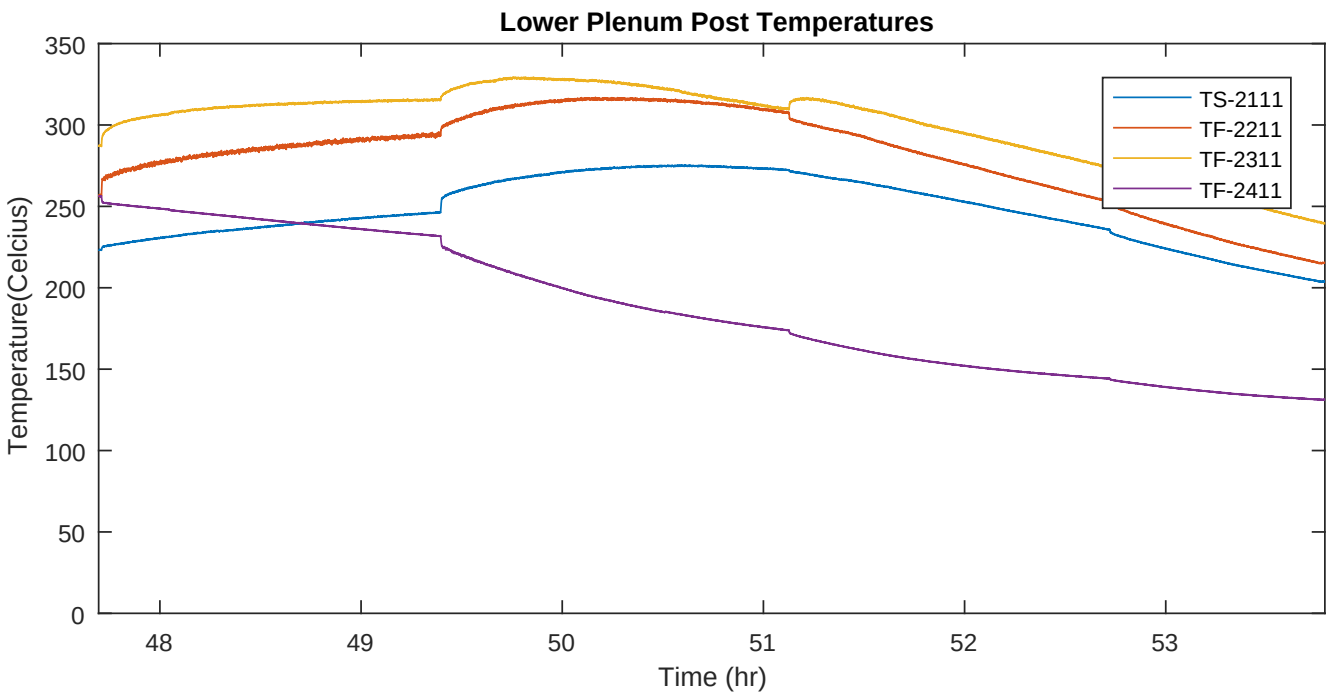

Figure 2.11: Plot of Lower Plenum Post temperatures during the test.

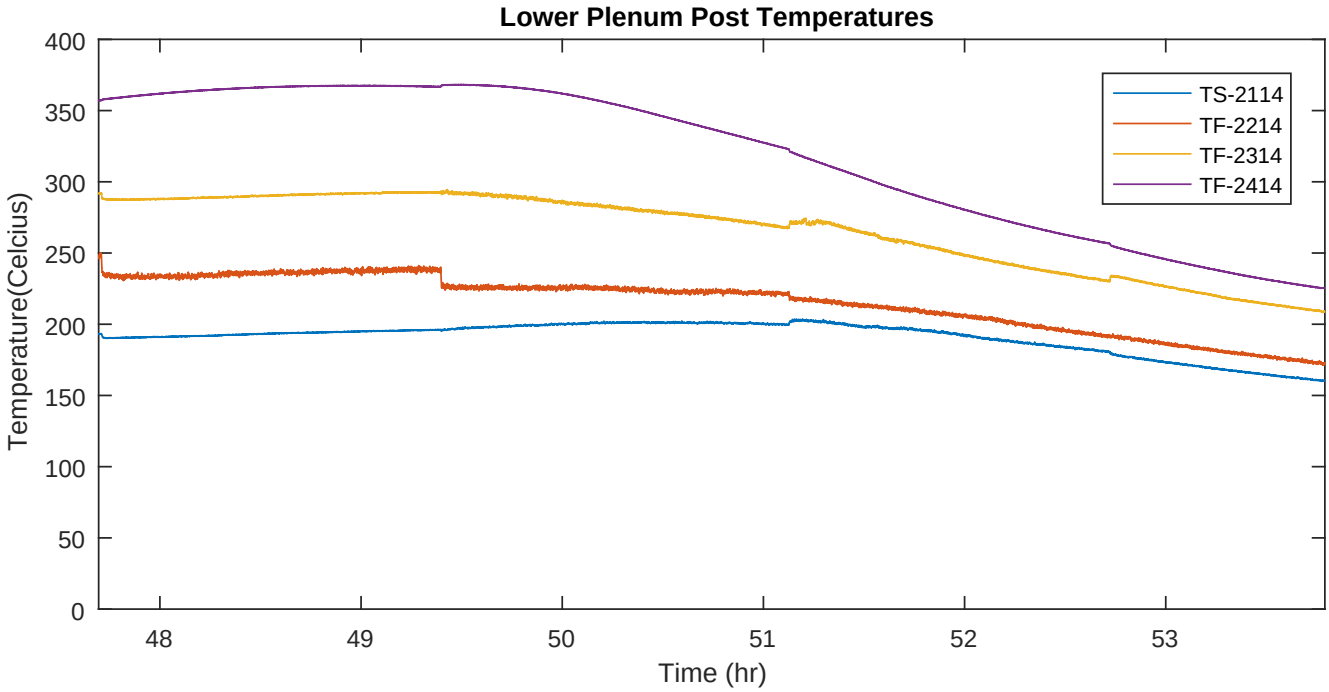

Figure 2.12: Plot of Lower Plenum Post temperatures during the test.

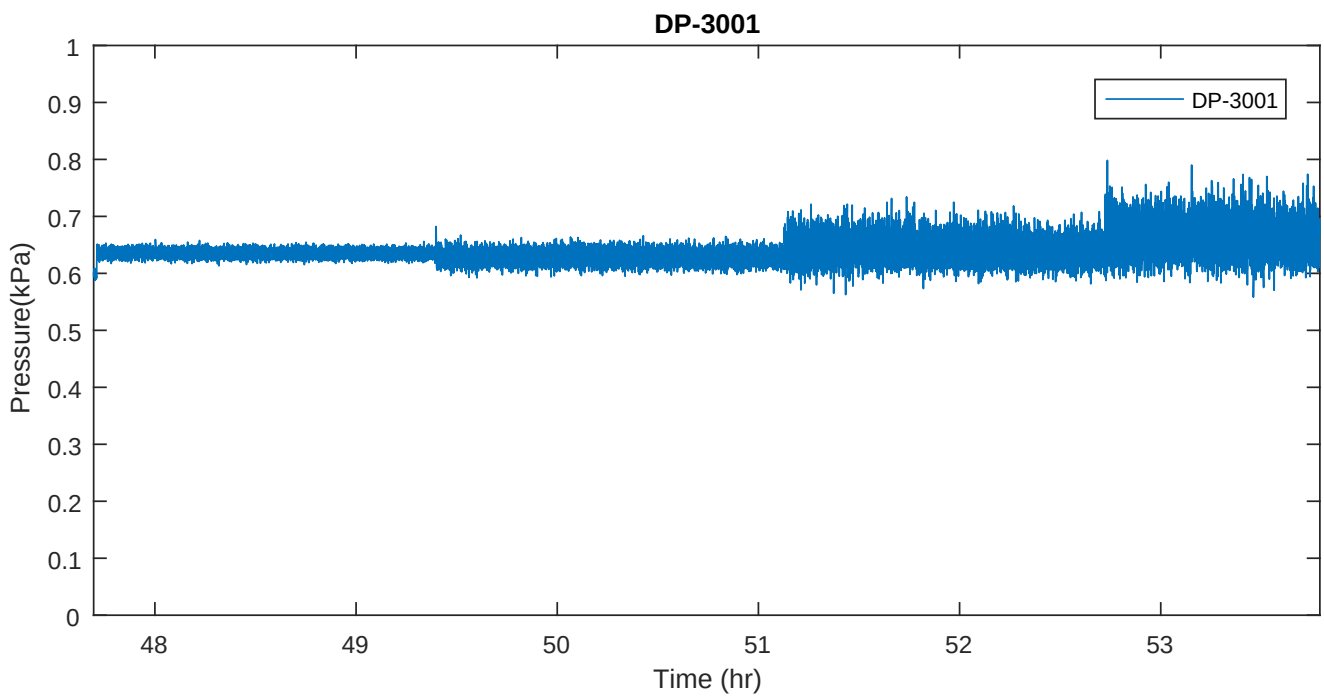

Figure 2.13: Plot of the differential pressure in the hot leg during the test.

The temperature of the core ceramics during this test also shows a significant response to the increases in flow rate. Shown below in 2.14 are the solid core temperatures at position 07 for each odd numbered core block during the test. The first gas flow rate change is clearly visible in the 50th hour as a sharp increase in the rate of cooling for the three central core blocks. As the flow rate increases, an accompanying increase in the cooling rate of core block 1 is visible, while the central core blocks asymptotically approach equilibrium with core block 1.

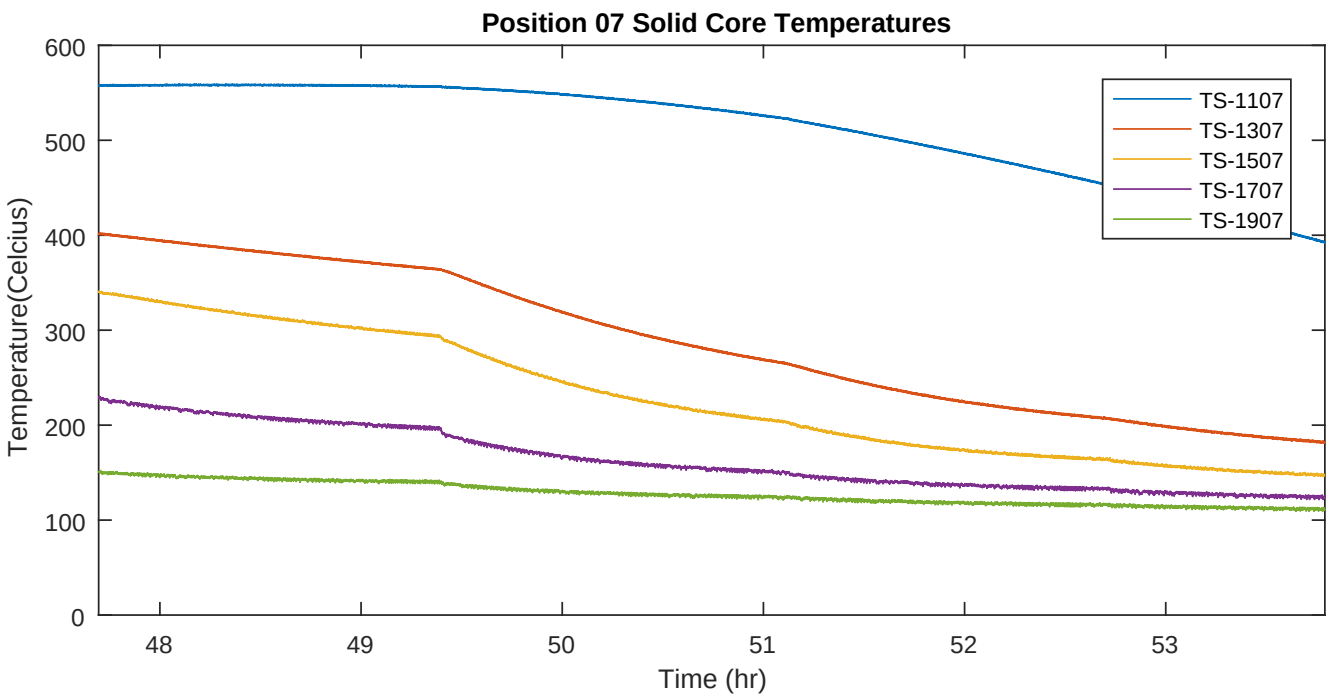

Figure 2.14: Plot of the solid core temperatures at position 07 for odd numbered core blocks.

Chapter 3. PG-29 Low Power (<350kW) Double Ended Inlet-Outlet Crossover Duct Break, Hybrid Heater

The purpose of this test is to examine the progression of the Double Ended Inlet-Outlet Crossover Duct Break transient in an integral test facility scaled to General Atomics' Modular High Temperature Gas Reactor (MHTGR) design. This test is referred to as a Depressurized Conduction Cooldown (DCC). Initial conditions were met using a hybrid heater bank at low power (<350kW). Transient decay power is scaled to the MHTGR. This test began on 7/24/2019 and was completed on 7/26/2019. The facility heatup went as expected, and the Transient Diffusion Phase was initiated in the 81st hour following heatup start. The facility transitioned into the Natural Circulation Phase in the 82nd hour following heatup start, and in the 89th hour following heatup start the electric heaters failed. The RCCS function was stopped at 95 hours and 33 minutes into the test and the heating system was secured. At this time the test was terminated. This test was started and completed in one session, and there is only one data file. In this report the data set, PG28_PG29_A_data, will be presented and discussed. A more detailed discussion of the test that started 7/24/2019 and completing 7/26/2019 follows.

3.1. Initial Conditions

On July 24, 2019, the HTTF operators, Brian Woods, Seth Cadell, and Tommy Moore began to follow the test procedure OSU-HTTF-TEST-029-R0. All members of the testing team were certified as HTTF Test Engineers and were briefed on the purpose of the test before they began operating the facility.

The facility had been conditioned following OSU-HTTF-TEST-028-R0. The facility conditions at the time of the start of the test are presented in Table 9.1. All pumps were secured and the flow rate was zero in each fluid carrying system at the start of the test.

Table 3.1: Initial conditions for the start of the test.

Primary Loop:	>200 kPa helium
RCSS:	<200 kPa nitrogen
Cooling Water System:	filled with water, ambient pressure
Steam Generator:	60 to 80% water level, ambient pressure
RCCS Tank:	filled with water, ambient pressure
RCCS Panels:	filled with water, ambient pressure

3.2. Heater Operation

The heater was operated during the entire test. Heater bank 104 was operated, where the power output started at 25kW reached a peak of more than 40 kW. The heater controllers do not possess any feedback mechanism, so the power requested (figure 3.2) is not identical to the measured power (figure 3.1). The operators were instructed to watch the measured power and to control HO-103/104 on these readings.

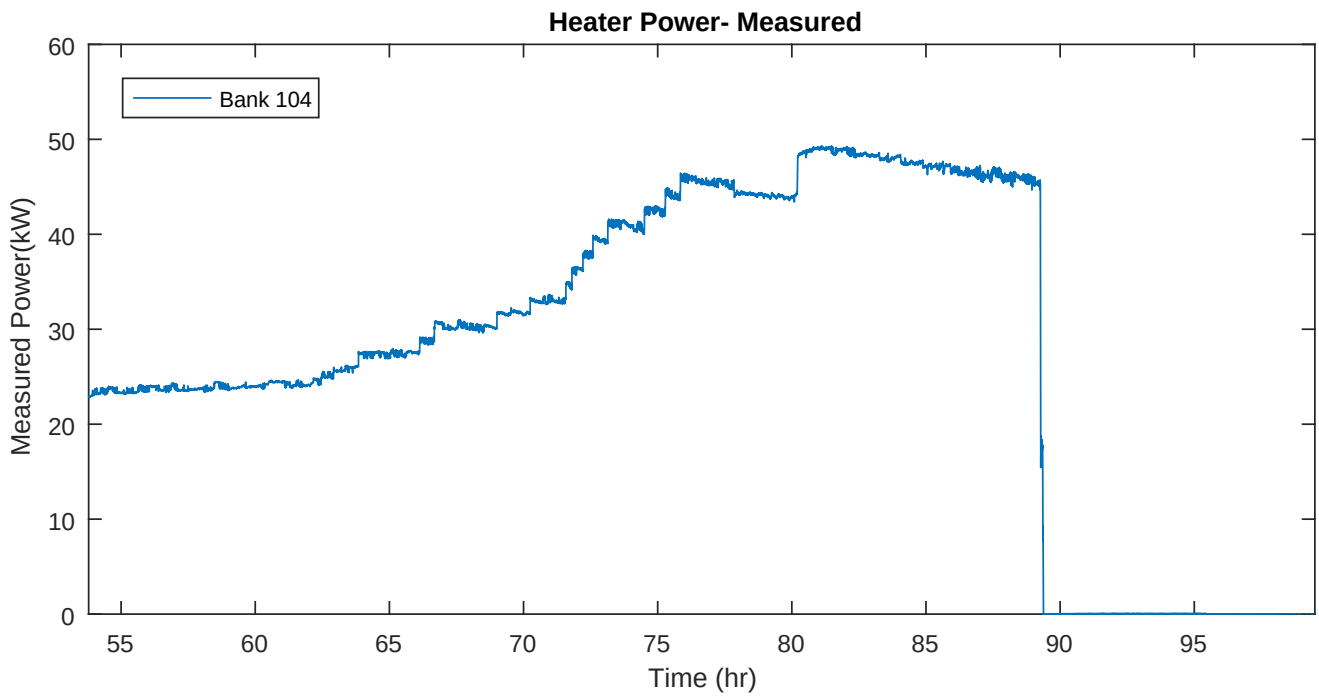

Figure 3.1: Measured heater power output on channels HO-103/104

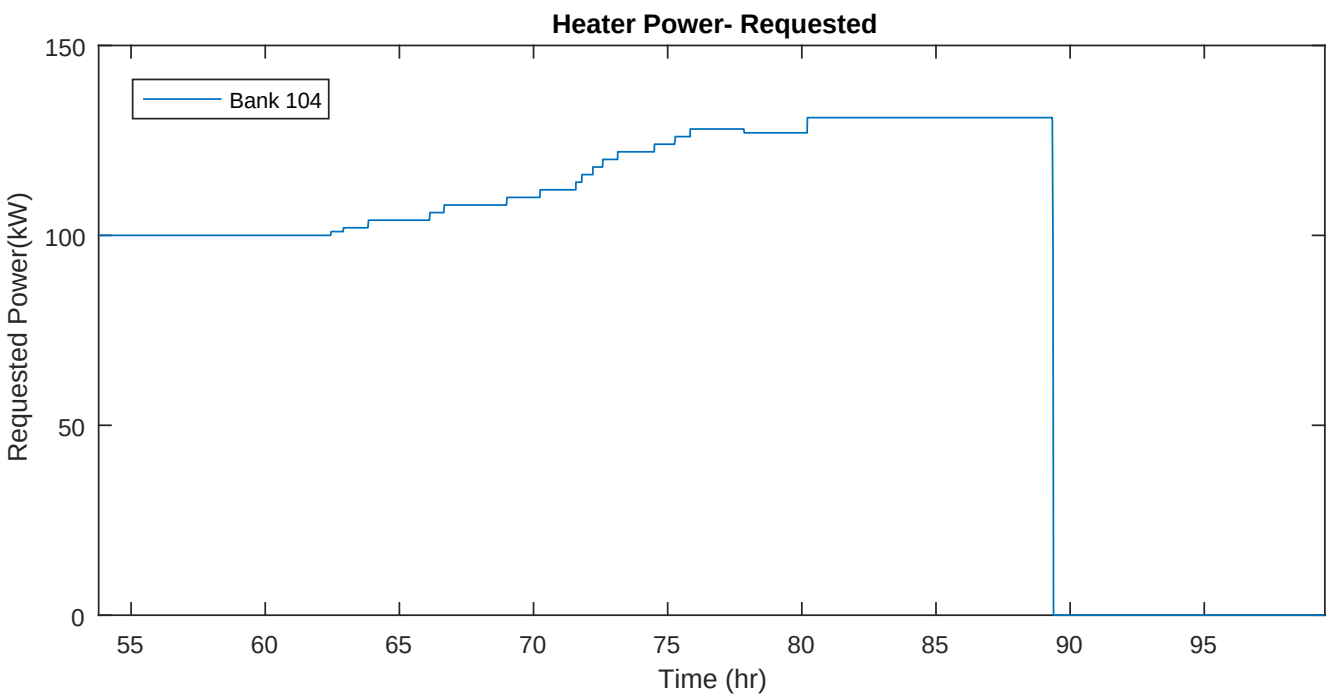

Figure 3.2: Requested heater power output on channels HO-103/104

3.3. Reactor Cavity Cooling System

The RCCS panels were operated consistently at 30% motor speed for the duration of this test.

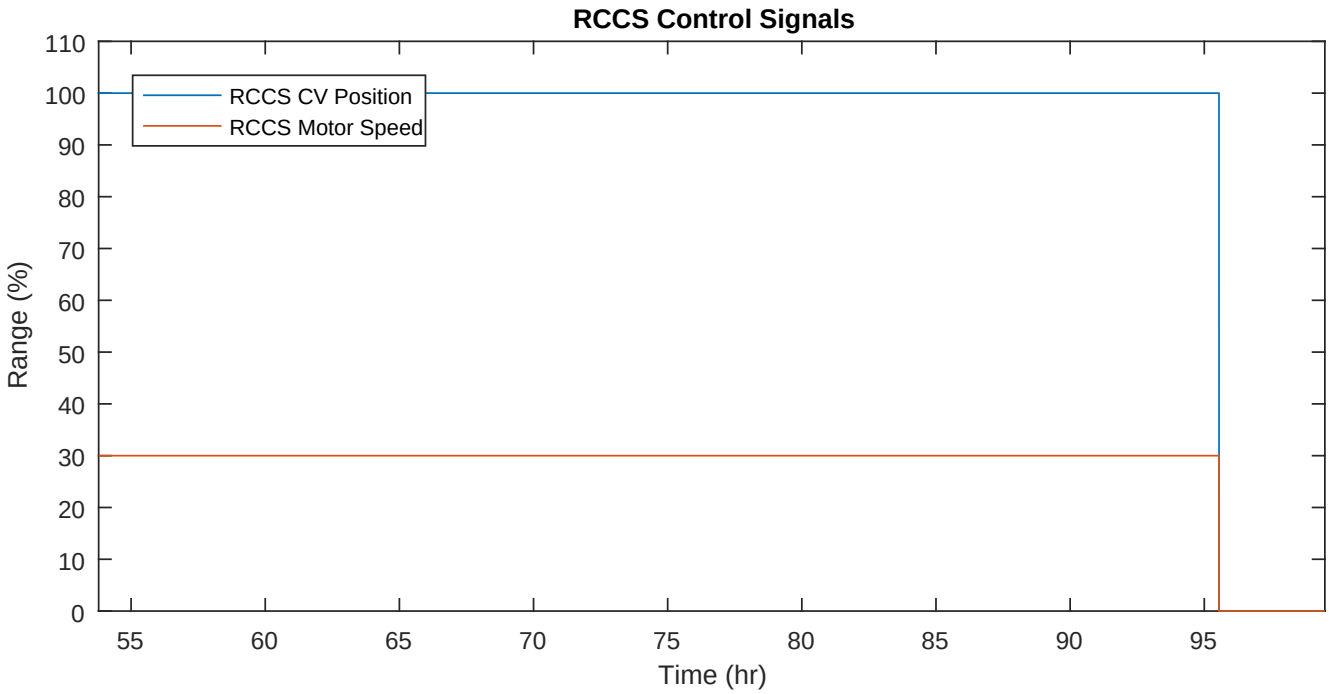

Figure 3.3: RCCS Control signals: MS-9001 and CV-9001

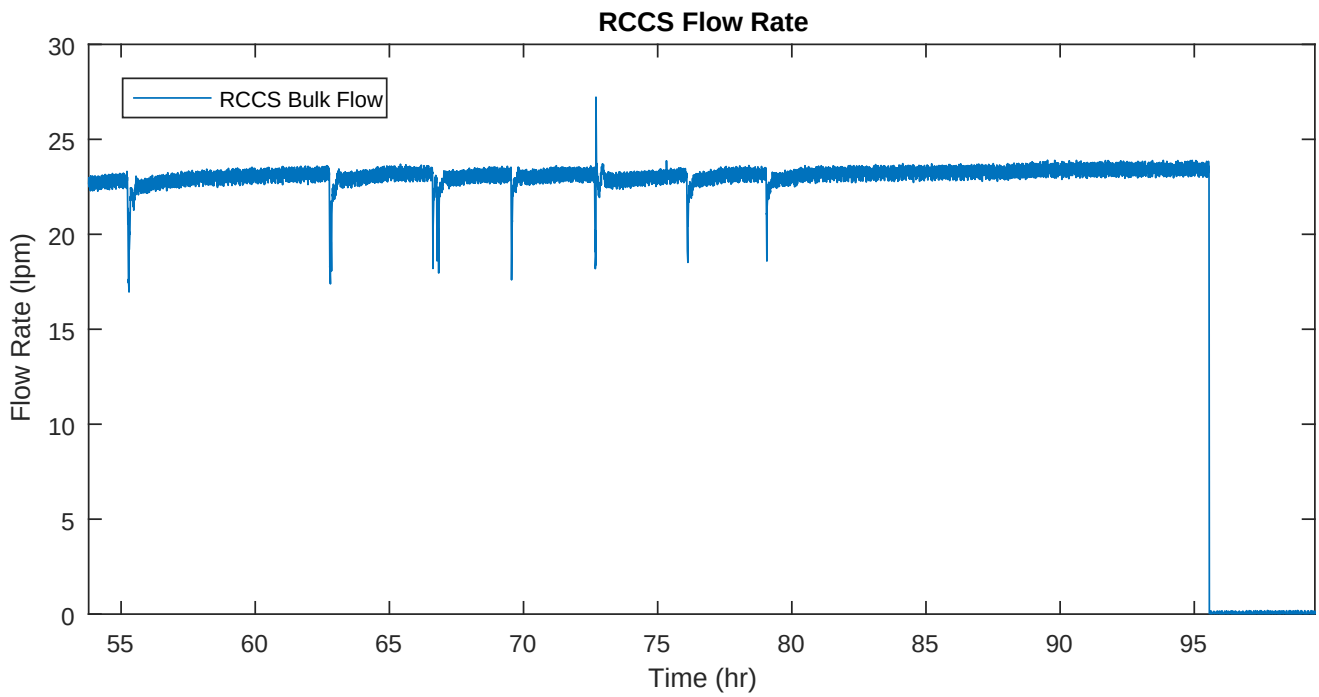

Figure 3.4: RCCS flow rate during the test.

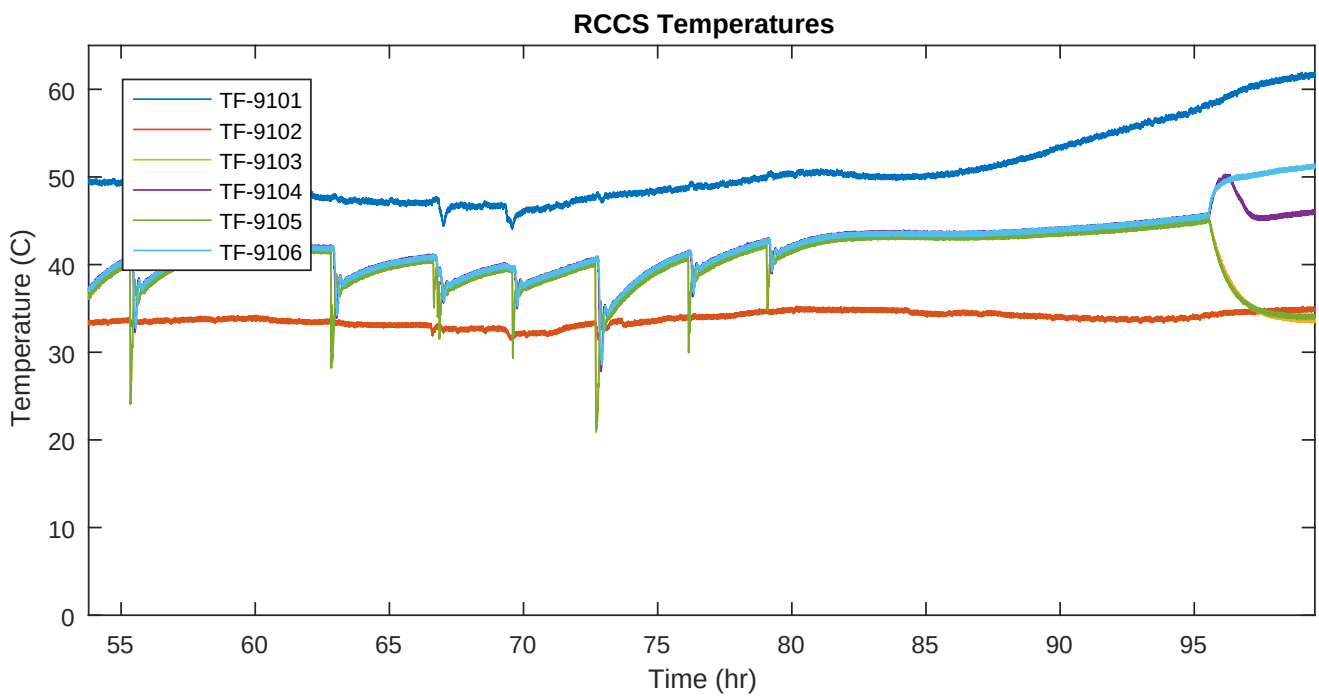

Figure 3.5: Temperatures on the Northeast corner of the RCCS. These are typical of the other three corners.

3.4. Steam Generator Performance

During the previous test, the steam generator was filled to 75% of its volume before the test. Water was added as needed to maintain the level between 60 and 80%. The control signals are shown in figure 3.6 and the level is shown in figure 3.8. The water inlet flow rate is measured and shown in figure 3.7.

During the test, he SG pressure settled to a steady state pressure of about 170 kPa, see figure 3.9. This steady state pressure provided a SG fluid temperature of about 118 ℃ and the SG temperatures are shown in figure 3.10.

After the DCC was initiated, the SG was allowed to cool down and ended the test in the wet layup state.

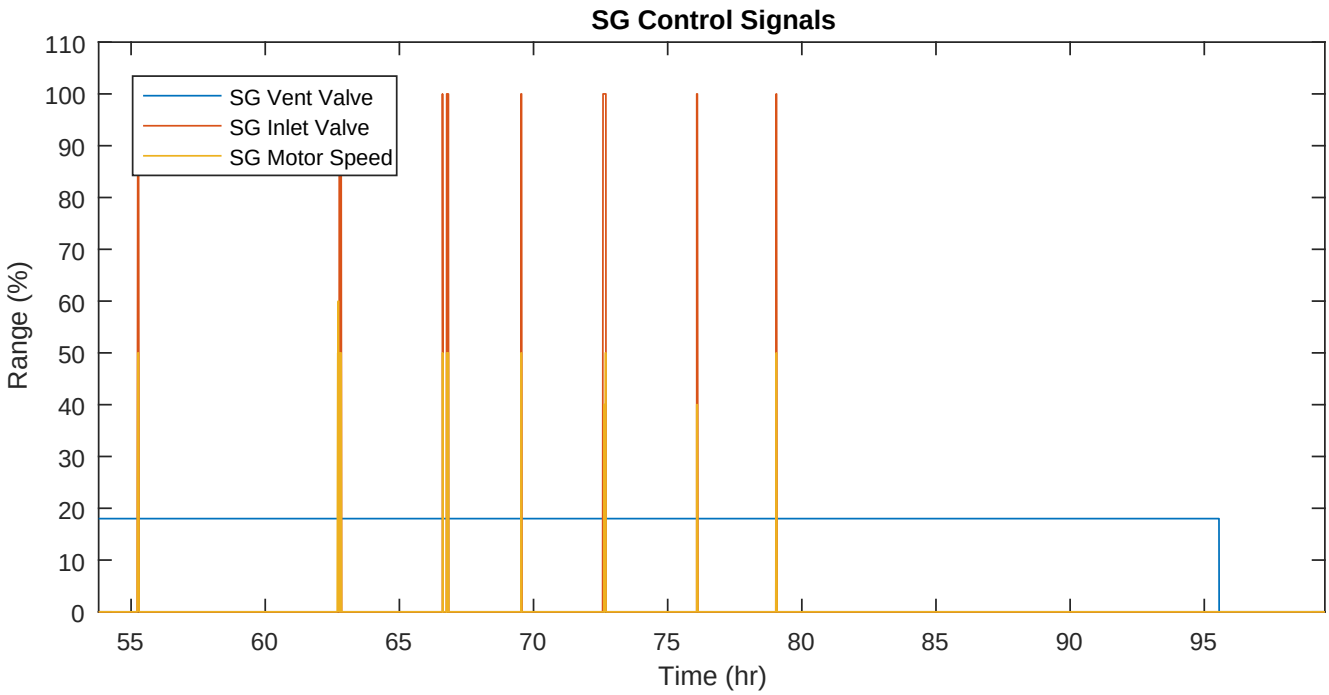

Figure 3.6: Steam Generator control signals: CV-5001 Vent valve position, CV-5002 water inlet valve position, and MS-9001 water inlet pump speed.

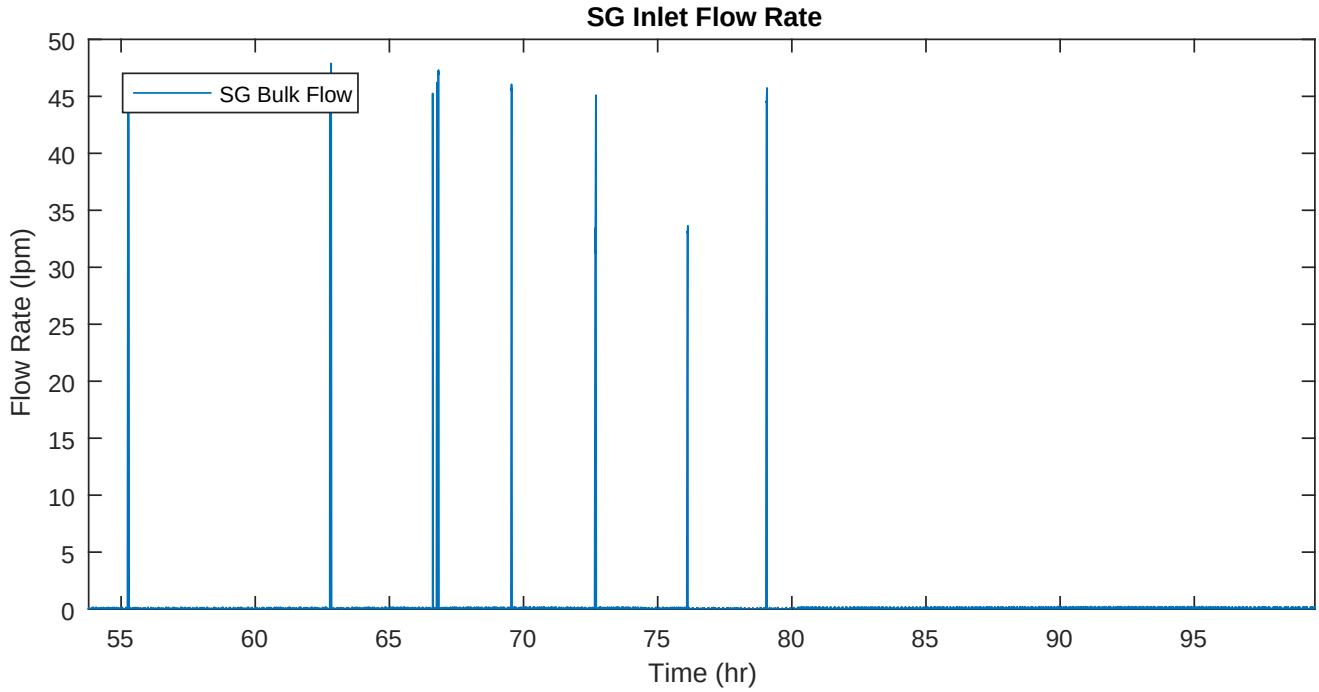

Figure 3.7: Steam Generator inlet flow rate, FT-5001

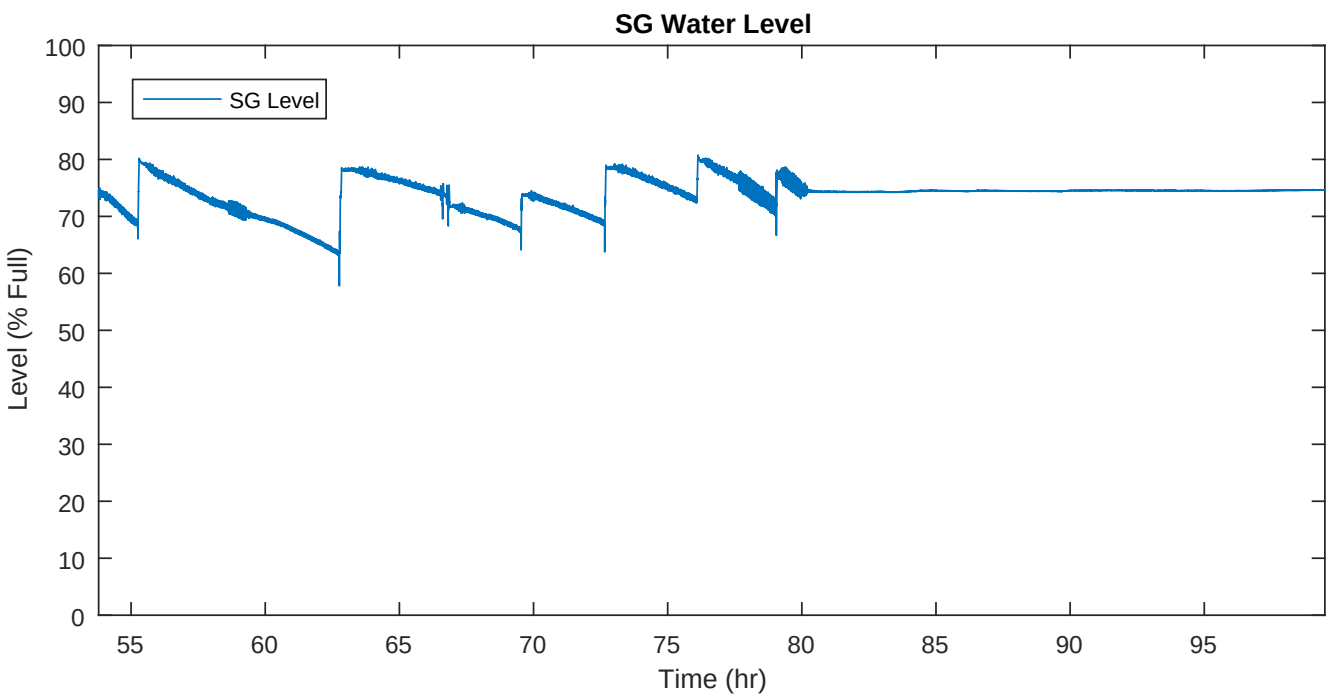

Figure 3.8: Steam Generator Water Level, LF-5002

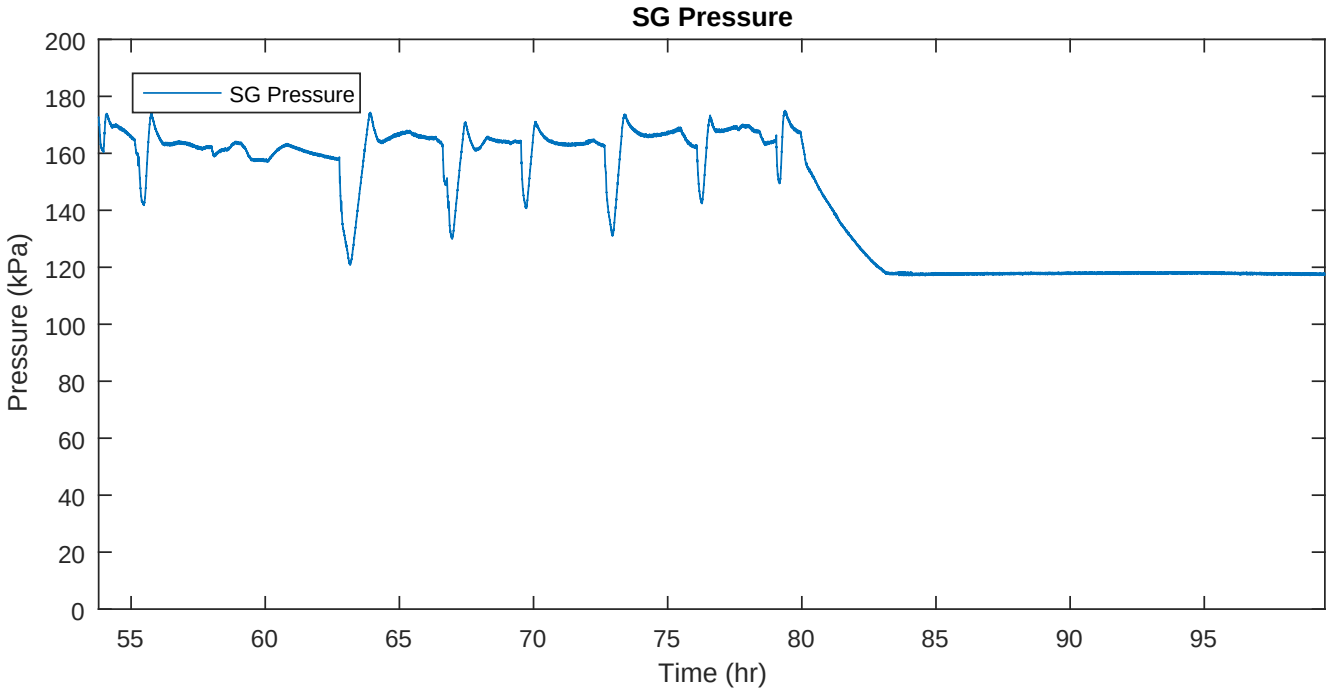

Figure 3.9: Steam Generator Pressure, PT-5001

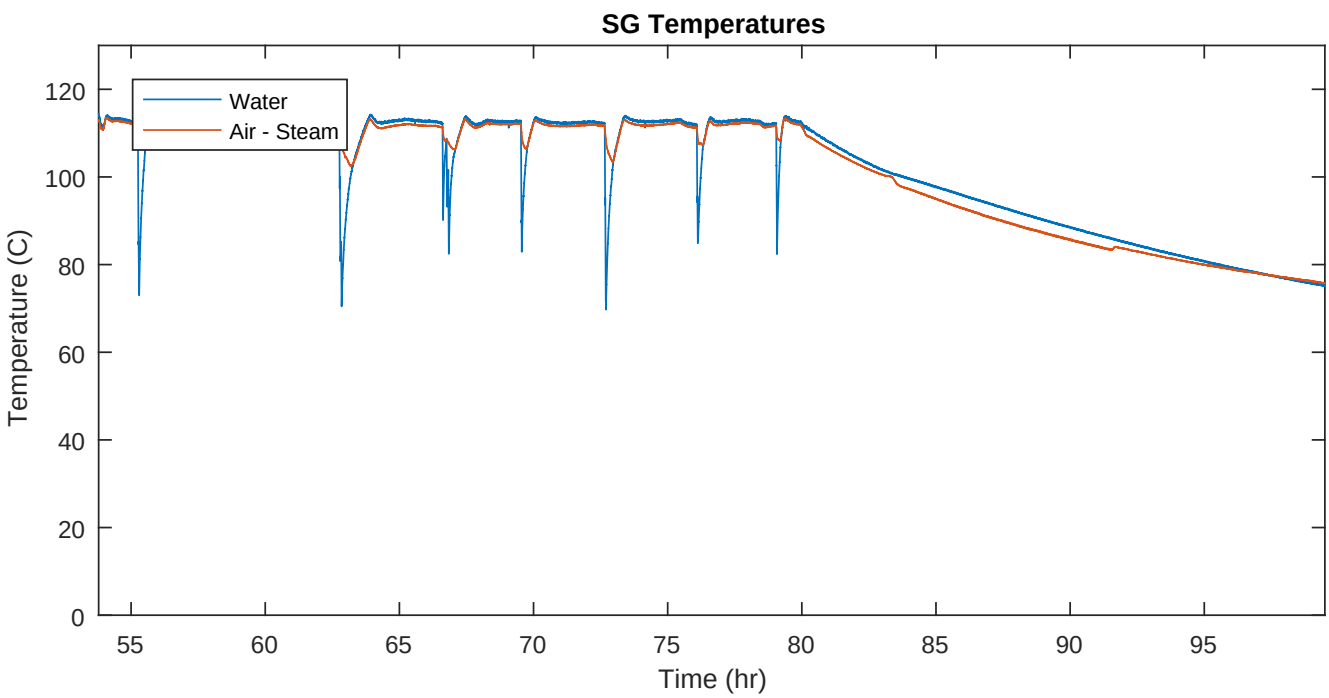

Figure 3.10: Steam Generator Fluid Temperatures, TF-5001 water temperature, TF-5002 air-steam temperature

3.5. Test Results

After SV-3001 and SV-6001 were opened, the hot helium flowed into the RCST as the cold nitrogen flowed into the primary loop. The gases flowed in a counter current fashion, where the top half of the hot duct contained hot helium flowed in one direction and cold nitrogen flowed in the other direction in the bottom half of the duct. This can be seen in Figure3.12, where after hour 80 the measurements of TF-3202 and TF-3203 are shown to increase. These two thermocouples are in the middle and upper regions of the ducts. In contrast, TF-3201 shows a decrease as it is in the lower section of the hot leg.

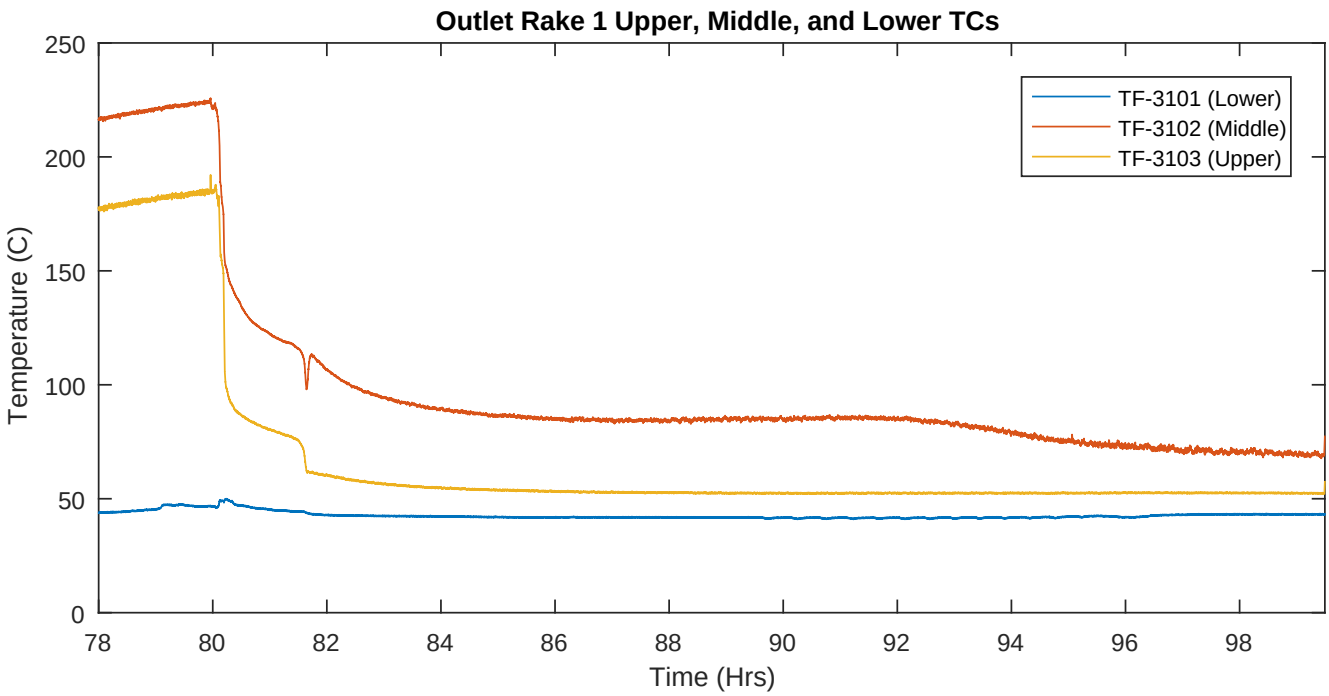

Figure 3.11: Plot of the Hot leg's Rake 1 Thermocouples starting in the 79th hour of the test, TF-310X

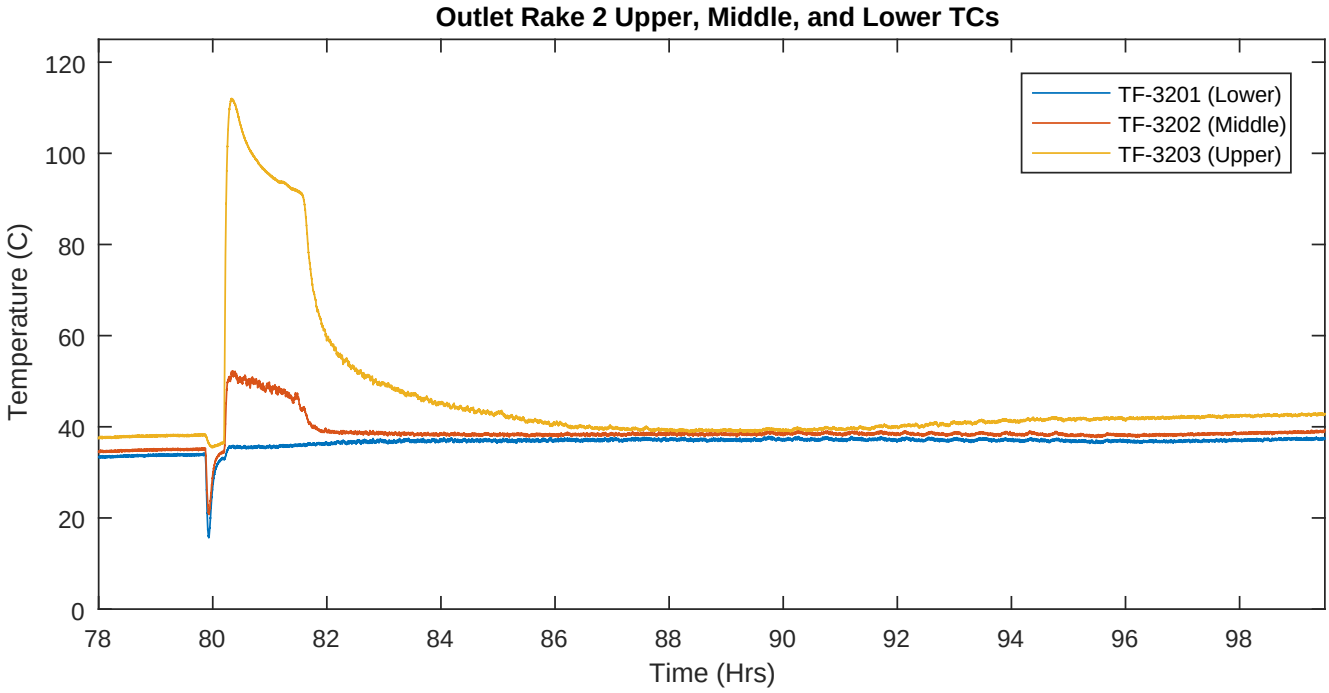

Figure 3.12: Plot of the Hot leg's Rake 2 Thermocouples starting in the 79th hour of the test, TF-320X

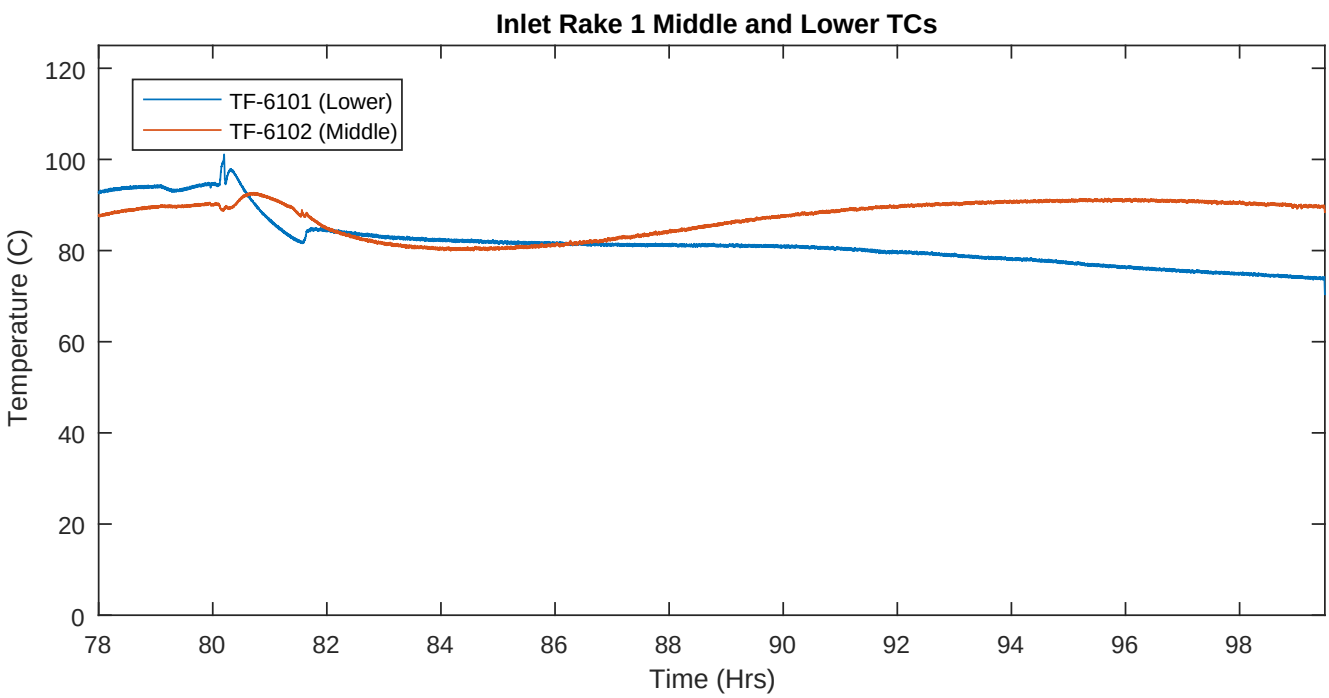

Figure 3.13: Plot of the Cold leg's rake 1 Thermocouples starting in the 79th hour of the test, TF-610X

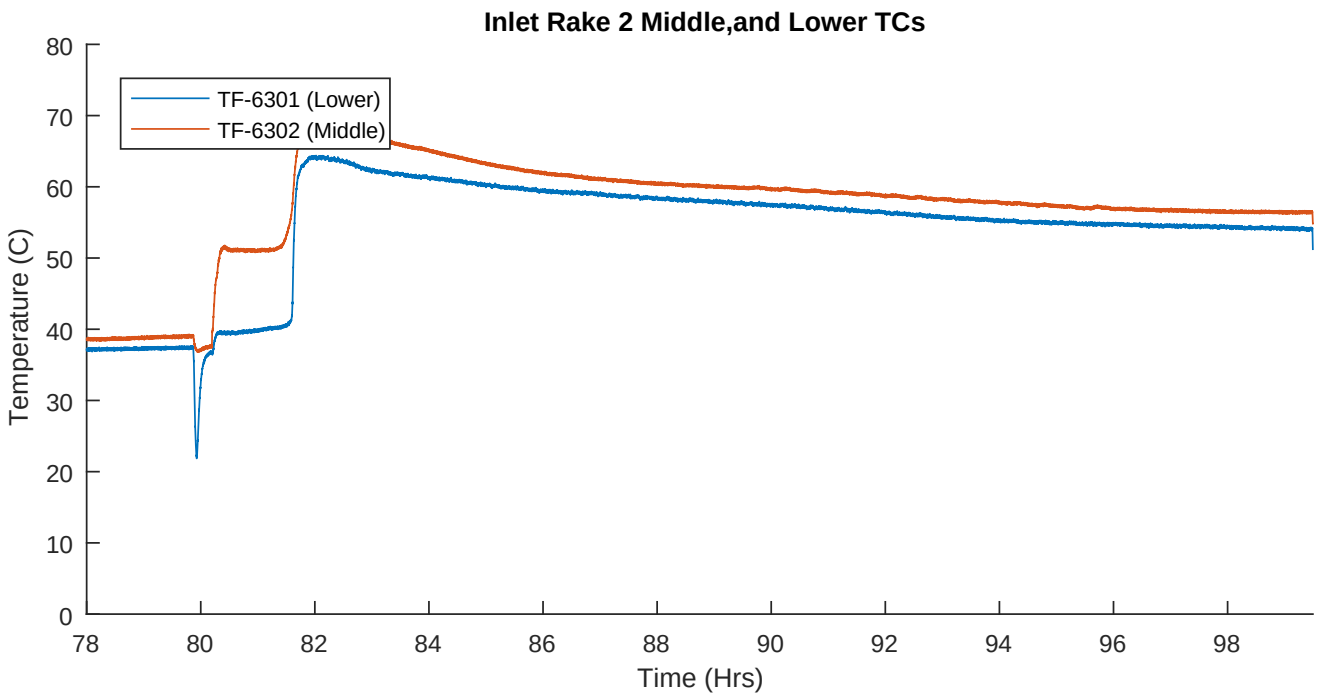

Figure 3.14: Plot of the Cold leg's rake 2 Thermocouples starting in the 79th hour of the test, TF-630X

The upcomer region sees disturbance between the opening of SVs-3001 and 6001 and hour 82 of the test. After hour 82 the temperatures rise and level out smoothly. This region does not see significant deviation in the temperature stratification patterns from before and after the DCC.

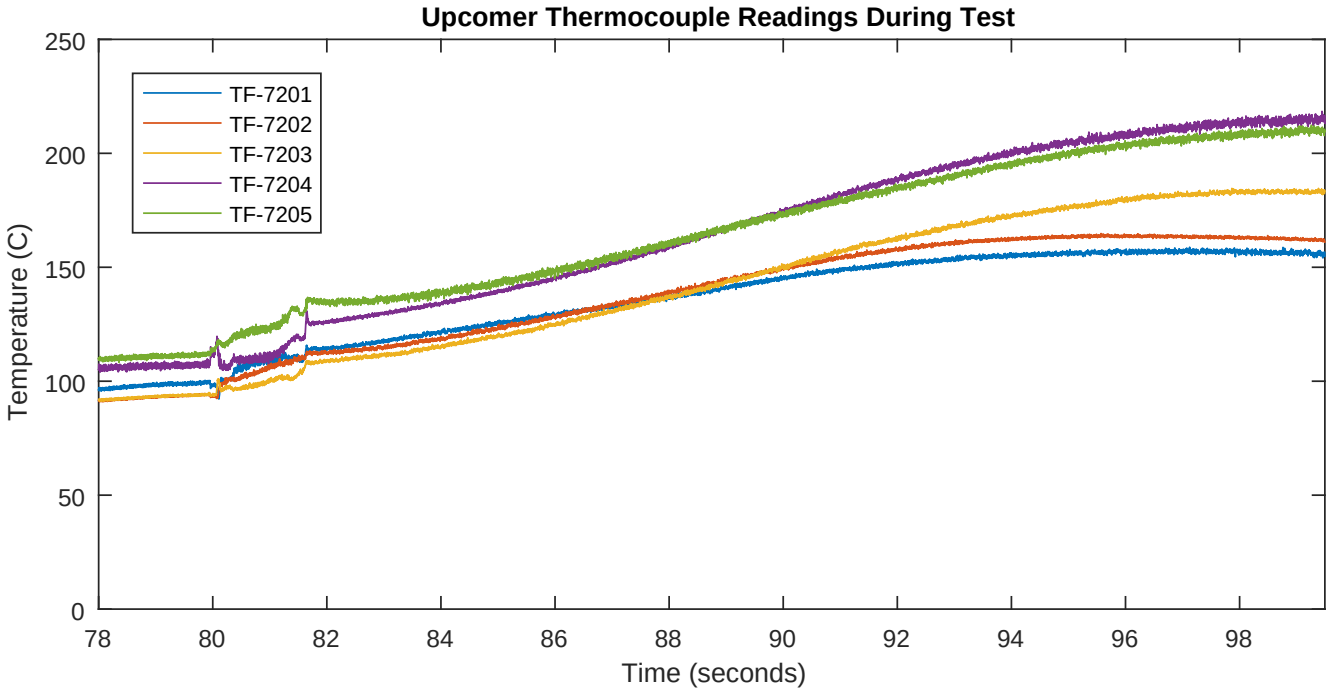

Figure 3.15: Plot of the Upcomer Thermocouples starting in the 79th hour of the test, TF-720X

The Upper Plenum sees a small drop in temperature when SV-3001 and SV-6001 are opened, leveling out after approximately two hours and rising from hour 82 onward. The upper plenum appears to be well mixed as there is little to no temperature difference between the upper and lower regions.

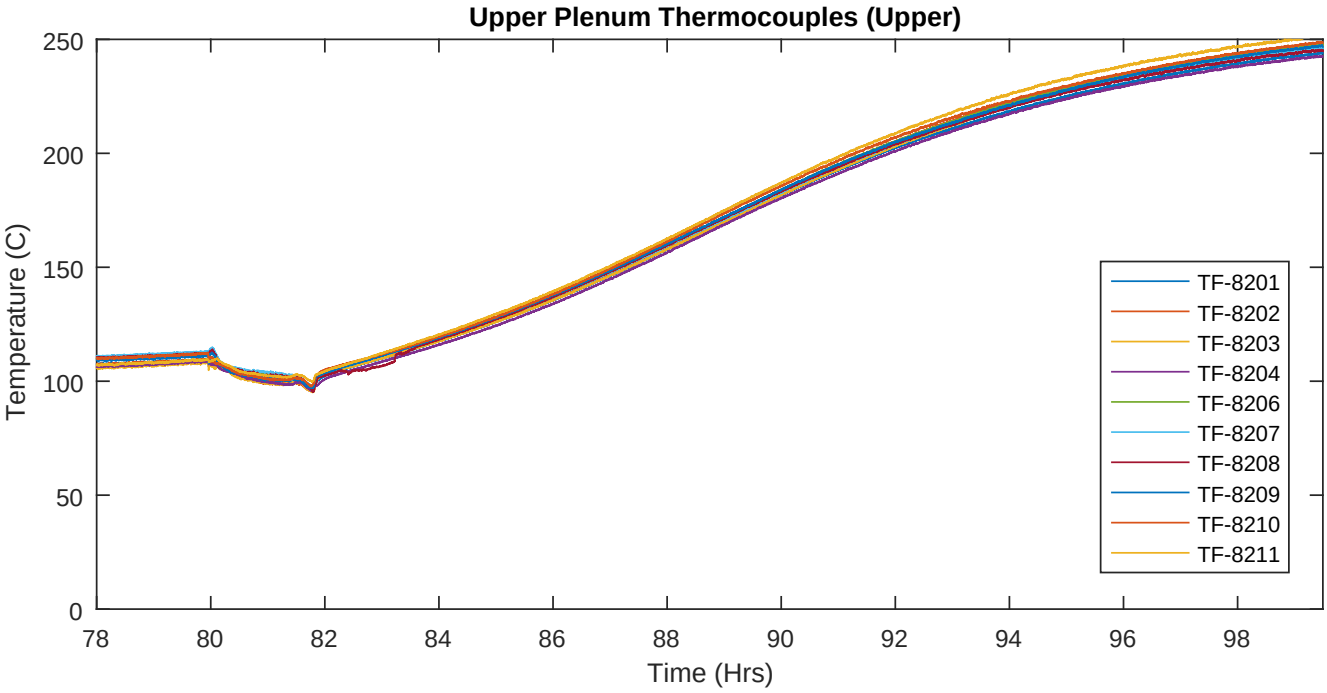

Figure 3.16: Plot of the Upper Plenum's Upper Thermocouples starting in the 79th hour of the test, TF-720X

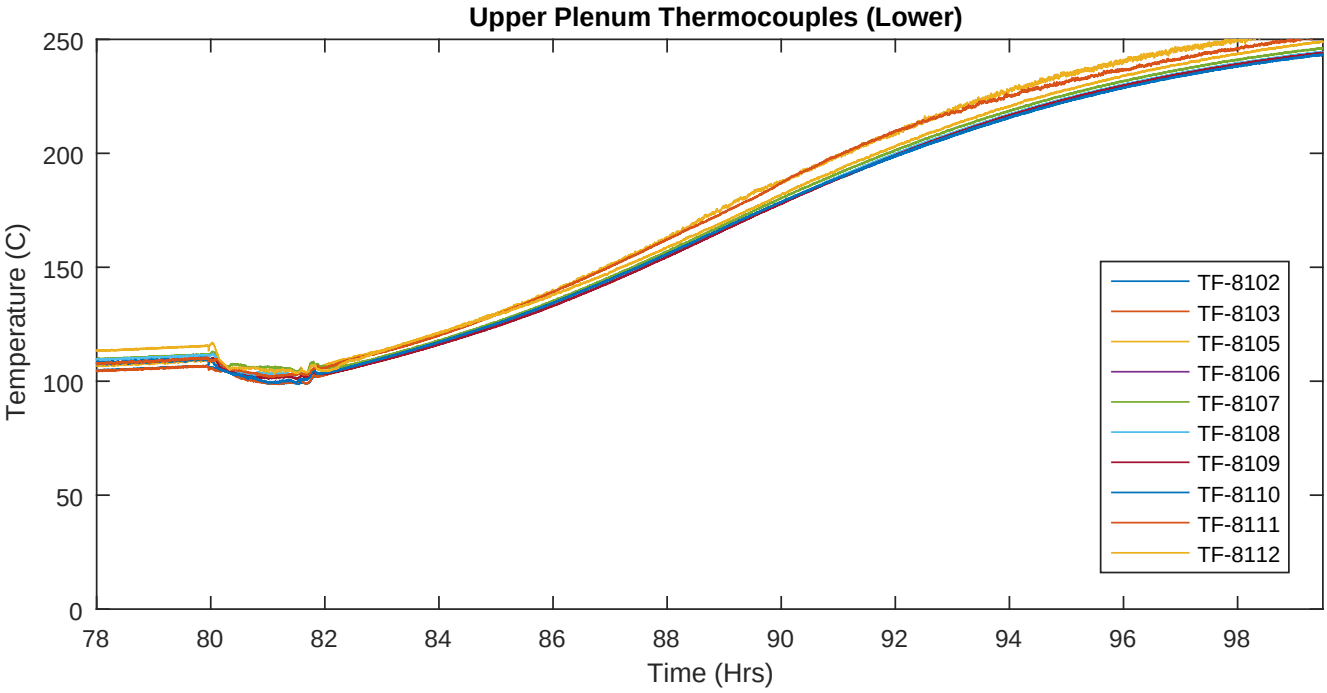

Figure 3.17: Plot of the Upper Plenum's Lower Thermocouples starting in the 79th hour of the test, TF-720X

When SV-3001 and SV-6001 were opened, the RCST temperatures dropped uniformly to approximately 20℃. The temperatures then stratified with clearly defined separations between the lower, mid, and upper regions of the RCST with increasing temperatures in each region.

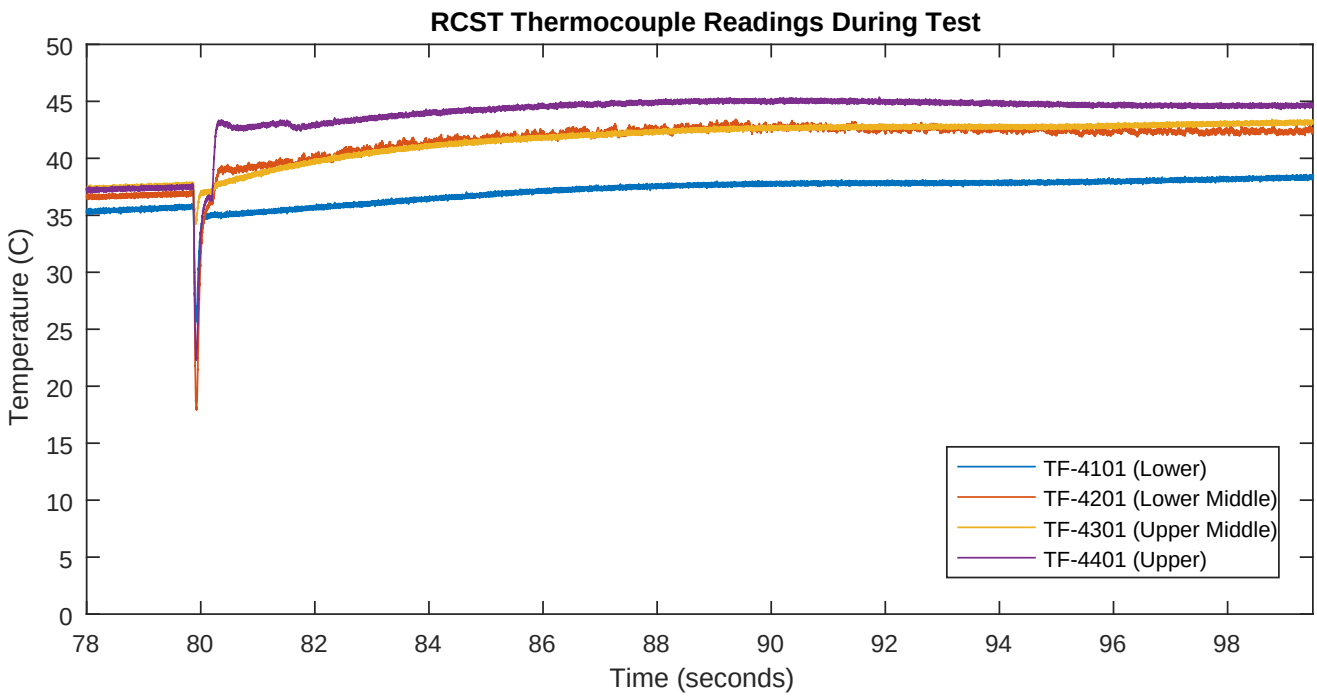

Figure 3.18: Plot of the RCST's Thermocouples starting in the 79th hour of the test, TX-4X01

Chapter 4. PG-32 Low Power (<350kW) Asymmetric Core Heatup

The purpose of this test is to examine the facility heatup under asymmetric heating conditions in an integral test facility scaled to General Atomics' Modular High Temperature Gas Reactor (MHGTR) design. Initial conditions will be met using low power (<350kW) with a partial heater bank. This test will terminate when the facility has reached hot standby conditions.

This test began on 8/28/2019 and was completed on 8/29/2019. This test was started and completed in one session, and there is only one data file. In this report the data set, PG32_data, will be presented and discussed. A more detailed discussion of the test that started 8/28/2019 and completing 8/29/2019 will be presented.

4.1. Initial Conditions

On August 28th, 2019, the HTTF was energized and operators Brian Woods, Tommy Moore, and Ben Nakhnikian-Weintraub began to follow the test procedure OSU-HTTF-TEST-032-R0. All members of the testing team were certified as HTTF Test Engineers and were briefed on the purpose of the test before they began operating the facility.

The facility had been conditioned prior to the test following OSU-HTTF-O&M-010-R2. The facility conditions at the time of the start of the test are presented in Table 9.1. All pumps were secured and the flow rate was zero in each fluid carrying system at the start of the test.

Table 4.1: Initial conditions for the start of the test.

Primary Loop:	>200 kPa helium
RCSS:	<200 kPa nitrogen
Cooling Water System:	filled with water, ambient pressure
Steam Generator:	60 to 80% water level, ambient pressure
RCCS Tank:	filled with water, ambient pressure
RCCS Panels:	filled with water, ambient pressure

4.2. Heater Operation

The heaters were operated during the entire test. Heater bank 104 was operated, where the power output began at approximately 10kW, and was increased steadily during testing to a peak final power of approximately 30kW.

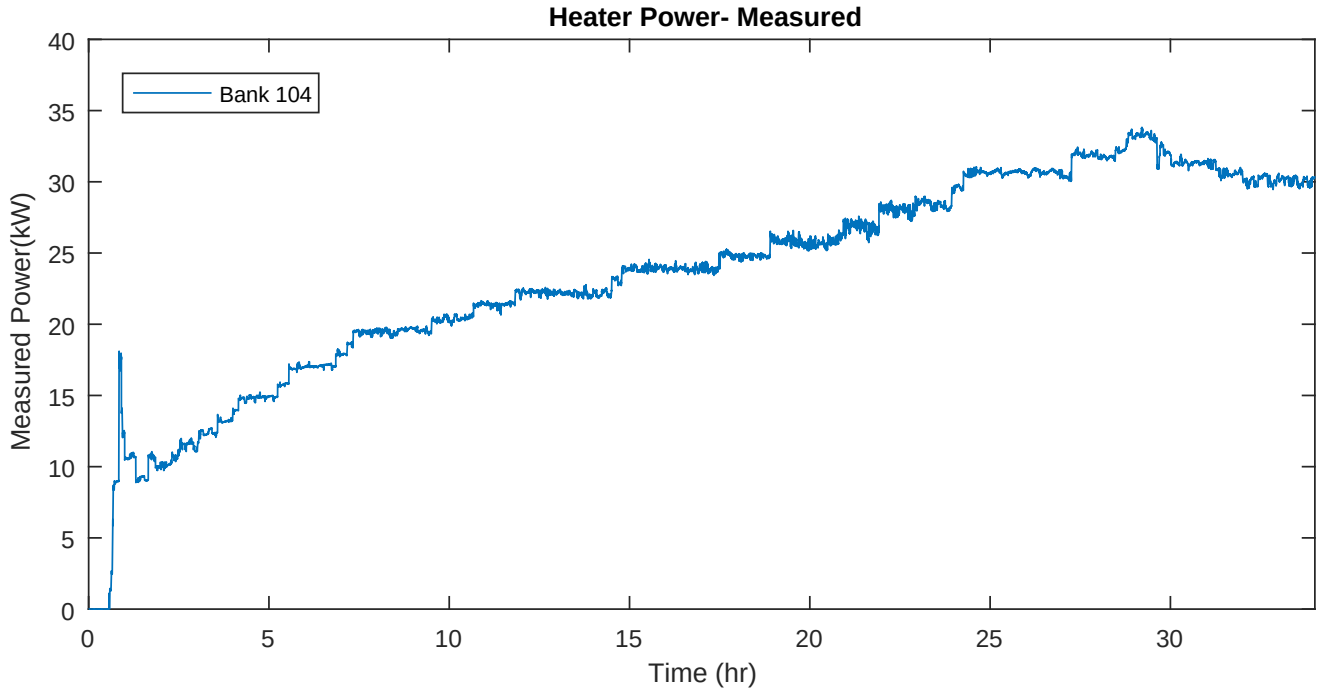

Figure 4.1: Measured heater power output on channel HO-103/104

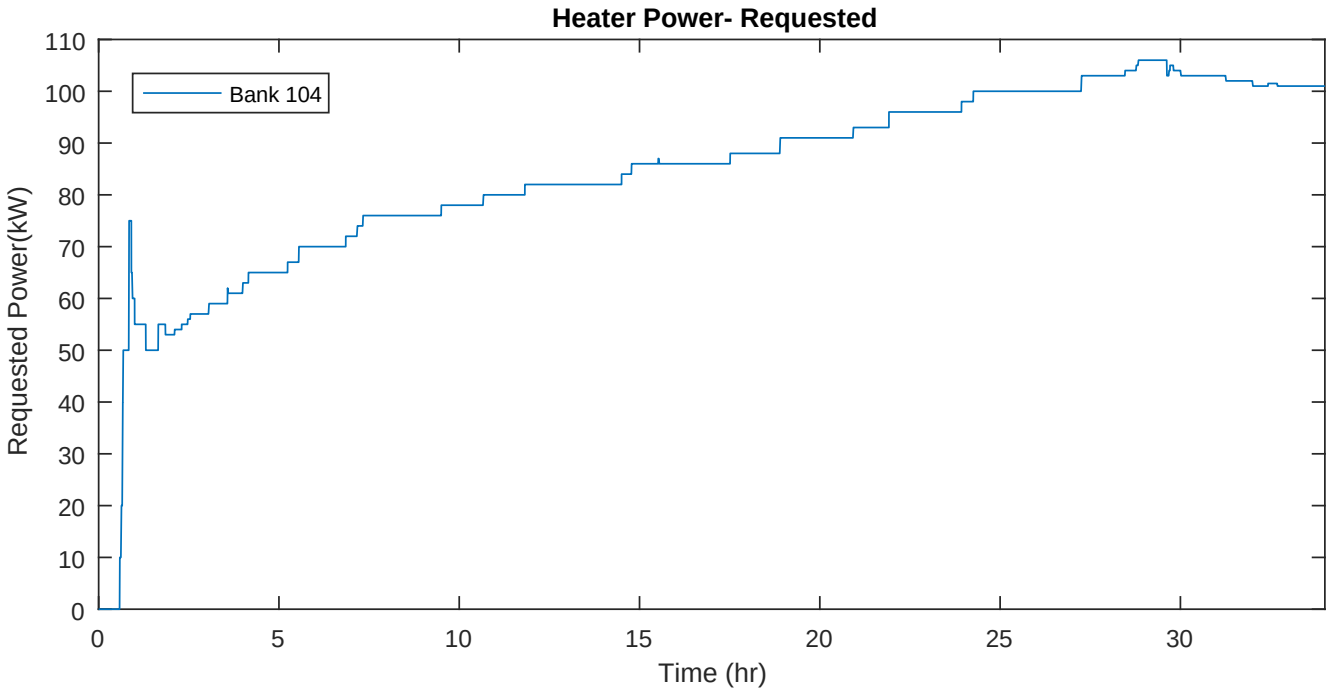

Figure 4.2: Requested heater power output on channel HO-103/104

4.3. Reactor Cavity Cooling System

The system was not operated for this test

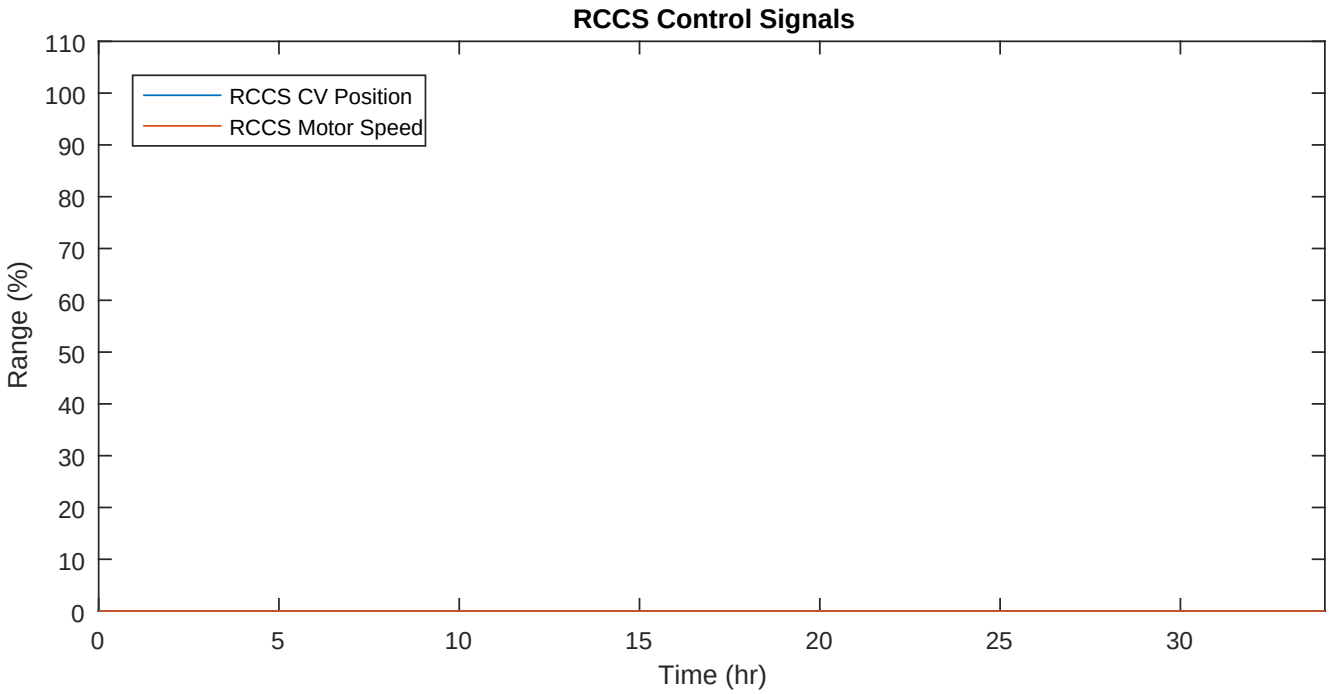

Figure 4.3: RCCS Control signals: MS-9001 and CV-9001

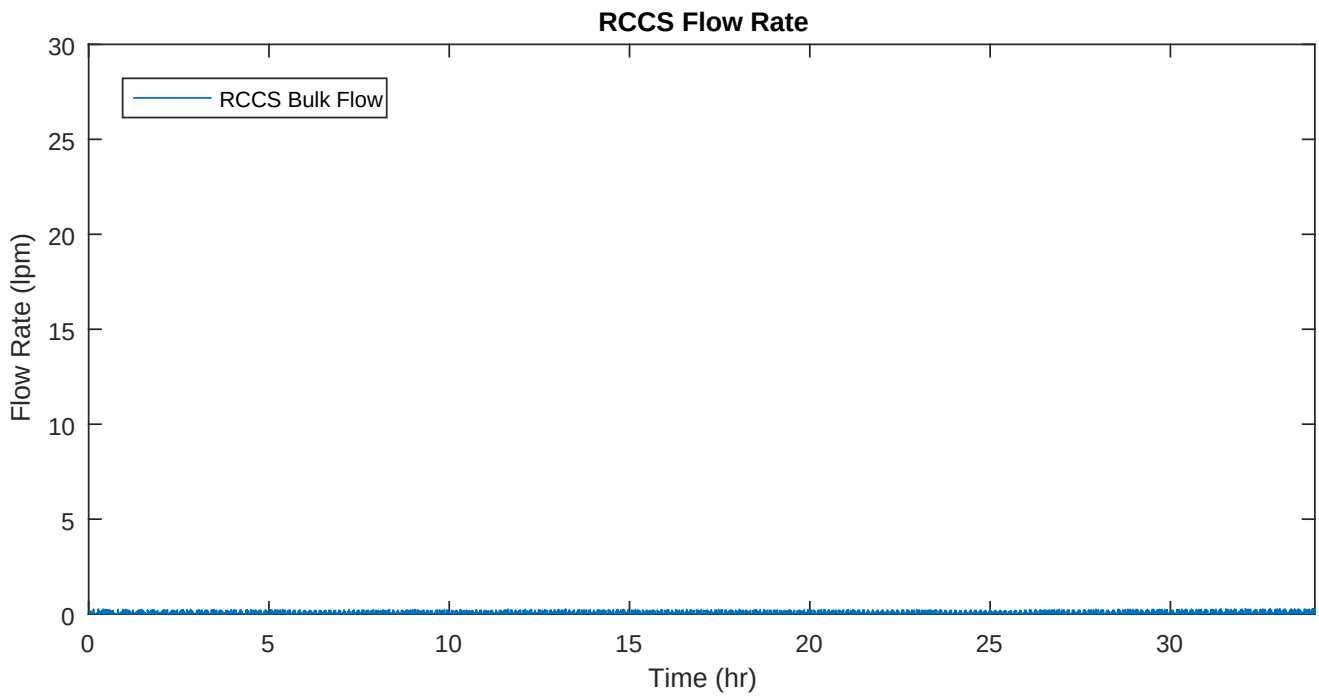

Figure 4.4: RCCS flow rate during the test.

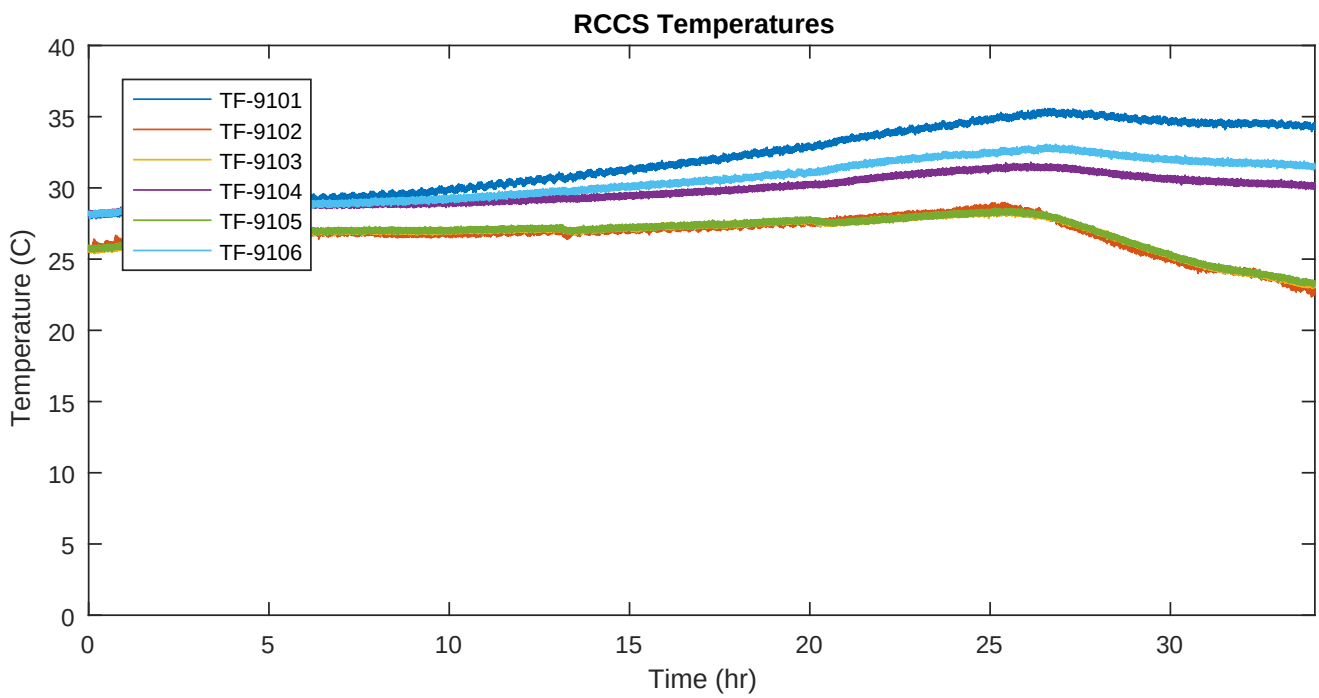

Figure 4.5: Temperatures on the Northeast corner of the RCCS. These are typical of the other three corners.

4.4. Steam Generator Performance

During this test, the steam generator was filled to 60% of its volume before the test. Water was not added or removed from the SG, as steam was never created.

The steam generator pressure was fairly steady, beginning and ending at approximately 115 kPa (figure 4.9). The temperature in the SG was initially approximately equal to the ambient temperature at 28 ℃, this temperature rose steadily through the test to a maximum final temperature of approximately 88 ℃ (figure 4.10).

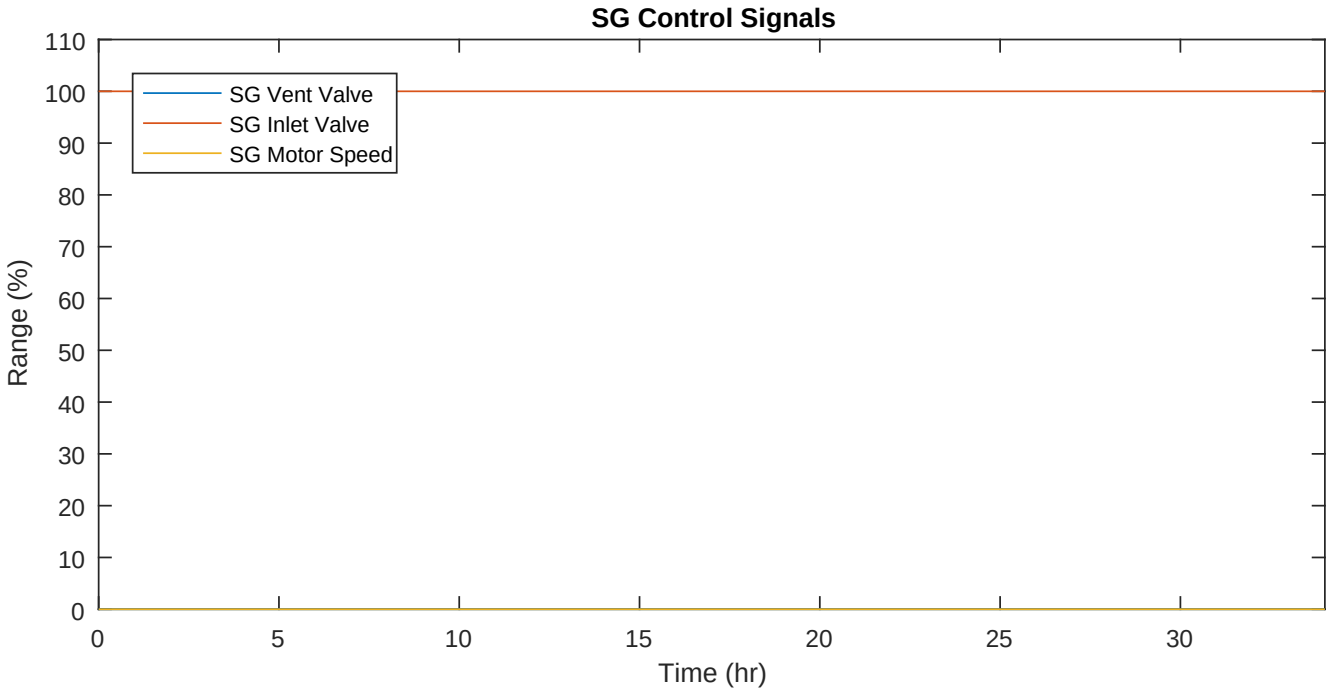

Figure 4.6: Steam Generator control signals: CV-5001 Vent valve position, CV-5002 water inlet valve position, and MS-9001 water inlet pump speed.

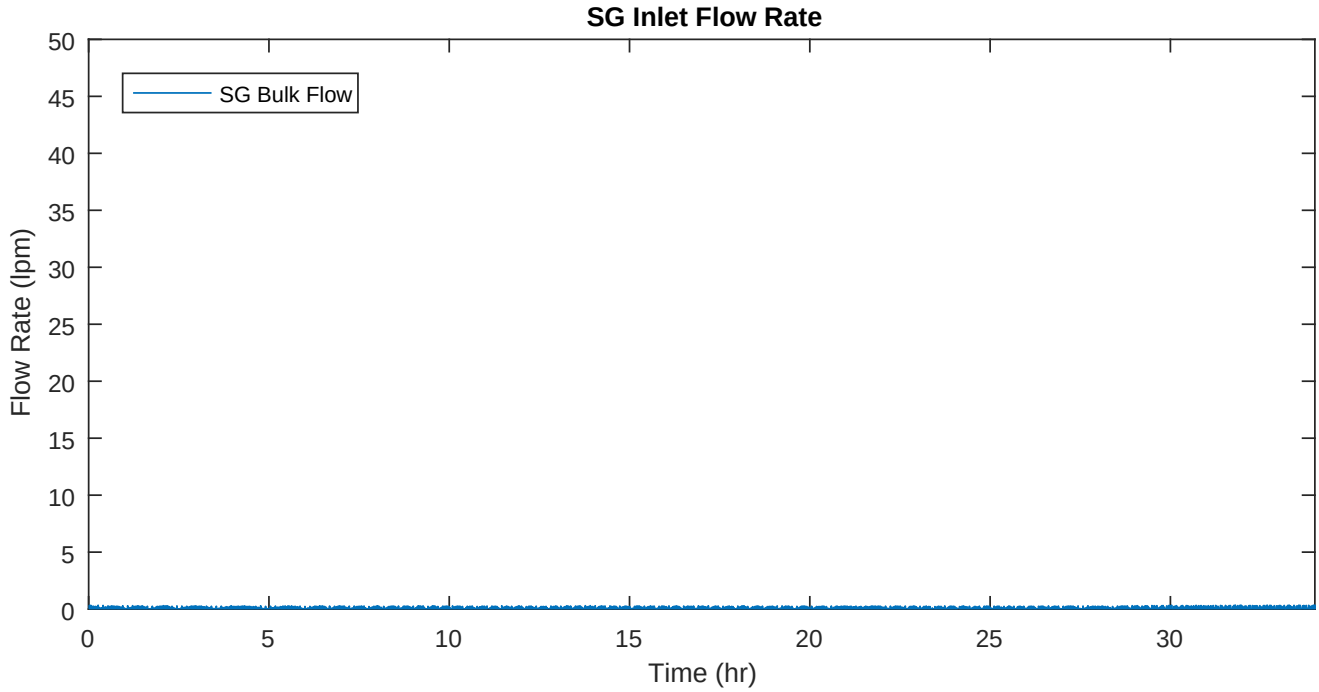

Figure 4.7: Steam Generator inlet flow rate, FT-5001

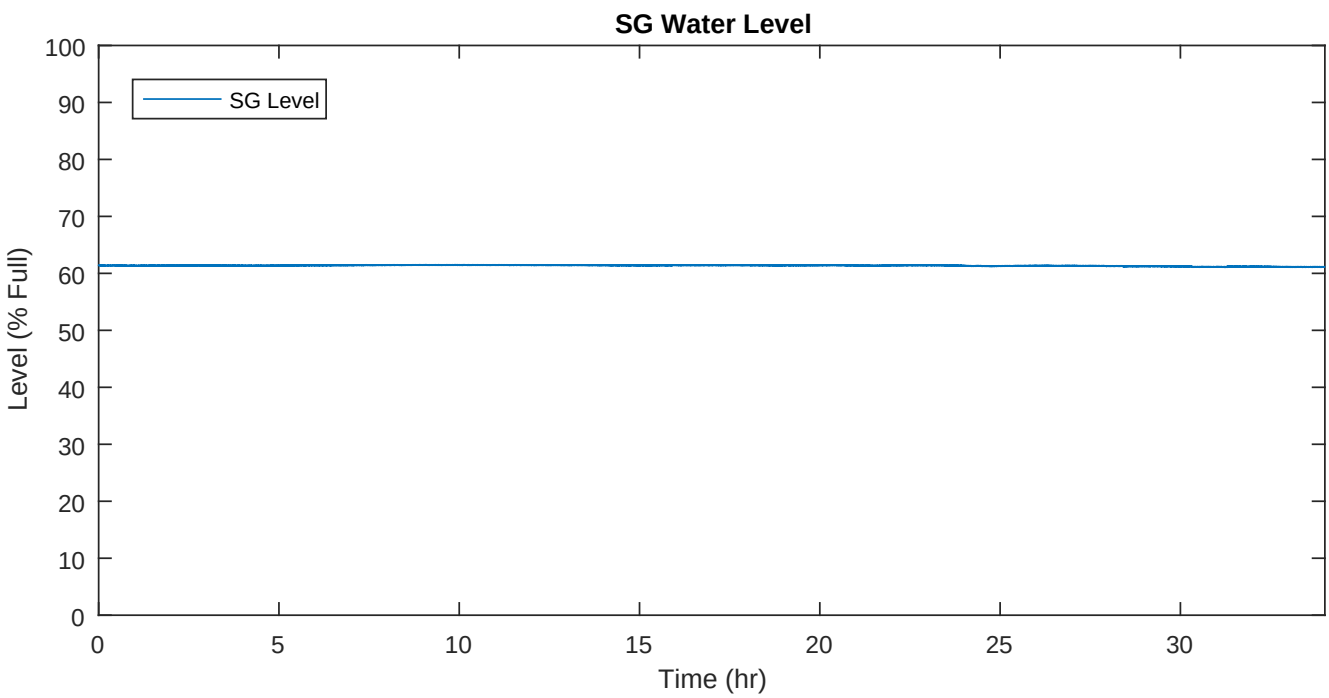

Figure 4.8: Steam Generator Water Level, LF-5002

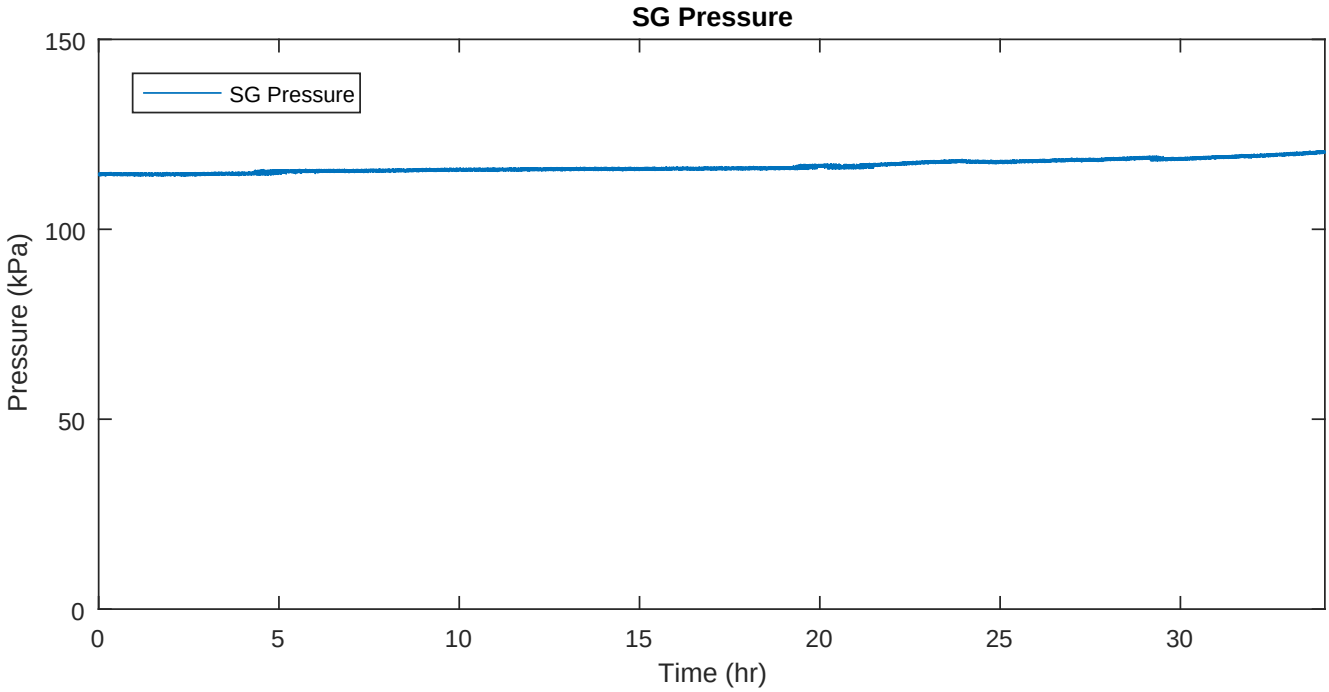

Figure 4.9: Steam Generator Pressure, PT-5001

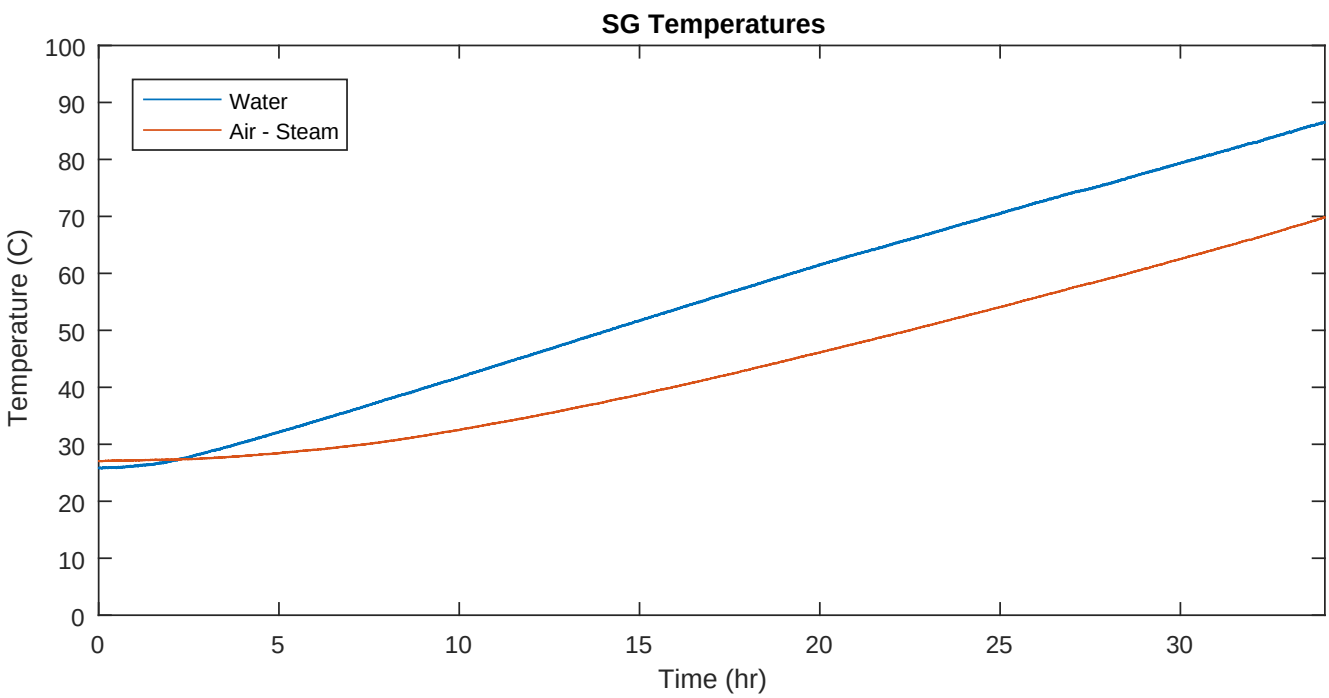

Figure 4.10: Steam Generator Fluid Temperatures, TF-5001 water temperature, TF-5002 air-steam temperature

4.5. Test Results

PG-32 is a test that examines the heat up of the test facility using an asymmetric heater configuration. Figure 4.11 shows the heat up of 3 ceramic core temperatures at 3 axial locations during the performance of PG-32. These thermocouples are located in the primary core sector where the heaters are active for the duration of this test.

Figure 4.12 shows the heat up of 3 ceramic core temperatures at 3 axial locations during the performance of PG-32 in the secondary sector. In the secondary sector, the heaters are not active and thus the heat up profile is very different from that in the primary sector.

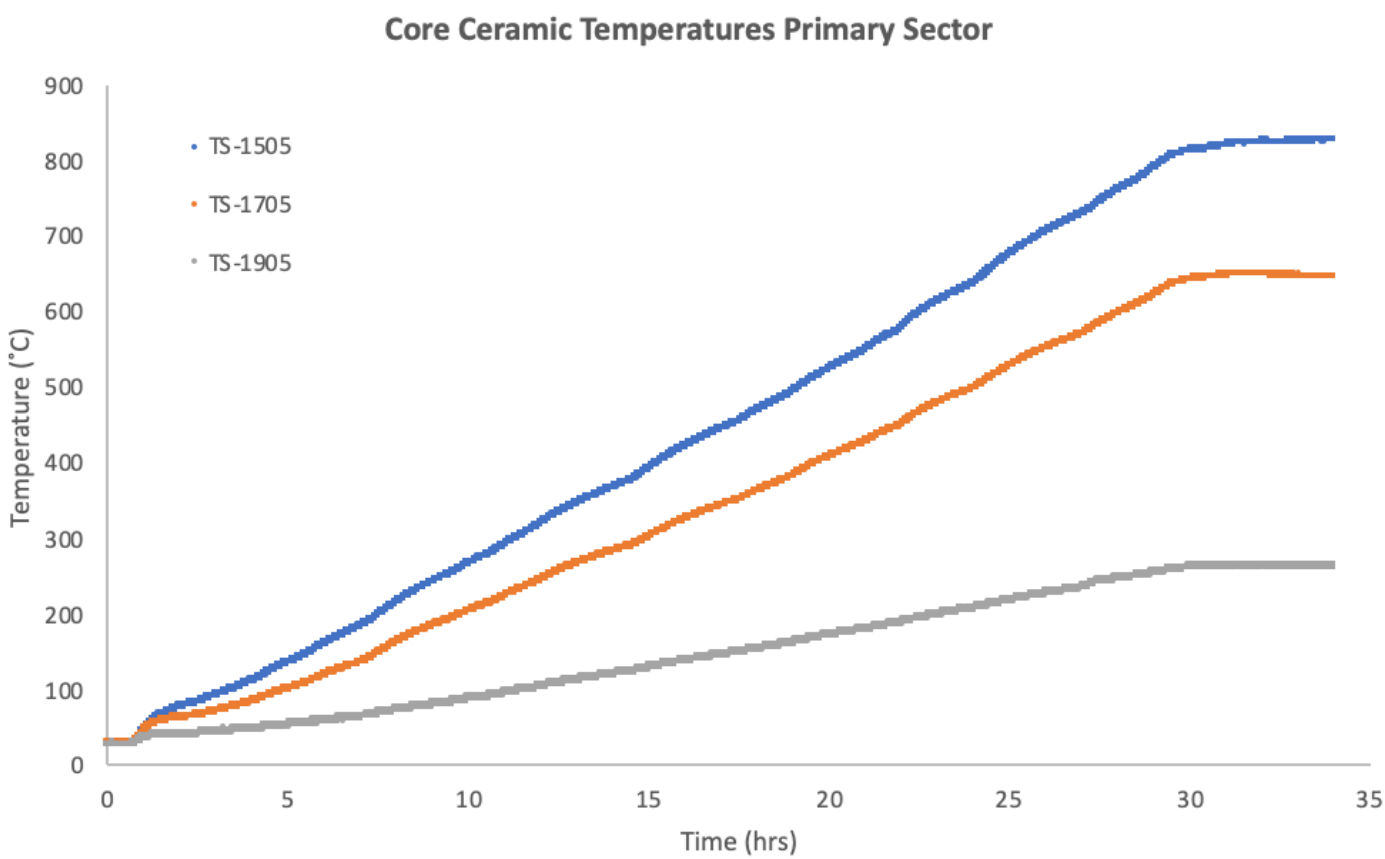

Figure 4.11: Plot of ceramic core temperatures, TS-1505, TS-1705, and TS-1905.

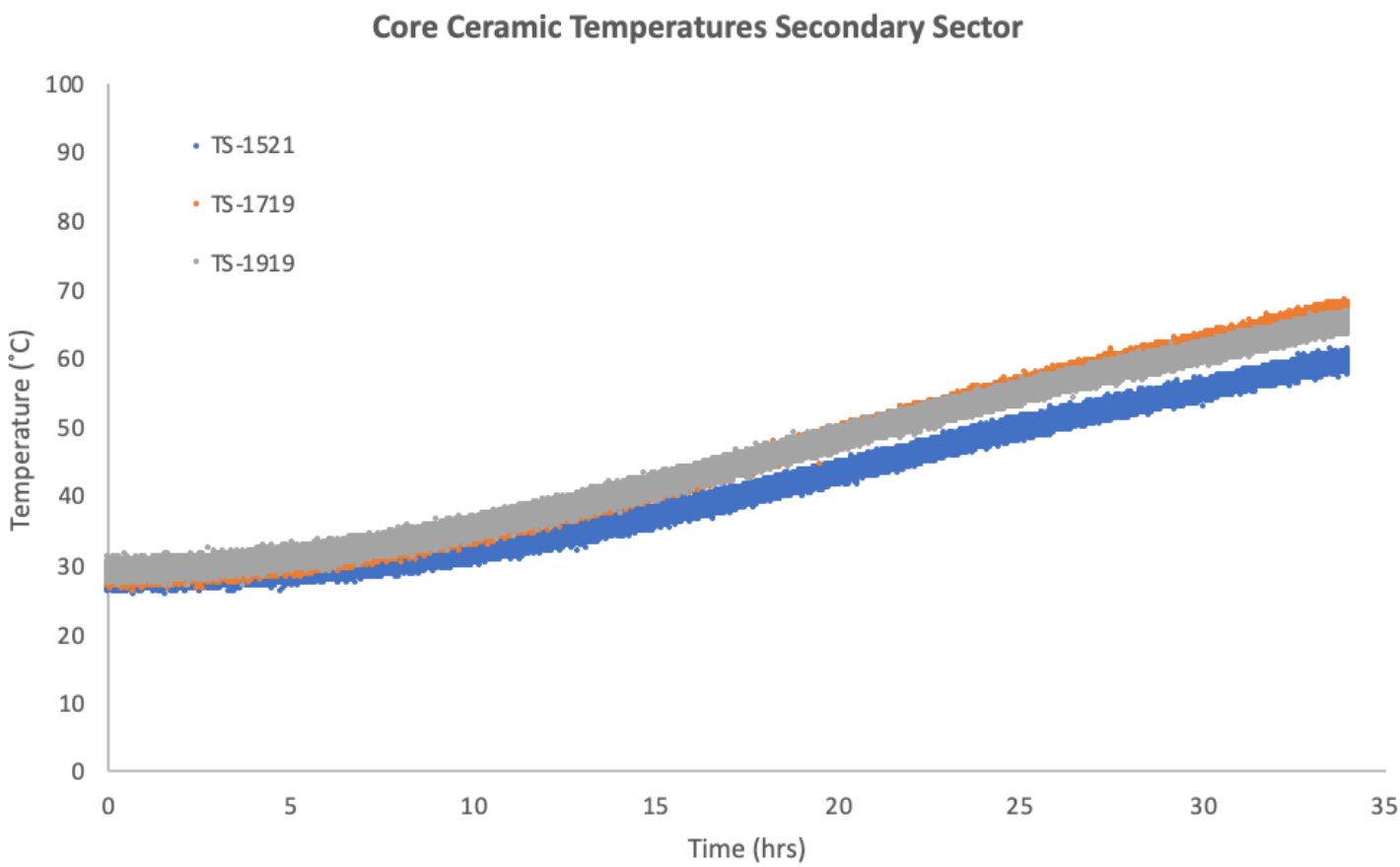

Figure 4.12: Plot of ceramic core temperatures, TS-1521, TS-1719, and TS-1919.

Chapter 5. PG-30 Low Power (<350kW) Lower Plenum Mixing, Constant Temperature Test

The purpose of this test is to investigate the impact on Lower Plenum thermal profiles and mixing due to changes in the system mass flow rate in an integral test facility scaled to General Atomics' Modular High Temperature Gas Reactor (MHTGR) design. This test is referred to as a Lower Plenum Mixing Test with constant core temperature. Initial conditions will be met using a hybrid heater configuration at low power (<350kW).

This test began on 8/29/2019 and was completed on 8/30/2019. It was initiated following the completion of PG-032. This test was started and completed in one session, and there is only one data file. In this report the data set, PG30_data, will be presented and discussed.

5.1. Initial Conditions

On August 28th, 2019, the HTTF was energized and operators Brian Woods, Tommy Moore, and Ben Nakhnikian-Weintraub began to heat up the HTTF using test procedure OSU-HTTF-TEST-032-R0. On August 29th, 2019, OSU-HTTF-TEST-032-R0 was completed and operators Brian Woods and Tommy Moore transitioned over to test procedure OSU-HTTF-TEST-030-R1. This transition was signaled by cycling SV-4002 in the test log. All members of the testing team were certified as HTTF Test Engineers and were briefed on the purpose of the test before they began operating the facility.

The facility conditions at the time of the start of the test are presented in Table 9.1. All pumps were secured and the flow rate was zero in each fluid carrying system at the start of the test.

Table 5.1: Initial conditions for the start of the test.

Primary Loop:	>180 kPa helium
RCSS:	<180kPa nitrogen
Cooling Water System:	filled with water and at operating conditions
Steam Generator:	60 to 80% water level and at operating conditions
RCCS Tank:	filled with water and at operating conditions
RCCS Panels:	filled with water and at operating conditions

5.2. Heater Operation

The heaters were operated during the entire test. Heater bank 104 was operated, where the power output started just above 30kW and was then increased to keep core temperature constant as the flow rate of coolant changed. The power was initially increased to approximately 40kW, before being lowered to 35kW. In the 37th hour the power was increased first to 40kW, and then to 50kW. In the 38th hour the power was increased to a final peak of almost 60kW. The time (in hours) represents the time since the start of OSU-HTTF-TEST-032-R0.

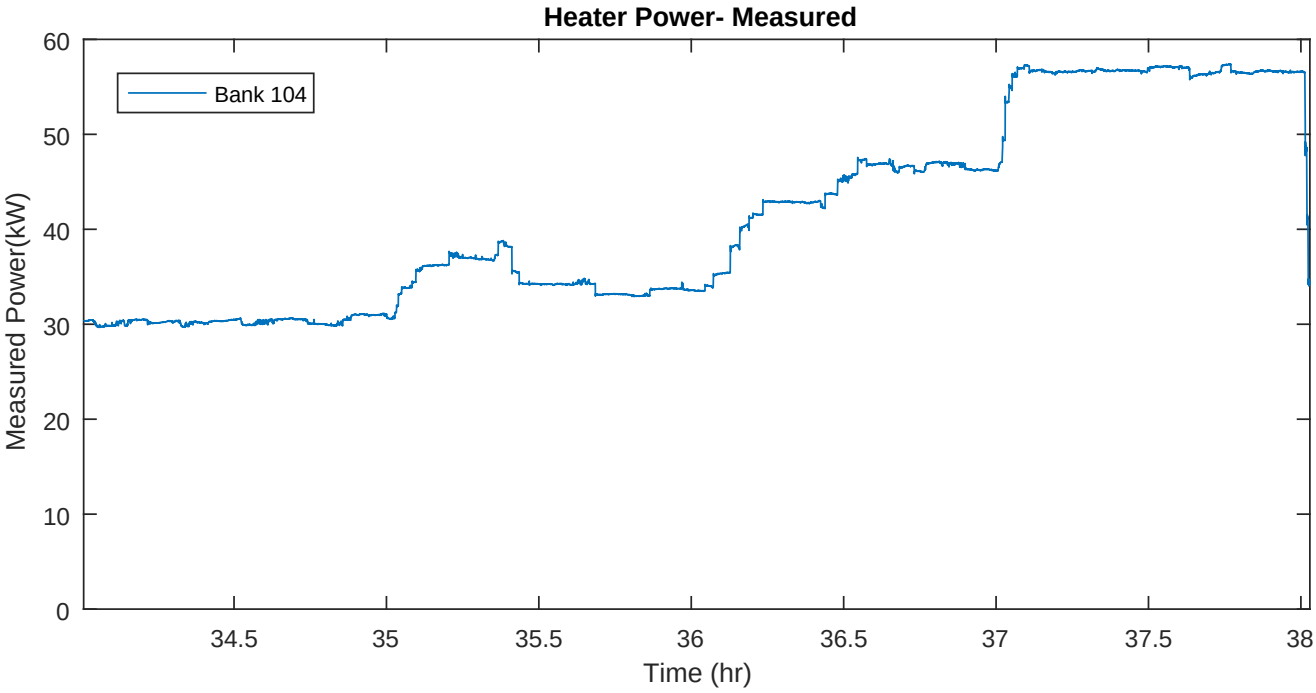

Figure 5.1: Measured heater power output on channel HO-103/104

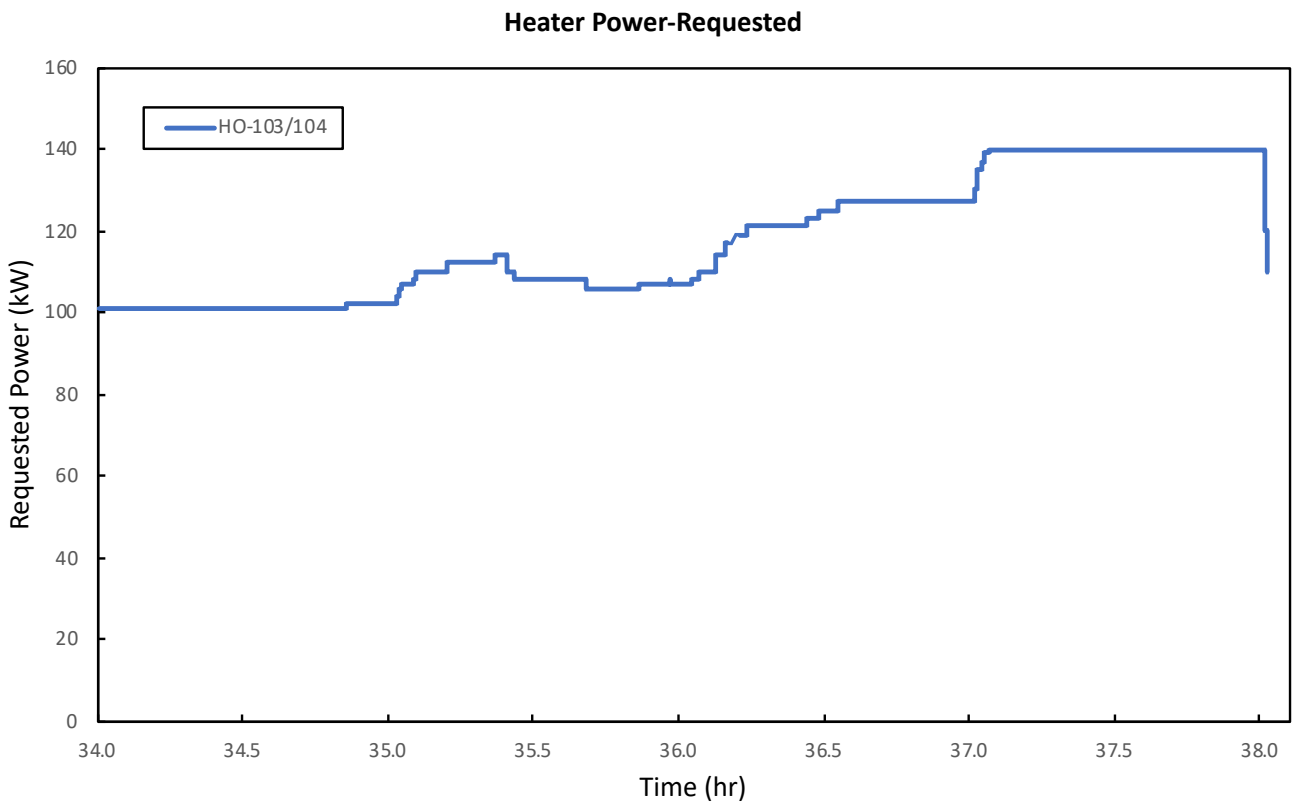

Figure 5.2: Requested heater power output on channel HO-103/104

5.3. Reactor Cavity Cooling System

The system was not operated for this test, with the motor speed kept at 0%.

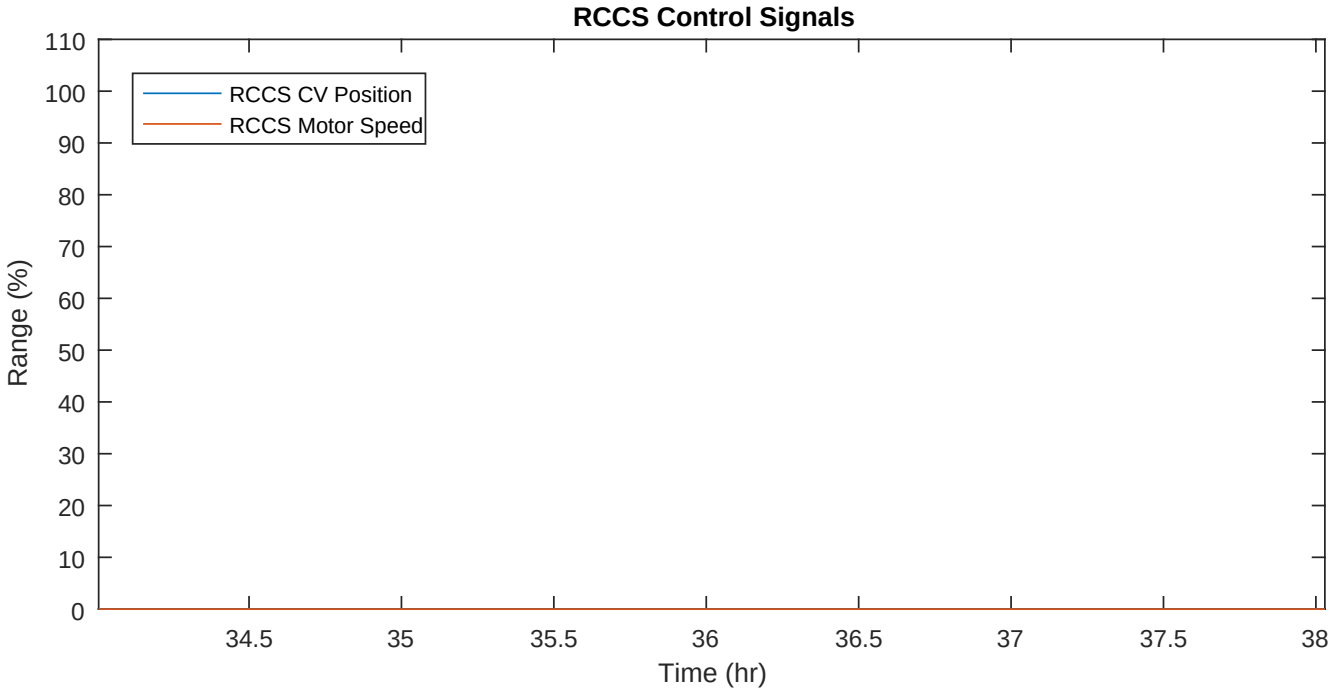

Figure 5.3: RCCS Control signals: MS-9001 and CV-9001

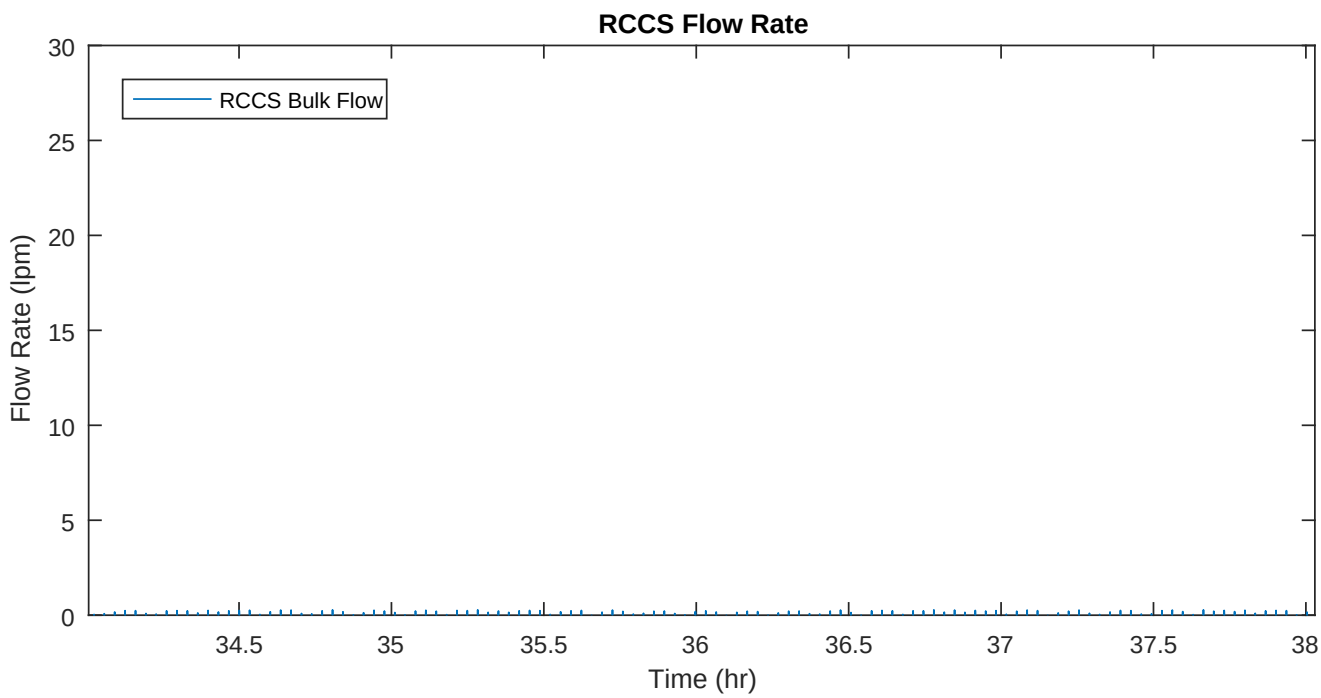

Figure 5.4: RCCS flow rate during the test.

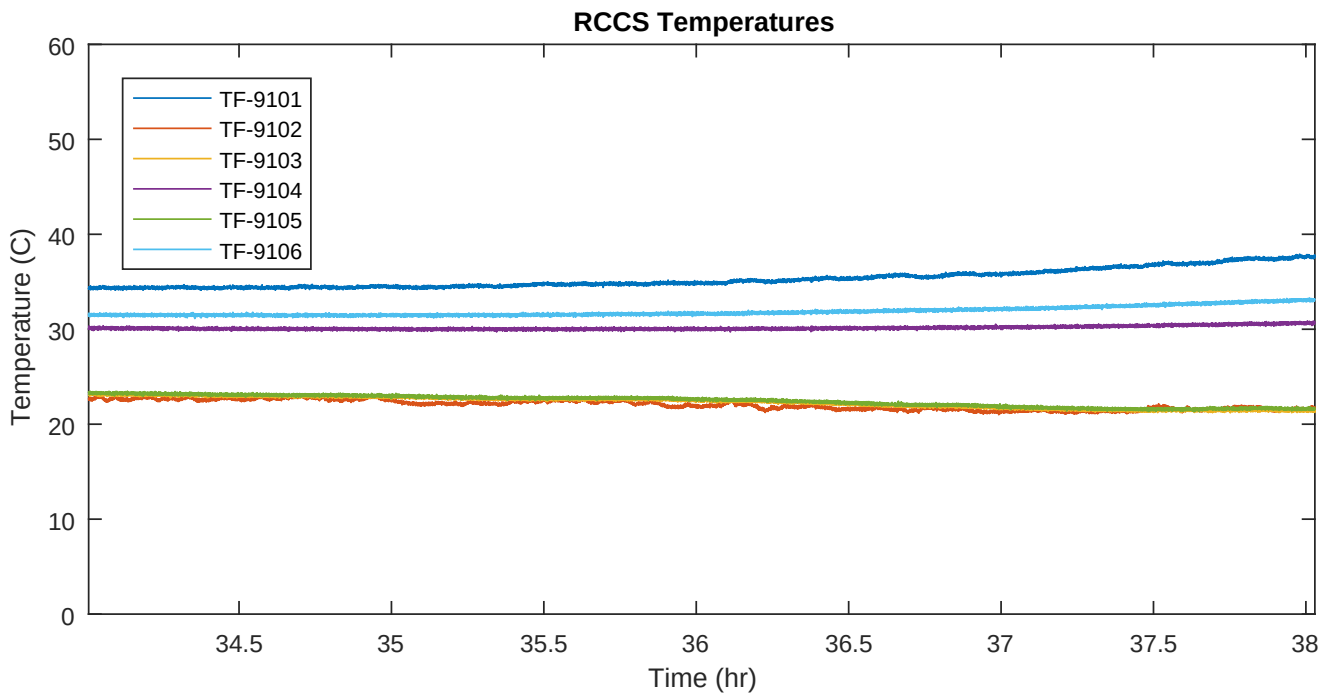

Figure 5.5: Temperatures on the Northeast corner of the RCCS. These are typical of the other three corners.

5.4. Steam Generator Performance

During this test, the steam generator was filled to approximately 60% of its volume before the test. Water was added in the 38th hour to bring the level to approximately 70% of its volume as pressure and temperature increased. The control signals are shown in figure 5.6 and the level is shown in figure 5.8. The water inlet flow rate is measured and shown in figure 5.7.

At the beginning of the test the steam generator was pressurized to approximately 120kPa. As the test progressed steam generator pressure gradually increased to approximately 200 kPa. A small dip in pressure can be seen in the 38th hour when the water level was increased, see figure 5.9. The steam generator temperatures, both water and air increased with the steam generator pressure. The water and air temperatures began at 65 ℃ and 82 ℃ respectively. Increasing until water was added in the 38th hour and the water temperature drops suddenly. The SG temperatures are shown in figure 5.10.

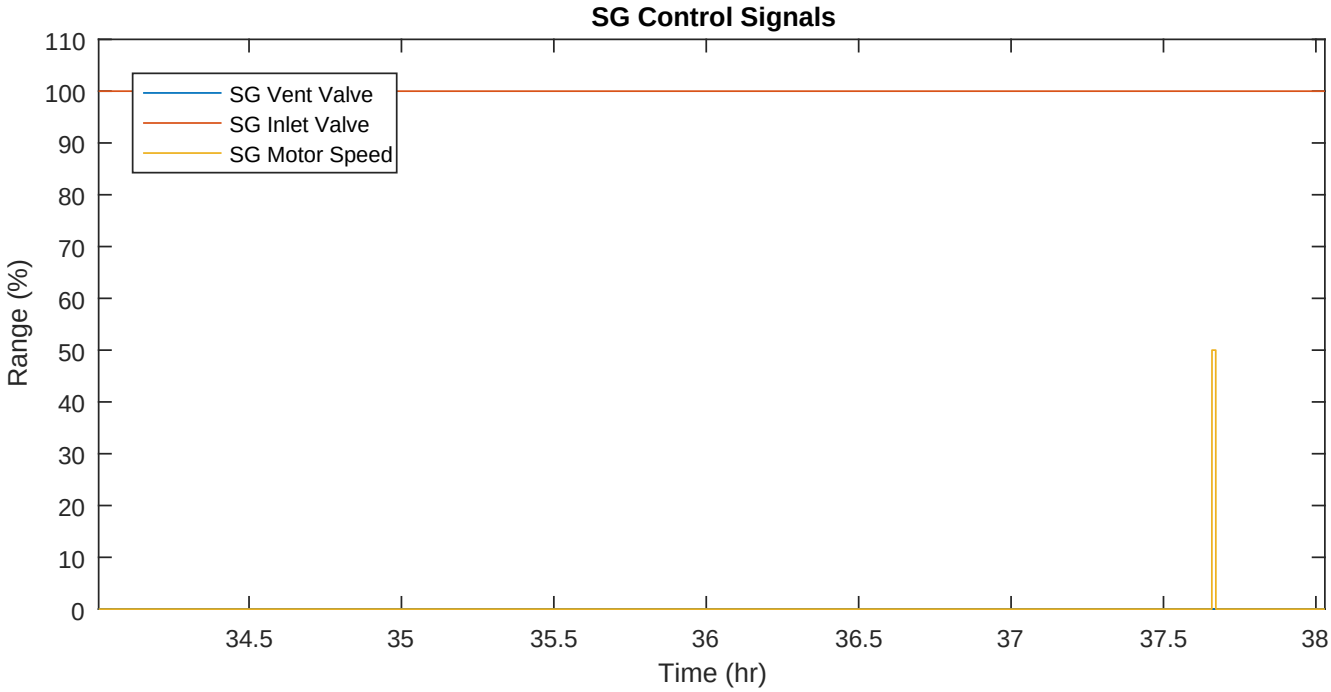

Figure 5.6: Steam Generator control signals: CV-5001 Vent valve position, CV-5002 water inlet valve position, and MS-5001 water inlet pump speed.

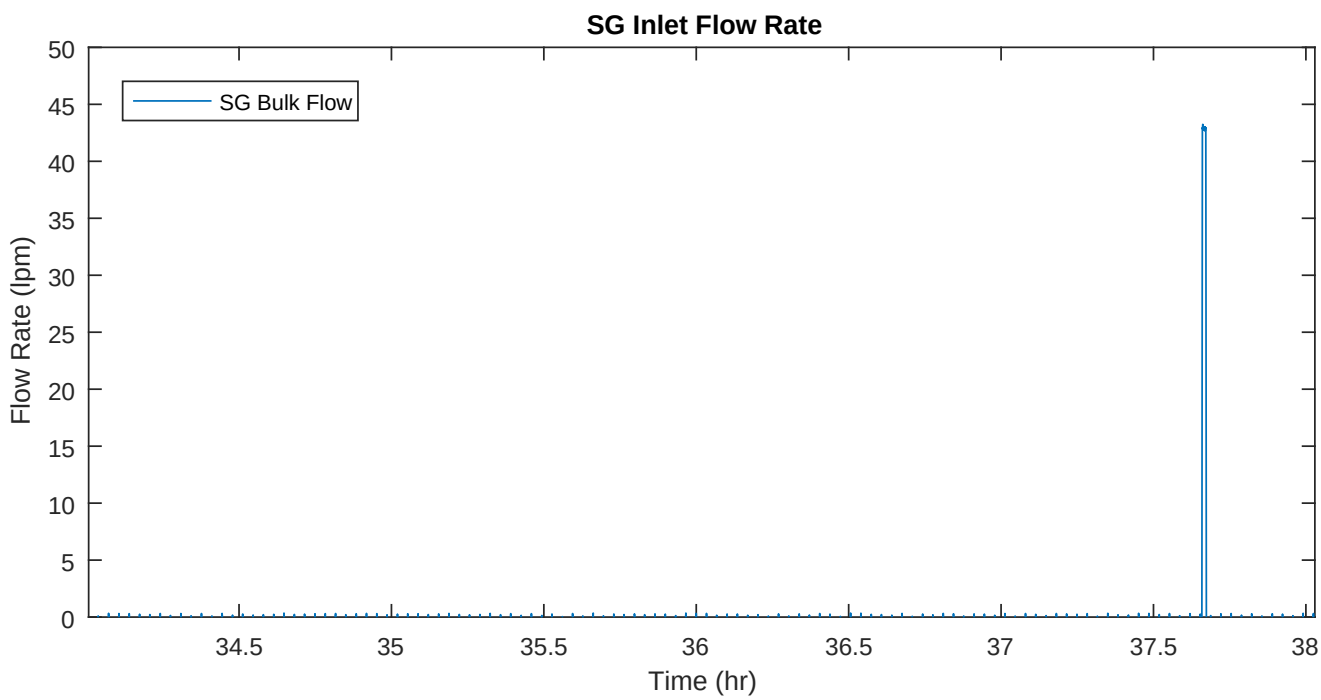

Figure 5.7: Steam Generator inlet flow rate, FT-5001

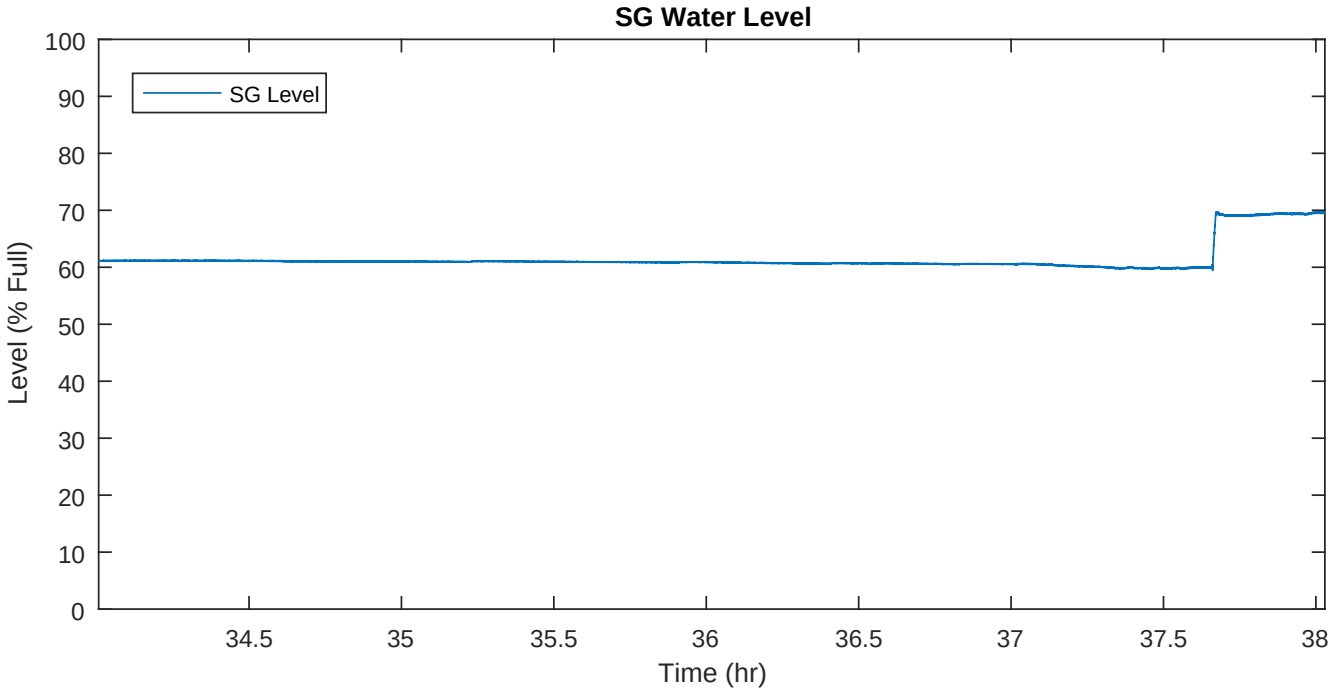

Figure 5.8: Steam Generator Water Level, LF-5002

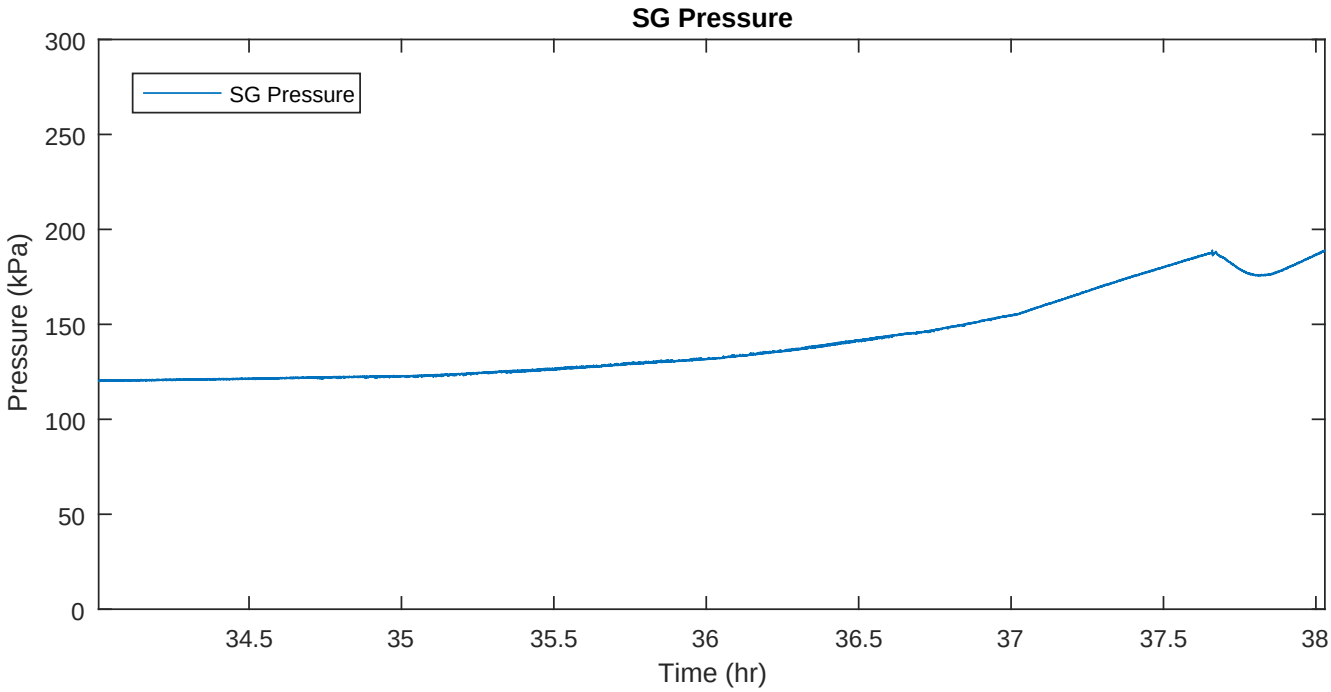

Figure 5.9: Steam Generator Pressure, PT-5001

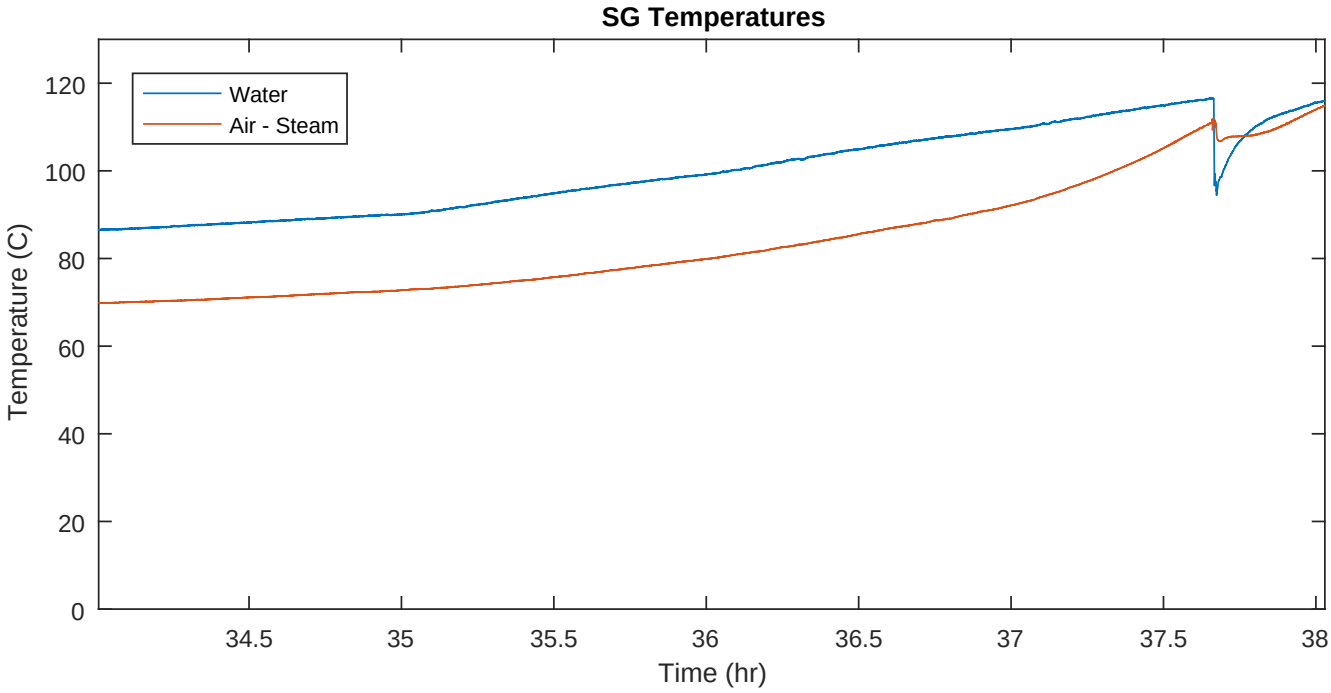

Figure 5.10: Steam Generator Fluid Temperatures, TF-5001 water temperature, TF-5002 air-steam temperature

5.5. Test Results

During the test flow rate was increased three times. The three changes in gas flow rate can be seen in 5.12 as the three sudden changes in differential pressure. With each change in flow there was a significant effect on the temperature of the lower plenum. The measurements from one set of lower plenum post thermocouples is shown in 5.11. In response to each gas flow rate change there was a small sudden change in temperature. From the start of the test until the first gas flow rate change, the lower plenum temperature is relatively stable, increasing only slightly in that time. With the first gas flow rate change, there is an increase both in temperature and the rate of heat increase, with the exception of TF-2411.

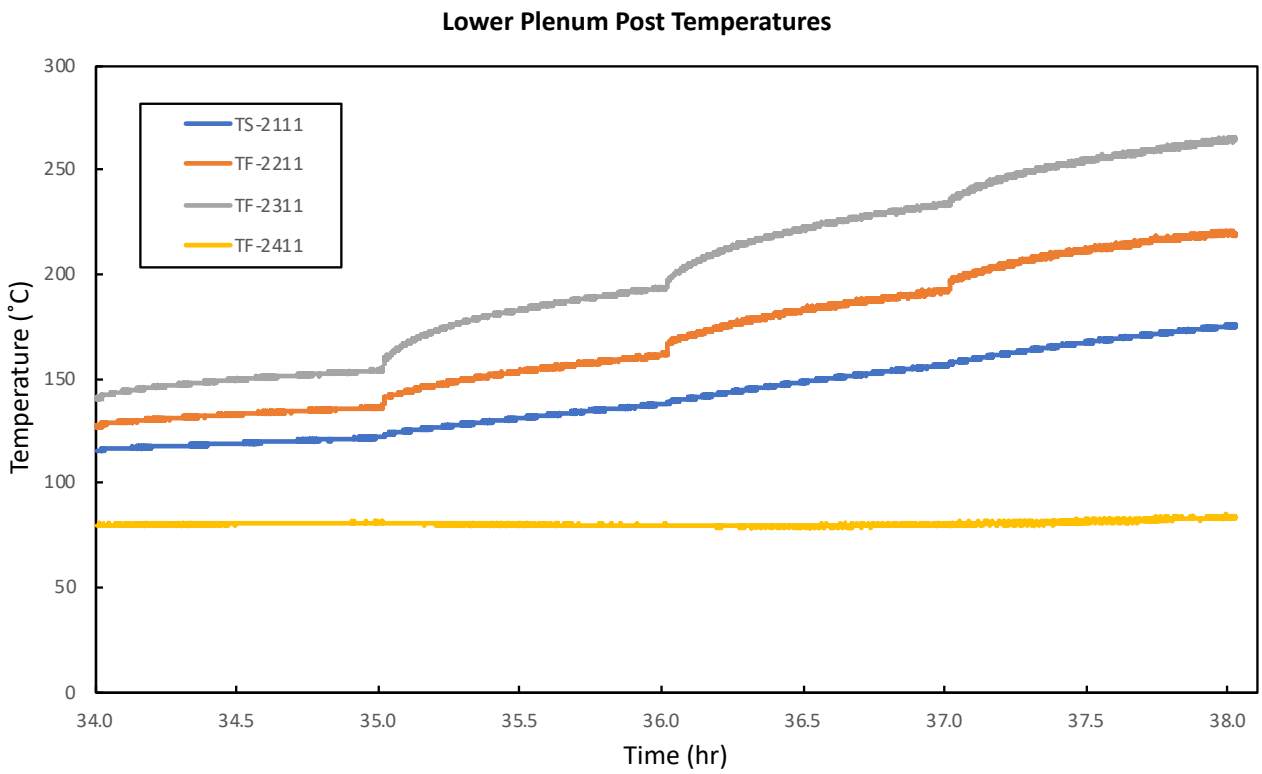

Figure 5.11: Plot of Lower Plenum Post temperatures during the test.

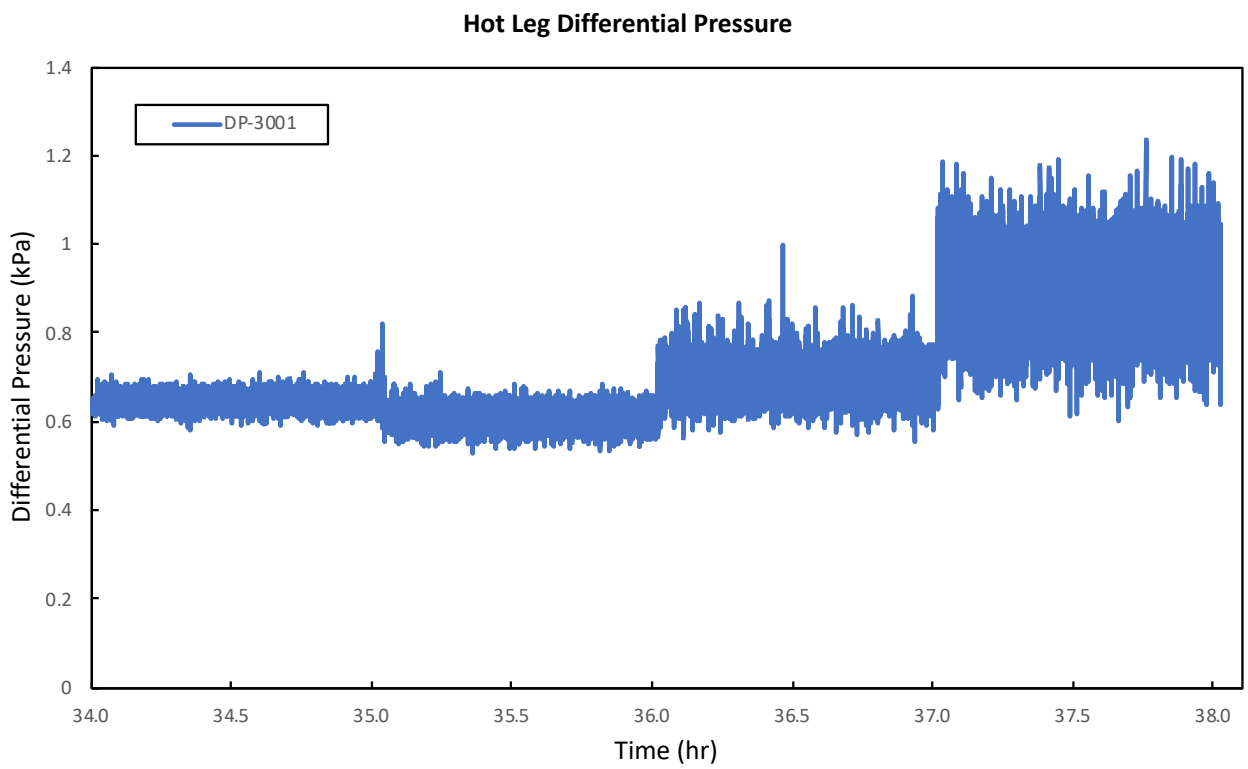

Figure 5.12: Plot of the differential pressure in the hot leg during the test.

The temperature of the core ceramics during this test also shows a significant response to the increases in flow rate. Shown below in 5.13 are the solid core temperatures at position 07 for each odd numbered core block during the test. The first gas flow rate change is clearly visible in the 36th hour as a sharp increase in the rate of cooling for the three central core blocks.

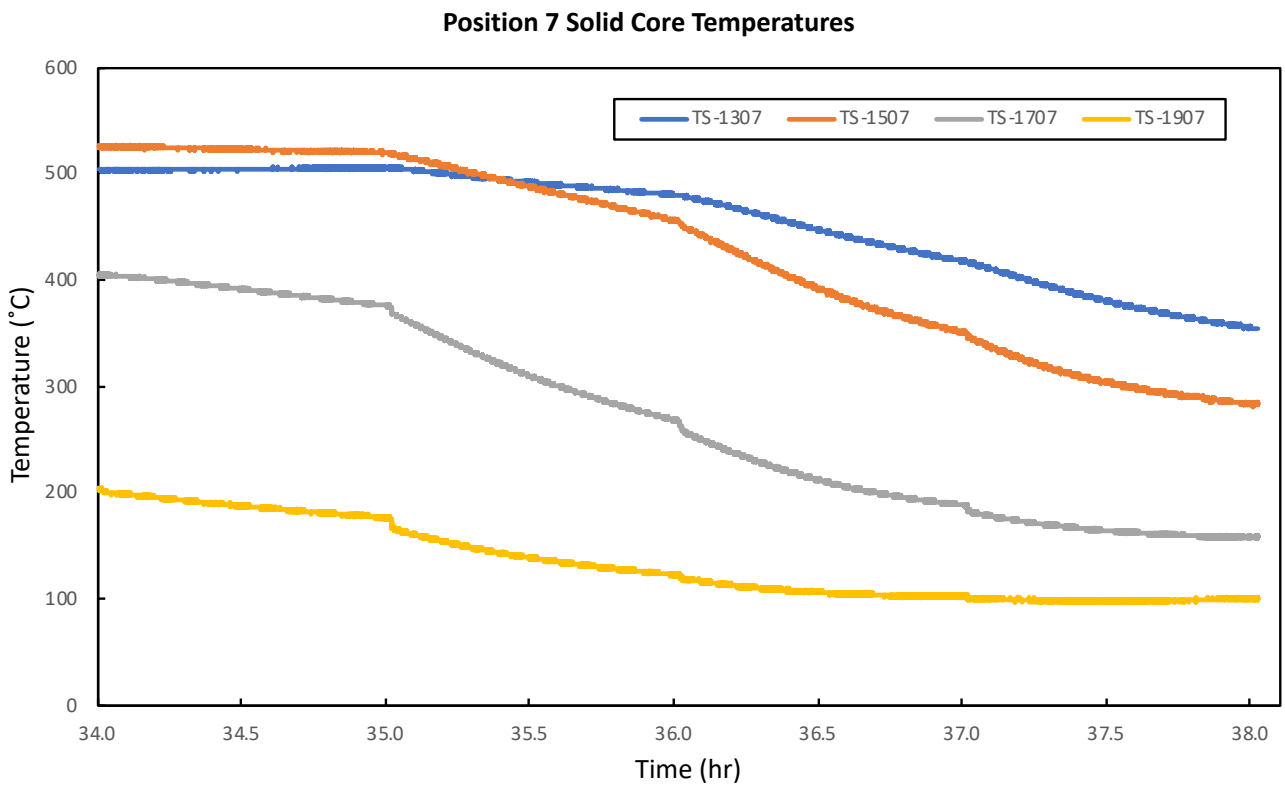

Figure 5.13: Plot of the solid core temperatures at position 07 for odd numbered core blocks.

Chapter 6. PG-31 Low Power (<350kW) Pressure Vessel Bottom Break with Restored Forced Convection Cooling Test

The purpose of this test is to examine the progression of the Pressure Vessel Bottom Break with Restored Forced Convection Cooling transient in an integral test facility scaled to General Atomics' Modular High Temperature Gas Reactor (MHTGR) design. Initial conditions will be met using low power (<350kW) with a hybrid heater bank. Transient decay power will be scaled to the MHTGR.

This test began on 8/30/2019 and was completed on 8/31/2019. It was initiated following the completion of PG-032 and PG-030. Following the completion of PG-30, the facility was brought back to steady-state conditions. The break valves were opened 46 hours and 18 minutes following the start of PG-032. After 3 hours, at 49 hours and 22 minutes from the start of PG-032, primary loop circulation was resumed. This test was started and completed in one session, and there is only one data file. In this report the data set, PG31_data, will be presented and discussed.

6.1. Initial Conditions

On August 28th, 2019, the HTTF was energized and operators Brian Woods, Tommy Moore, and Ben Nakhnikian-Weintraub began to heat up the HTTF using test procedure OSU-HTTF-TEST-032-R0. On August 29th, 2019, OSU-HTTF-TEST-032-R0 was completed and operators Brian Woods and Tommy Moore transitioned over to test procedure OSU-HTTF-TEST-030-R1. This transition was signaled by cycling SV-4002 in the test log. On August 30th, 2019, OSU-HTTF-TEST-030-R1 was completed and operators Brian Woods and Tommy Moore transitioned to conditioning the facility for test procedure OSU-HTTF-TEST-031-R1. This transition was signaled by cycling SV-4002 again in the test log. Test procedure OSU-HTTF-TEST-031-R1 was initiated following facility conditioning. All members of the testing team were certified as HTTF Test Engineers and were briefed on the purpose of the test before they began operating the facility.

The facility conditions at the time of the start of the test are presented in Table 9.1. All pumps were secured and the flow rate was zero in each fluid carrying system at the start of the test.

Table 6.1: Initial conditions for the start of the test.

Primary Loop:	>180 kPa helium
RCSS:	<180kPa nitrogen
Cooling Water System:	filled with water and at ambient pressure
Steam Generator:	60 to 80% water level and at ambient pressure
RCCS Tank:	filled with water and at ambient pressure
RCCS Panels:	filled with water and at ambient pressure

6.2. Heater and Circulator Operation

The heaters were operated during the entire test. Heater bank 104 was operated, where the power output was approximately 32kW. Note that the requested power is significantly different than measured power due to the operational using a hybrid heater configuration. The primary circulator was secured to initiate the test. Nearly 4 hours into the test, the forced convection through the primary loop was re-established.

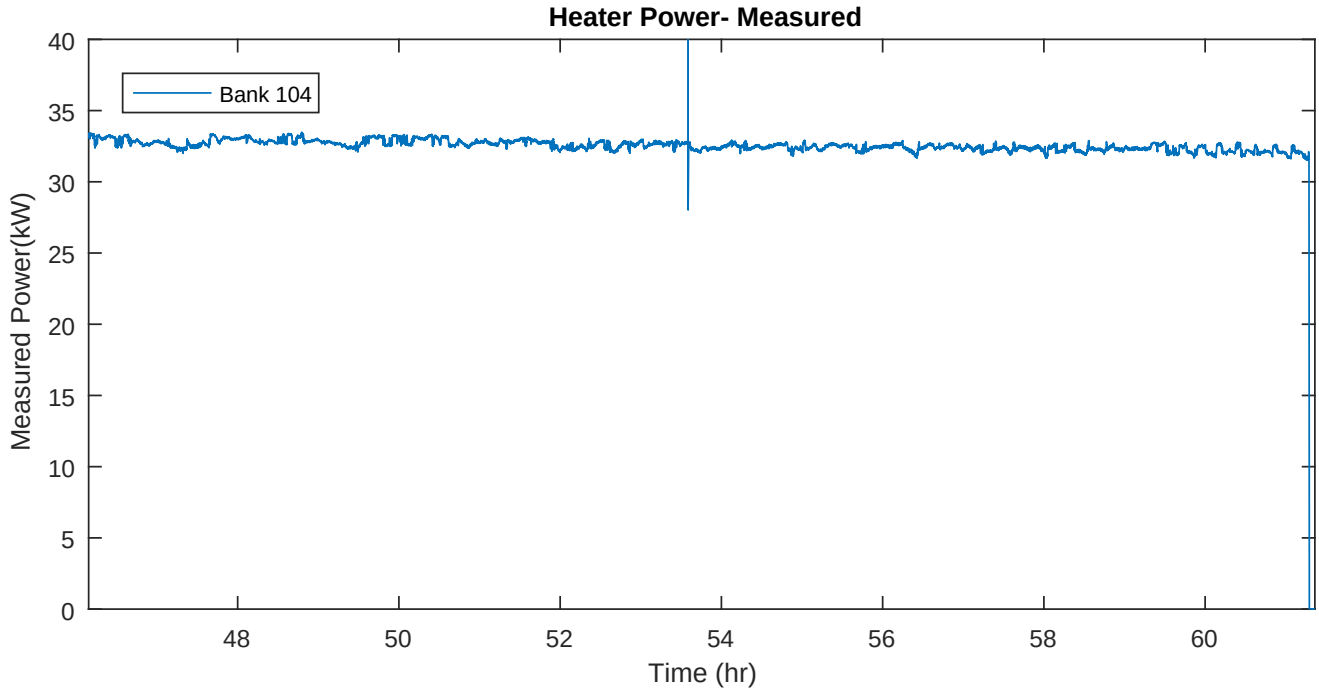

Figure 6.1: Measured heater power output on channel HO-103/104

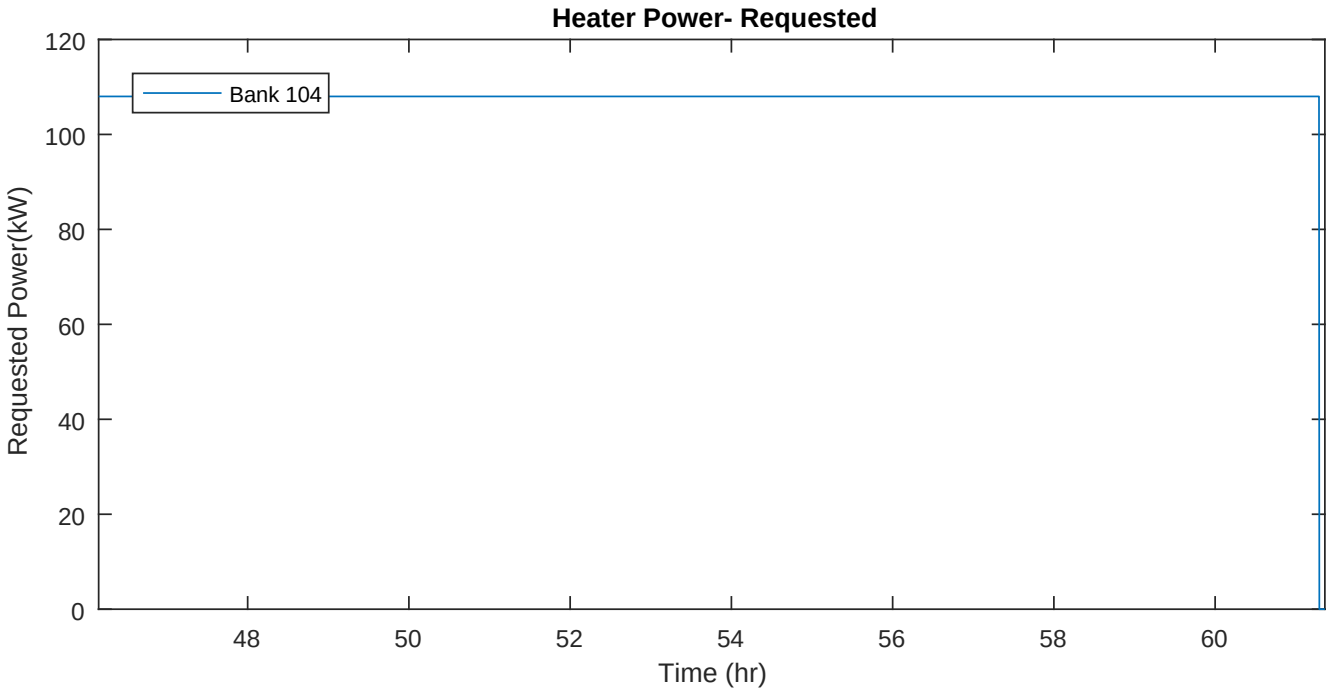

Figure 6.2: Requested heater power output on channel HO-103/104

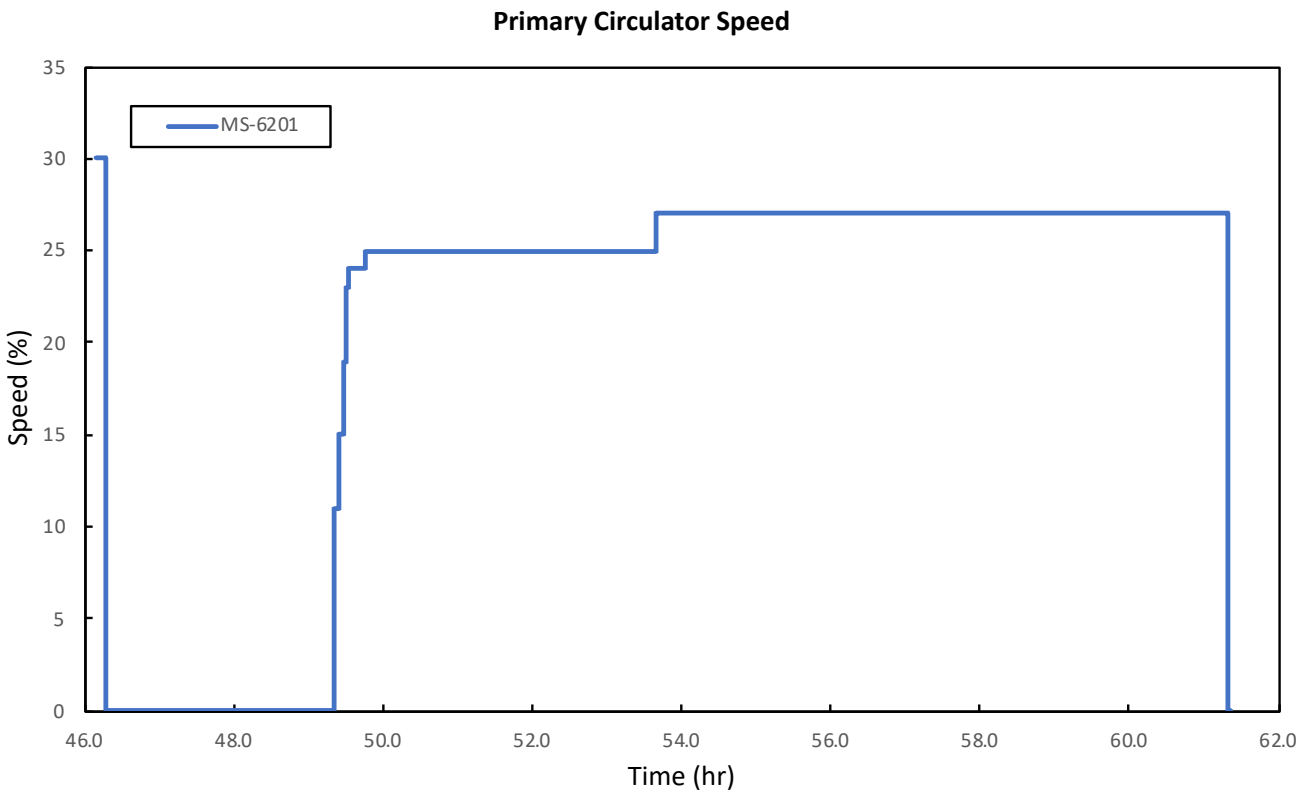

Figure 6.3: Primary circulator speed

6.3. Reactor Cavity Cooling System

The system was operated continuously with a motor speed of 30%.

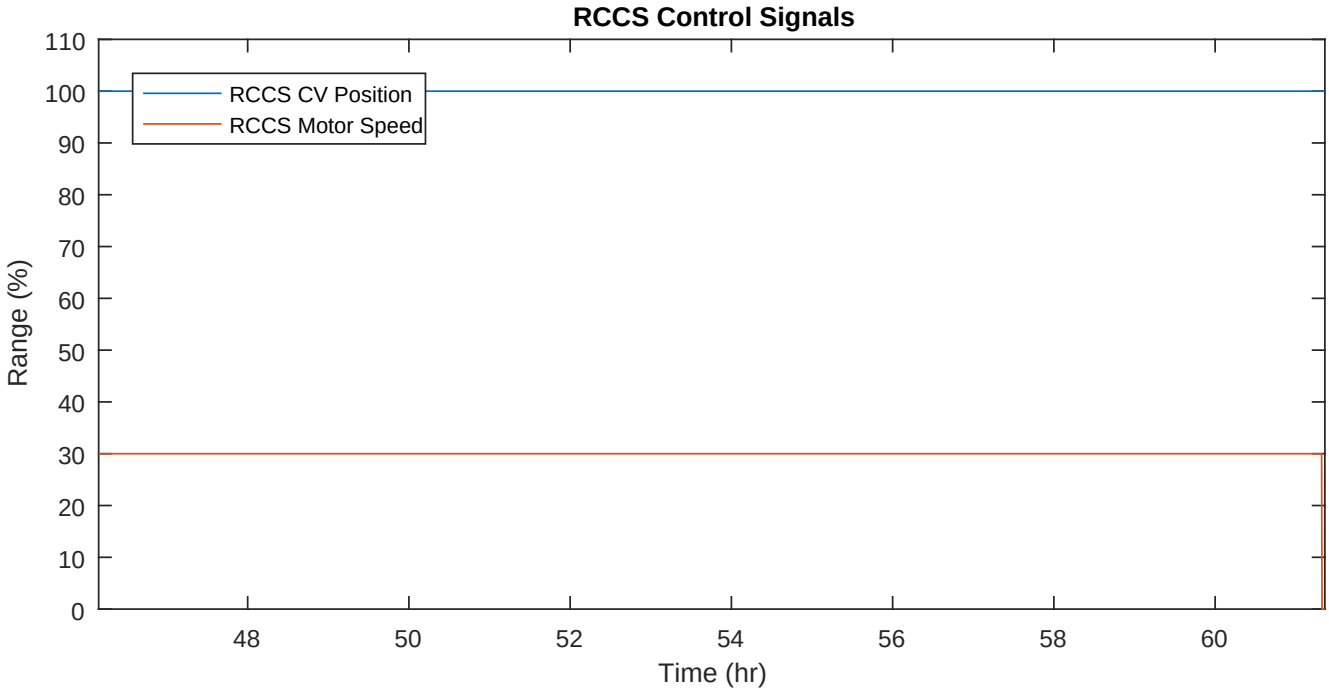

Figure 6.4: RCCS Control signals: MS-9001 and CV-9001

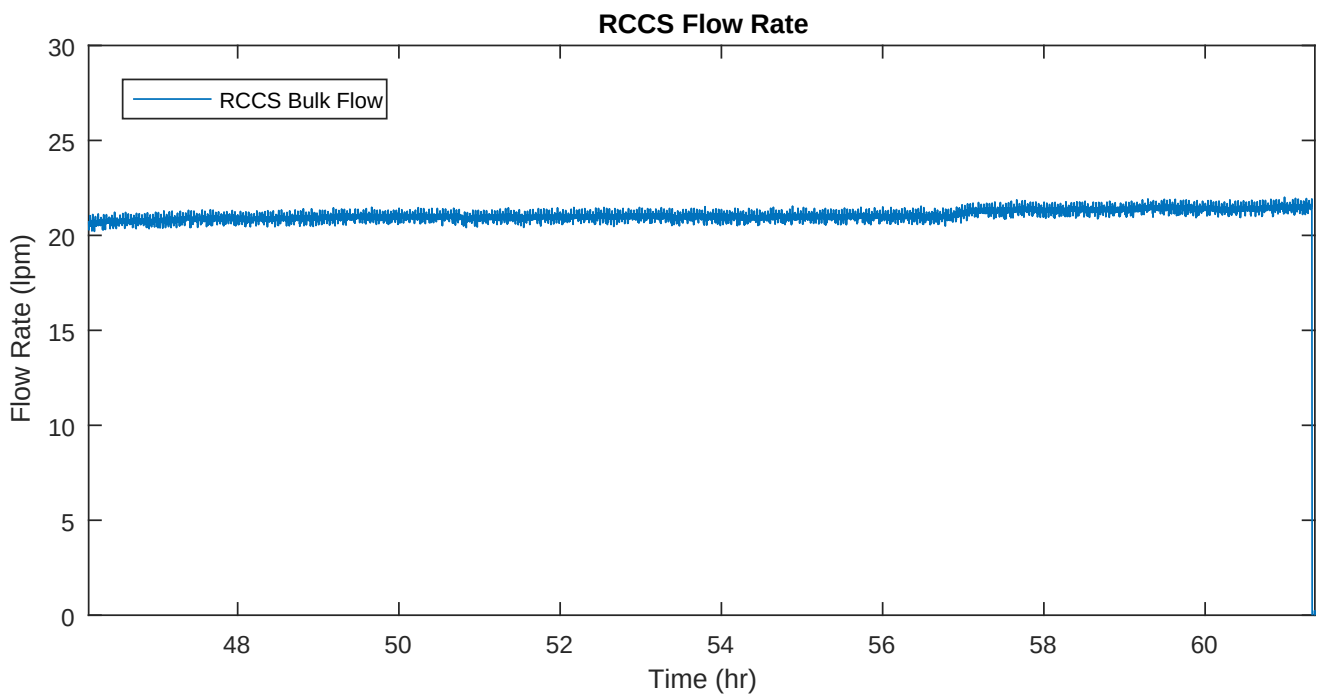

Figure 6.5: RCCS flow rate during the test.

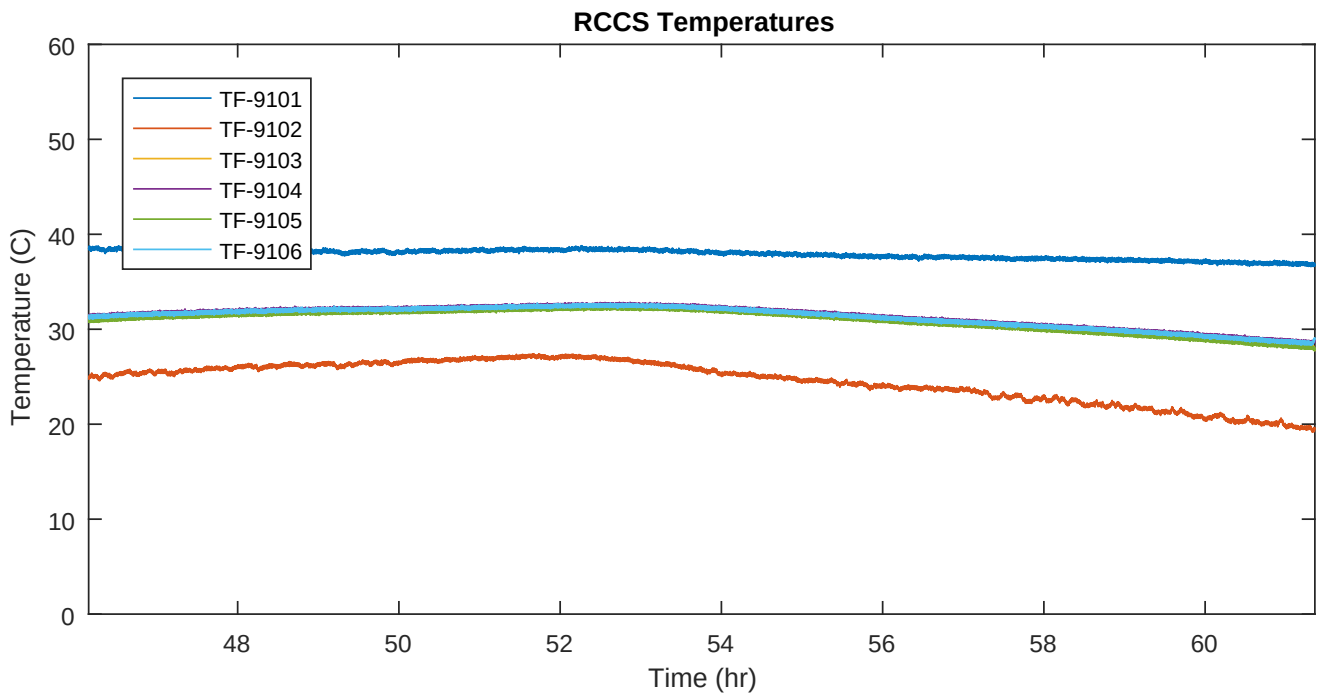

Figure 6.6: Temperatures on the Northeast corner of the RCCS. These are typical of the other three corners.

6.4. Steam Generator Performance

During this test, the steam generator was filled to approximately 70% of its volume before the test. As steam was not generated during the test, the steam generator did not require refilling. The control signals are shown in figure 6.7 and the level is shown in figure 6.9. The water inlet flow rate is measured and shown in figure 6.8.

The steam generator began the test with a pressure of about 175kPa, the SG pressure lowered relatively quickly to 120 kPa and then rose back to approximately 150kPa at the end of the test, see figure 6.10. The SG temperatures are shown in figure 6.11.

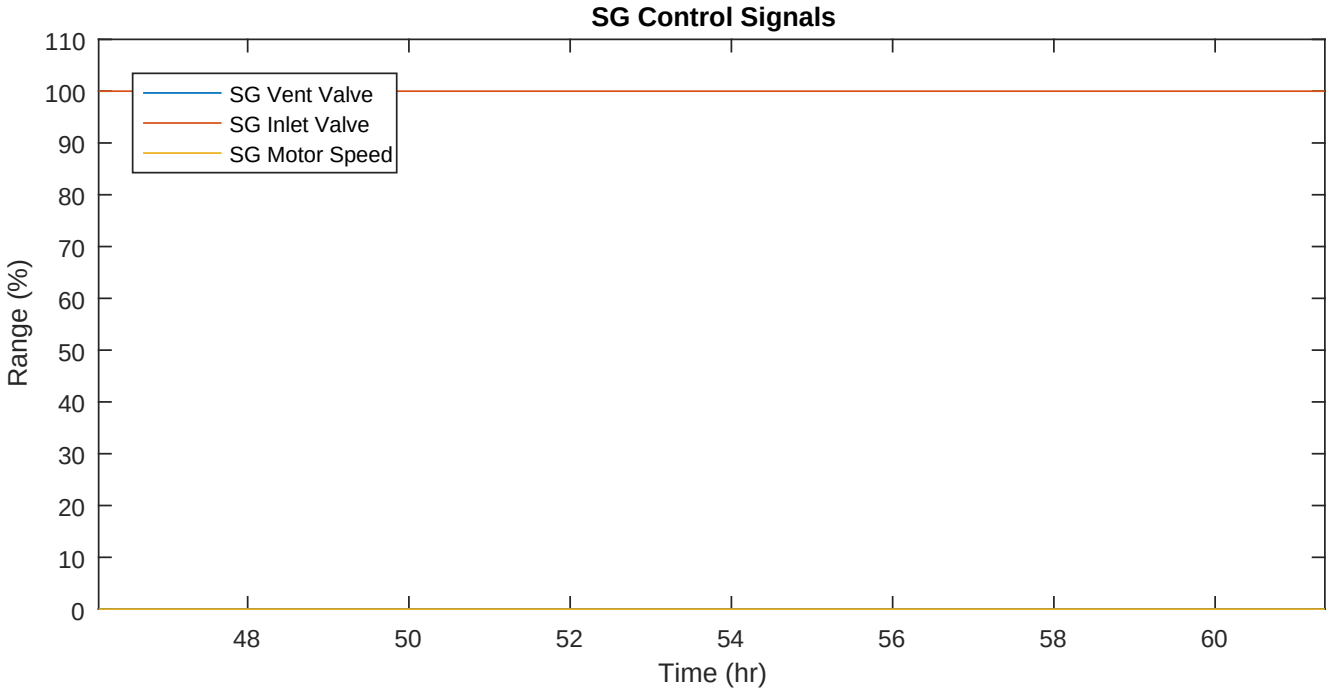

Figure 6.7: Steam Generator control signals: CV-5001 Vent valve position, CV-5002 water inlet valve position, and MS-9001 water inlet pump speed.

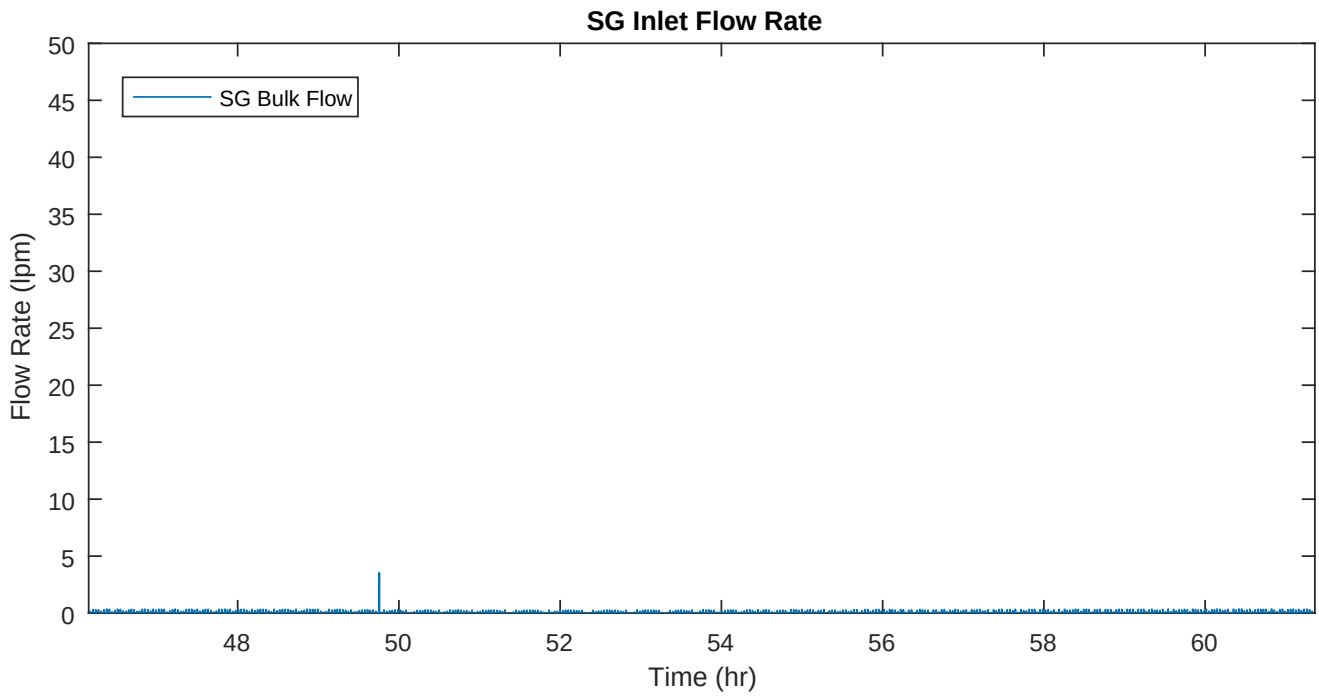

Figure 6.8: Steam Generator inlet flow rate, FT-5001

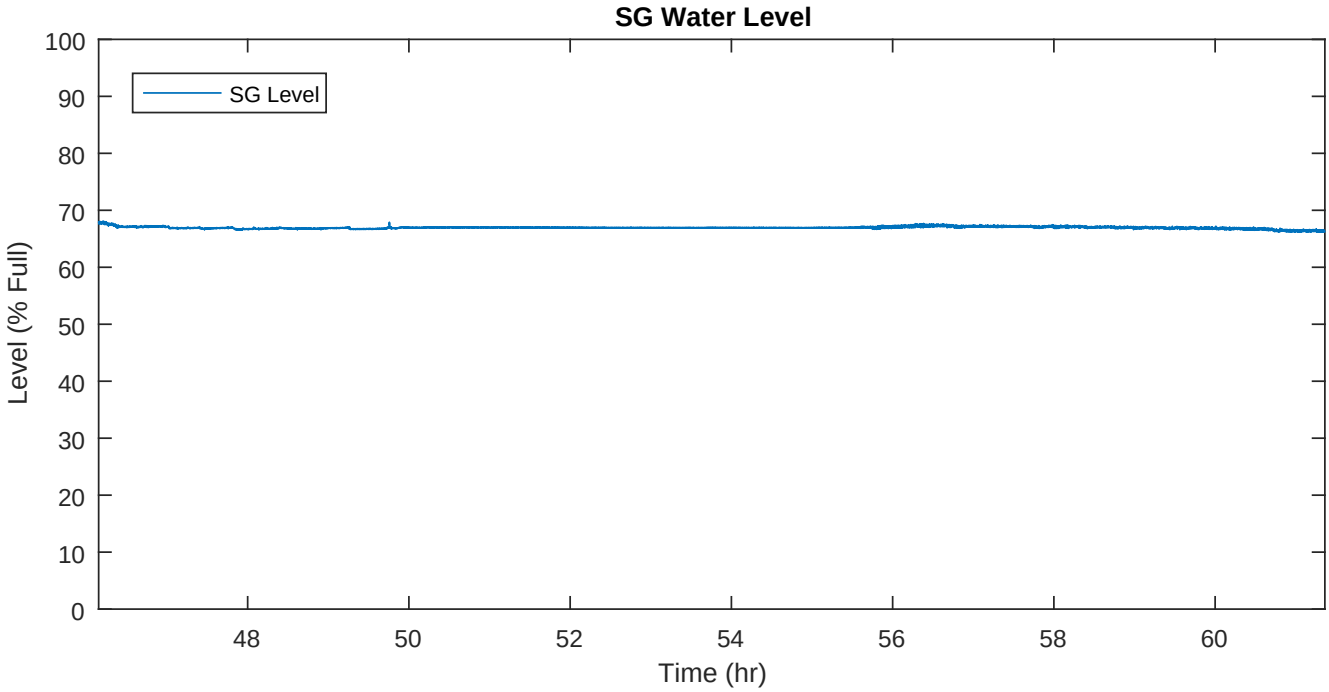

Figure 6.9: Steam Generator Water Level, LF-5002

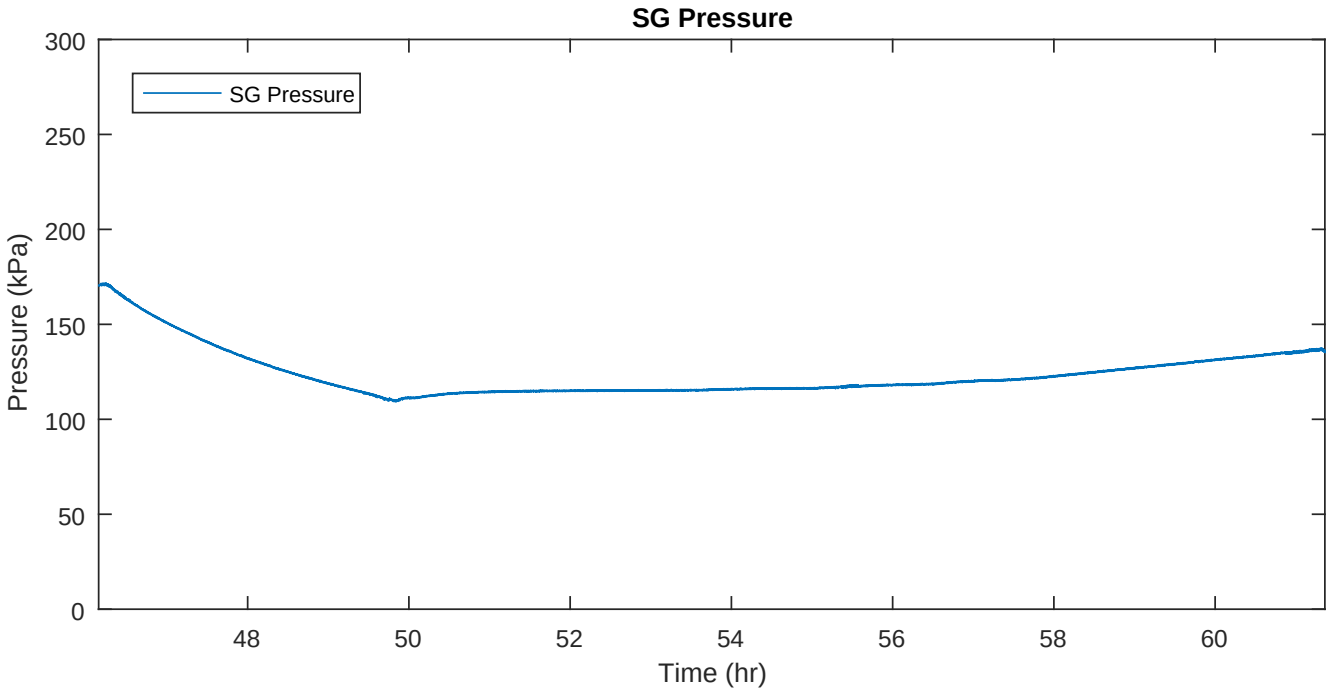

Figure 6.10: Steam Generator Pressure, PT-5001

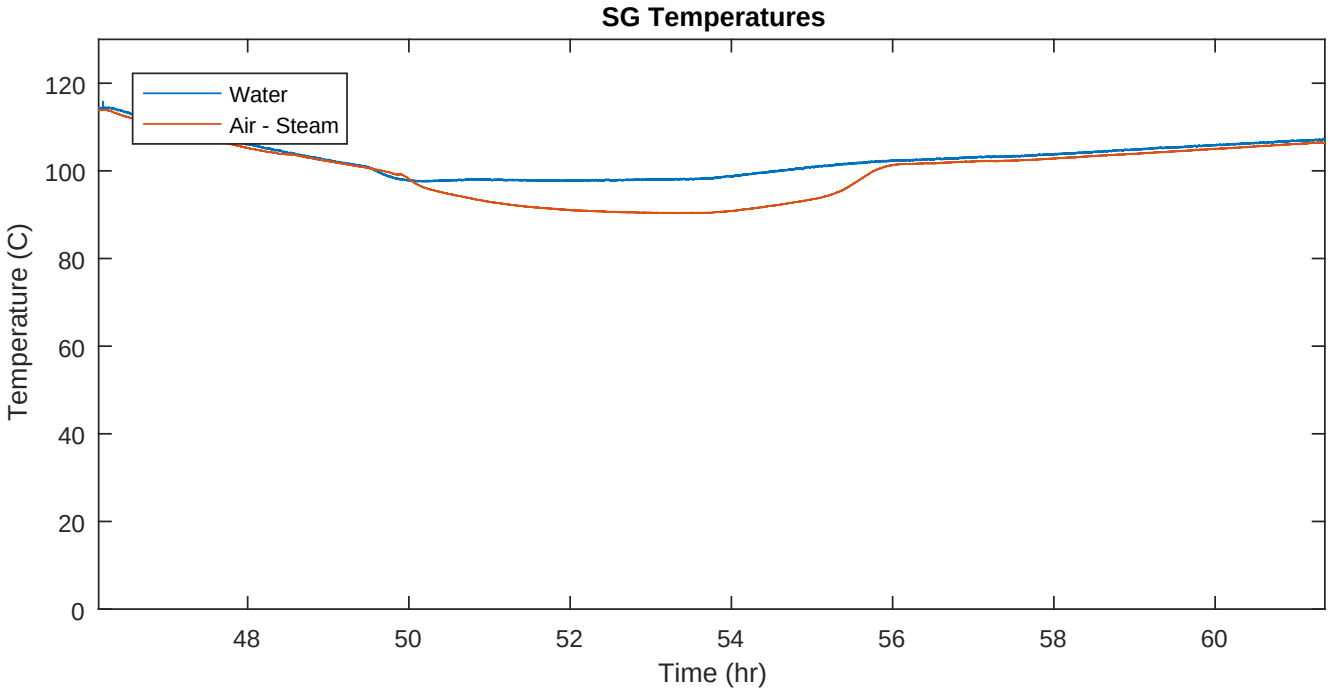

Figure 6.11: Steam Generator Fluid Temperatures, TF-5001 water temperature, TF-5002 air-steam temperature

6.5. Test Results

Figure 6.12 shows the core ceramic temperature at 4 different axial locations. The temperatures rise relatively rapidly upon the initial loss of forced convection. When forced convection is re-established the behavior of the temperatures at the various locations change. Higher in the core (TS-1707 and TS-1907) the temperature rise flattens out and eventually begins to fall. Lower in the core (TS-1307 and TS-1507) the temperatures continue to rise after the circulator restart.

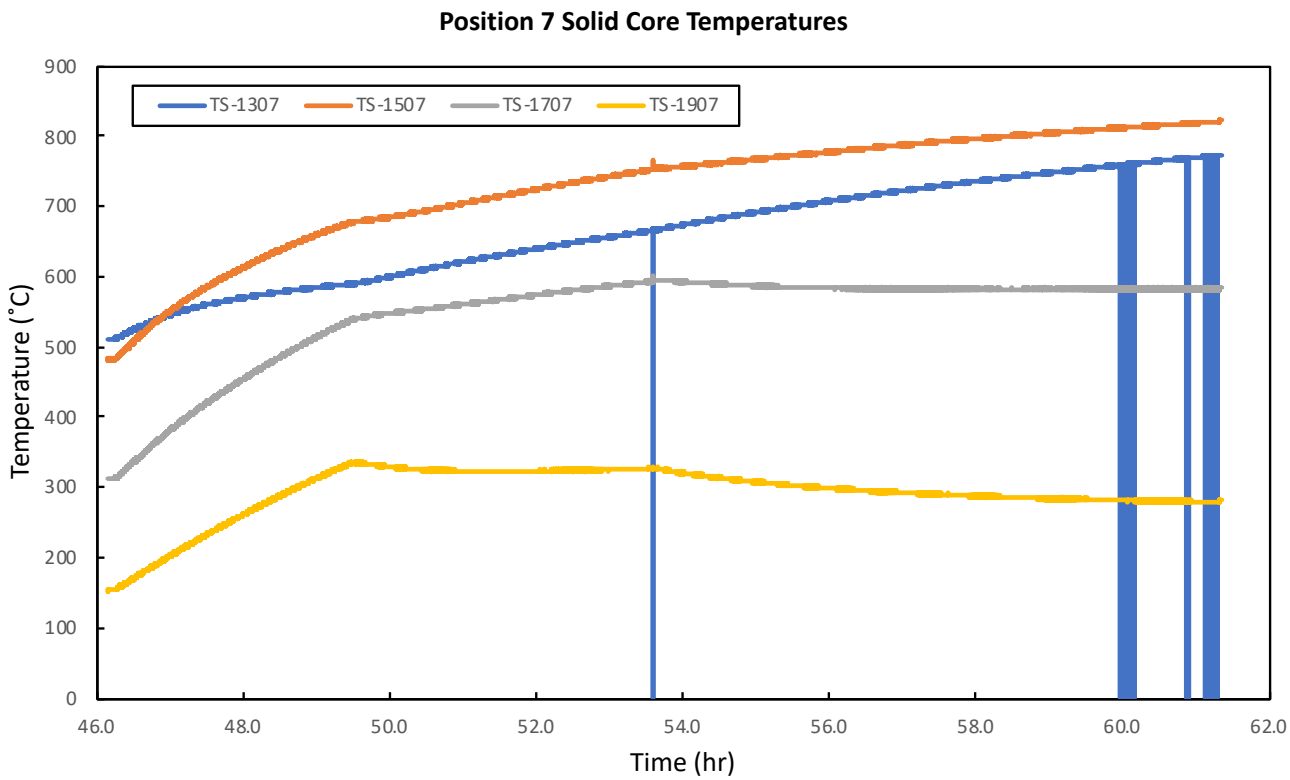

Figure 6.12: Core ceramic temperatures at location 7

Chapter 7. PG-33 Zero Power Long Term Cooldown Test

The purpose of this test is to examine long term passive cooling in an integral test facility scaled to General Atomics' Modular High Temperature Gas Reactor (MHGTR) design. This test began on 8/31/2019 and was completed on 9/4/2019. This test was started and completed in one session, and there is only one data file. In this report the data set, PG33_data, will be presented and discussed.

7.1. Initial Conditions

On August 31st, 2019, OSU-HTTF-TEST-031-R1 was completed and the heaters, main circulator, RCCS, and SG were secured. Operators Brian Woods and Tommy Moore transitioned over to test procedure OSU-HTTF-TEST-033-R0. For this test, the only active HTTF system was the data acquisition and control system. The facility conditions at the time of the start of PG_33 were not set specifically for the test but were rather the final conditions of PG_31. All members of the testing team were certified as HTTF Test Engineers and were briefed on the purpose of the test before they began operating the facility.

7.2. Heater Operation

The heaters were not operated during the test.

7.3. Reactor Cavity Cooling System

The system was not operated for this test, with the motor speed kept at 0%.

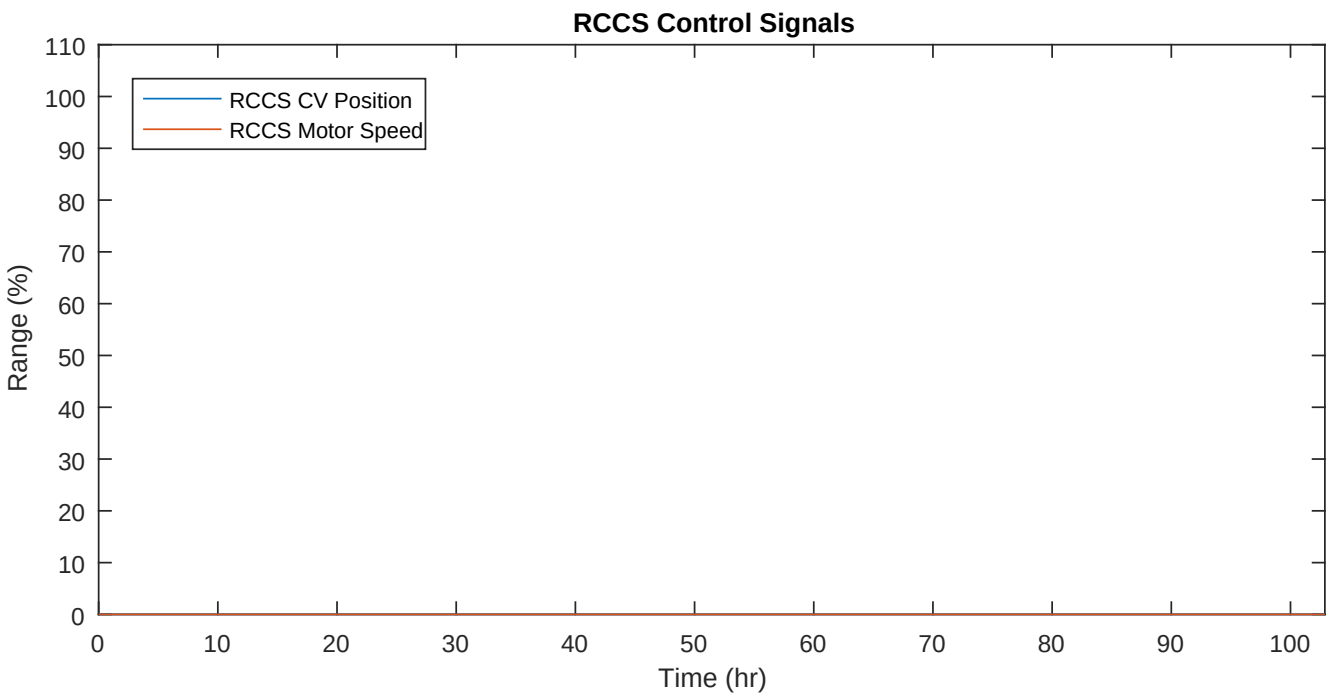

Figure 7.1: RCCS Control signals: MS-9001 and CV-9001

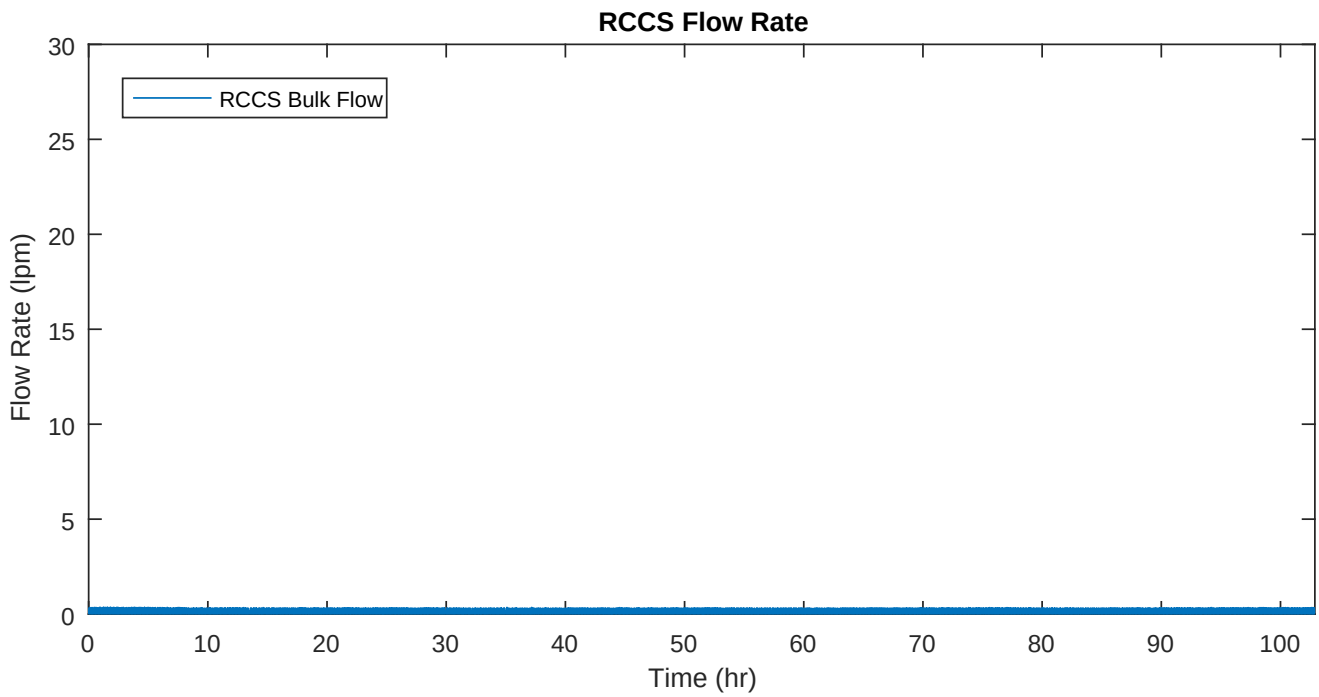

Figure 7.2: RCCS flow rate during the test.

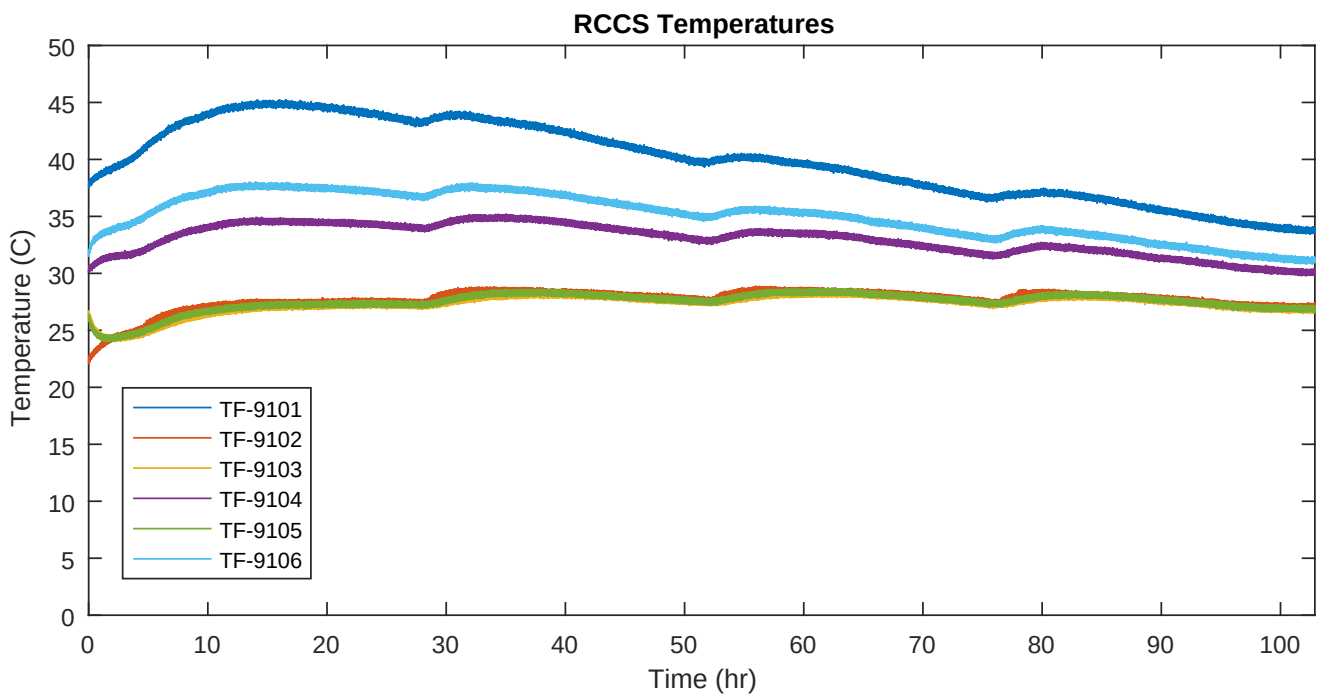

Figure 7.3: Temperatures on the Northeast corner of the RCCS. These are typical of the other three corners.

7.4. Steam Generator Performance

At the start of the test the steam generator level was approximately 66% and the SG pressure was reduced to approximately 115 kPa. During this test, water was not added or removed from the SG, as steam was never created. The SG pressure remained largely constant throughout the test.

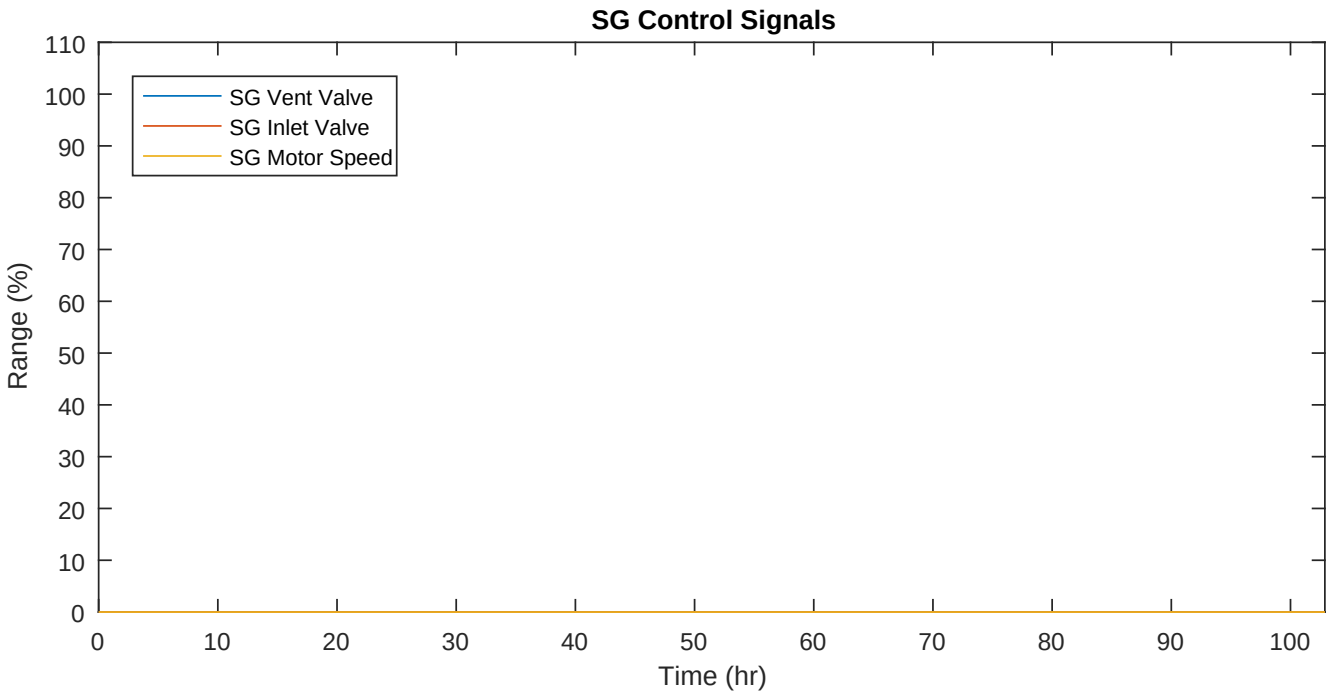

Figure 7.4: Steam Generator control signals: CV-5001 Vent valve position, CV-5002 water inlet valve position, and MS-9001 water inlet pump speed.

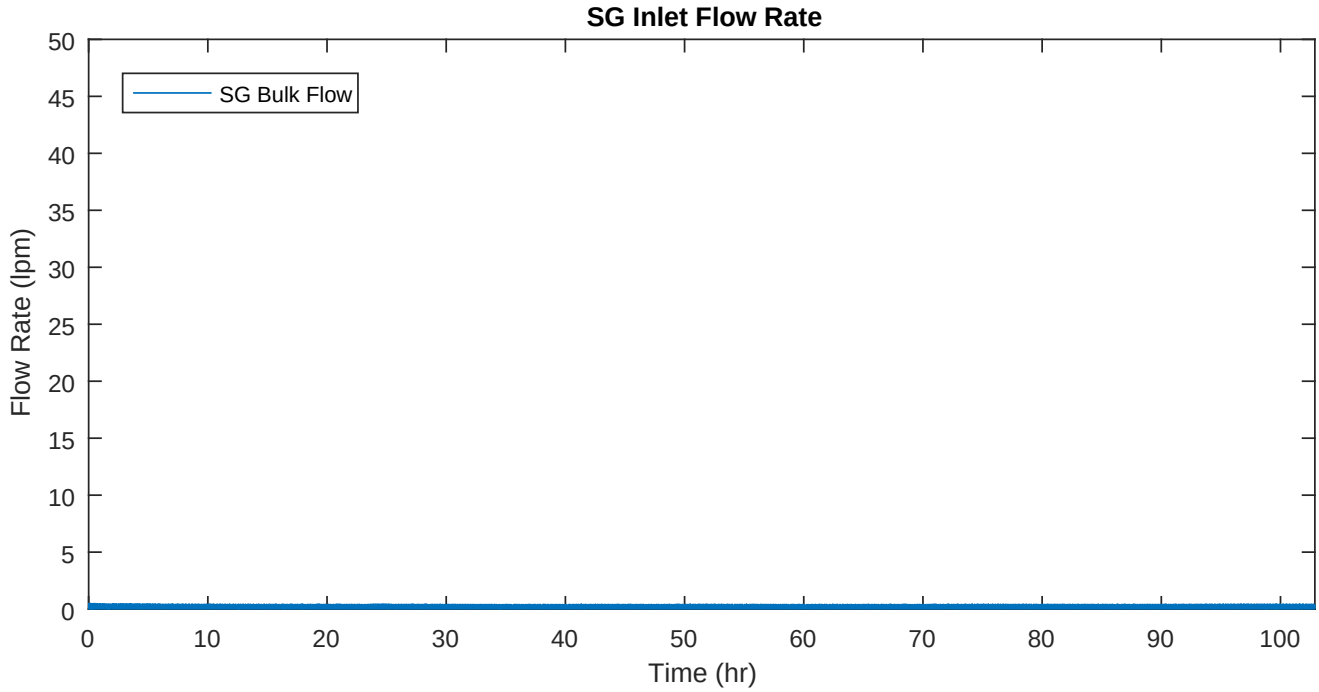

Figure 7.5: Steam Generator inlet flow rate, FT-5001

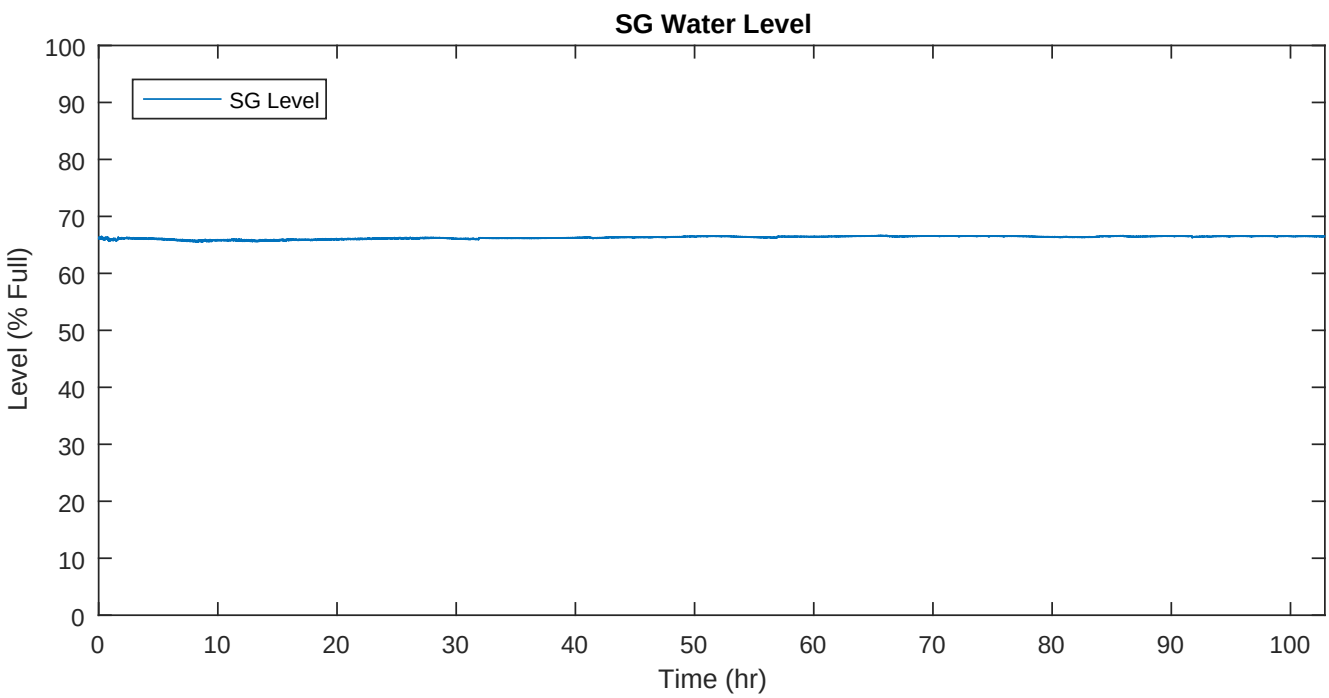

Figure 7.6: Steam Generator Water Level, LF-5002

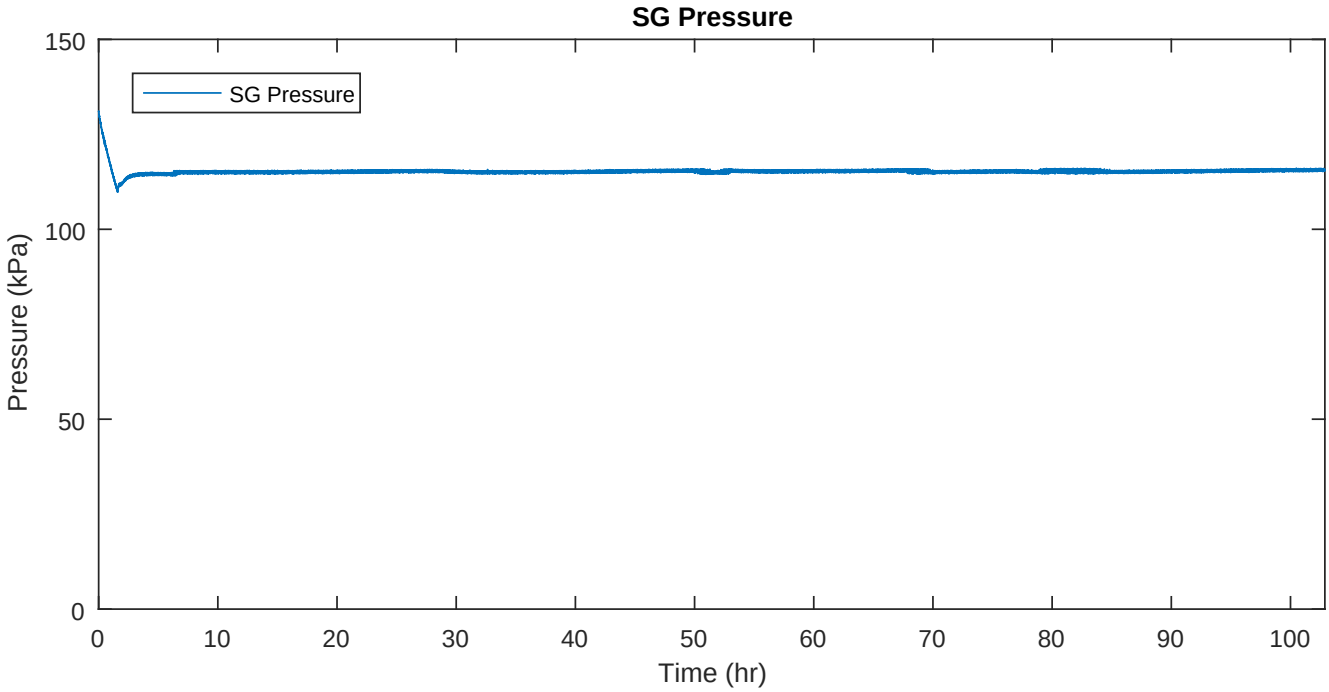

Figure 7.7: Steam Generator Pressure, PT-5001

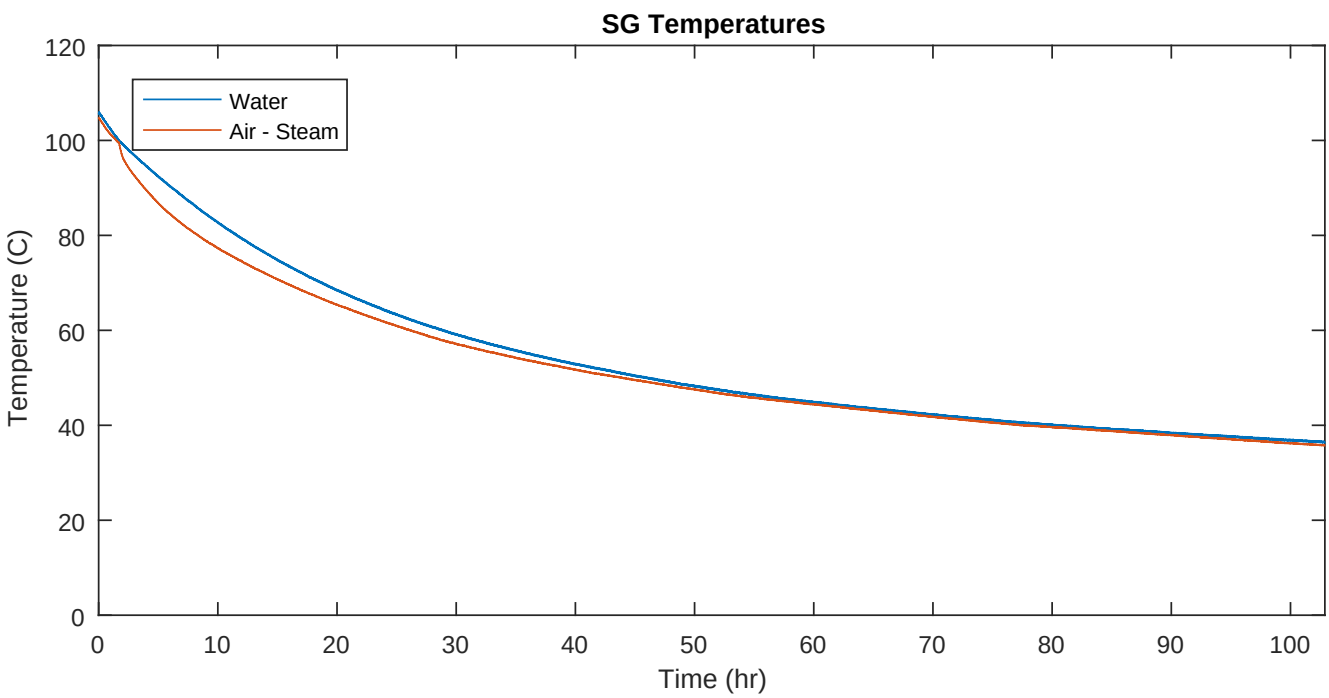

Figure 7.8: Steam Generator Fluid Temperatures, TF-5001 water temperature, TF-5002 air-steam temperature

7.5. Test Results

The purpose of this test is to examine the long term cooldown of the HTTF through conduction and convection within the vessel and radiation and convection outside of the vessel. The test continued for five days as the core and system cooled down. Figure 7.9 shows the core ceramic temperature at 4 different axial locations. Over the course of this test there is an exponential decrease in the core ceramic temperatures.

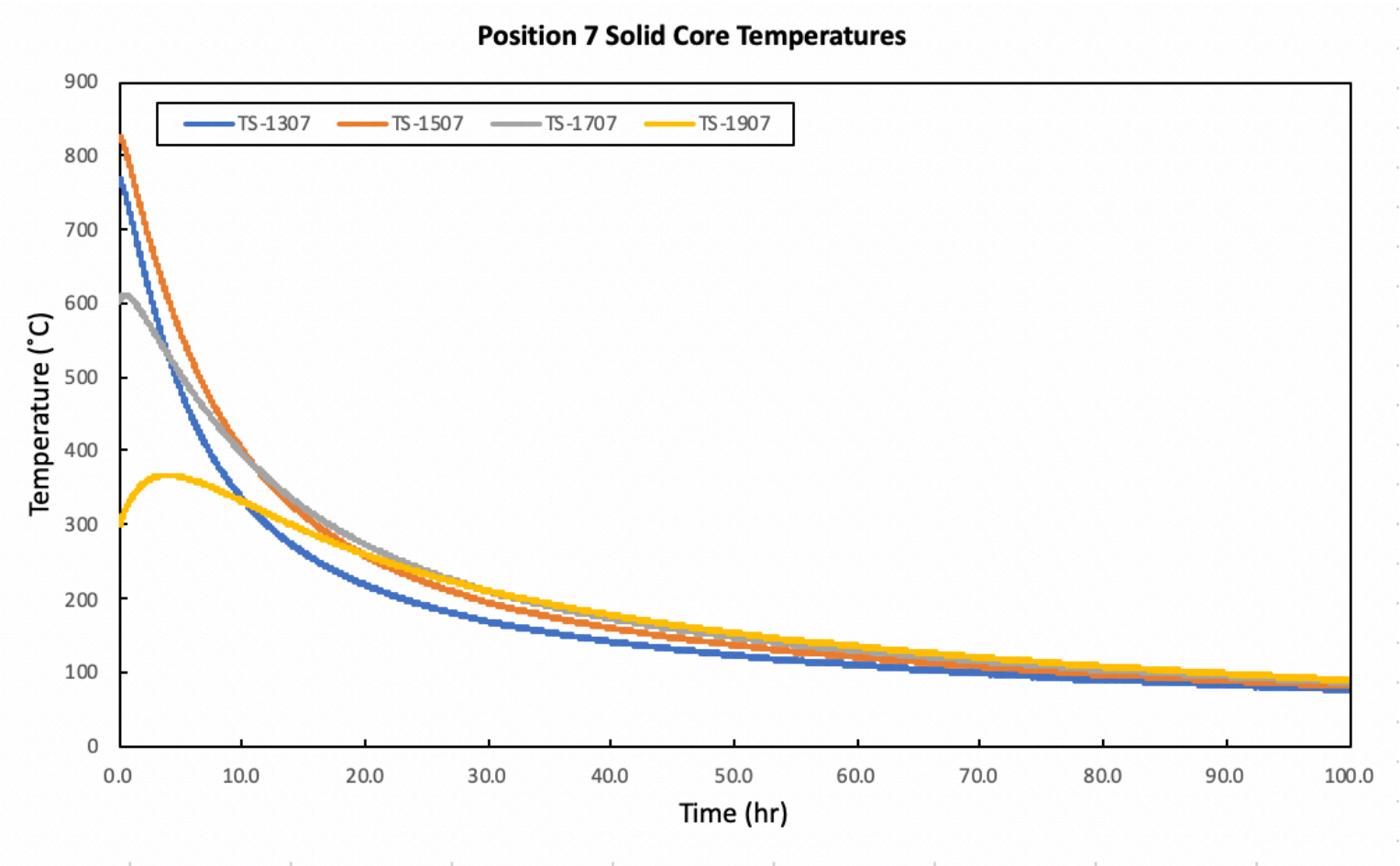

Figure 7.9: Core ceramic temperatures at location 7

Chapter 8. PG-34 Low Power (<350kW) Asymmetric Core Heatup Full Hybrid Heater

The purpose of this test is to examine the facility heatup under asymmetric heating conditions in an integral test facility scaled to General Atomics' Modular High Temperature Gas Reactor (MHGTR) design.

This test began on 7/31/2019 and was completed on 8/1/2019. This test was started and completed in one session, and there is only one data file. In this report the data set, PG30_PG31_a_data, will be presented and discussed.

8.1. Initial Conditions

On July 31st, 2019, the HTTF was energized using OSU-HTTF-O&M-011-R1 with the Hybrid Heater Configuration 3 outlined in OSU-HTTF-CORE-DWG-030-R3. This was a heatup in preparation for PG-030 and PG-031. 40 hours into the heatup there was a heater failure at which point the heatup was stopped. This heatup was re-designated as PG-034 following the heater failure. It serves as a companion test to PG-032 which was a heatup with only one leg of the Hybrid Heater Configuration 3 in operation. All members of the testing team were certified as HTTF Test Engineers.

The facility had been conditioned prior to the test following OSU-HTTF-O&M-010-R2. The facility conditions at the time of the start of the test are presented in Table 9.1. All pumps were secured and the flow rate was zero in each fluid carrying system at the start of the test.

Table 8.1: Initial conditions for the start of the test.

Primary Loop:	>200 kPa helium
RCSS:	>130 kPa helium
Cooling Water System:	filled with water, ambient pressure
Steam Generator:	60 to 80% water level, ambient pressure
RCCS Tank:	filled with water, ambient pressure
RCCS Panels:	filled with water, ambient pressure

8.2. Heater Operation

Hybrid heater configuration 3 was operated during the test using HO-103/104. In the 39th hour after test start the heaters failed and were secured to prevent damage to the heaters.

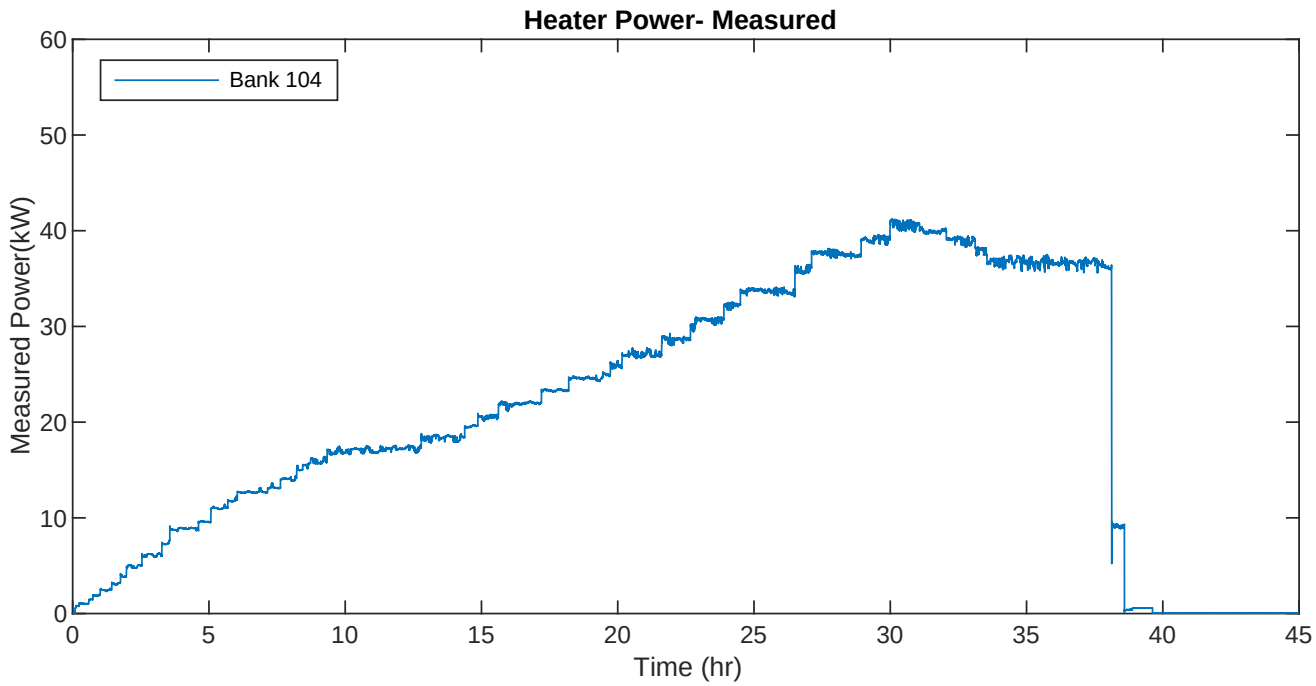

Figure 8.1: Measured heater power output on channel HO-103/104

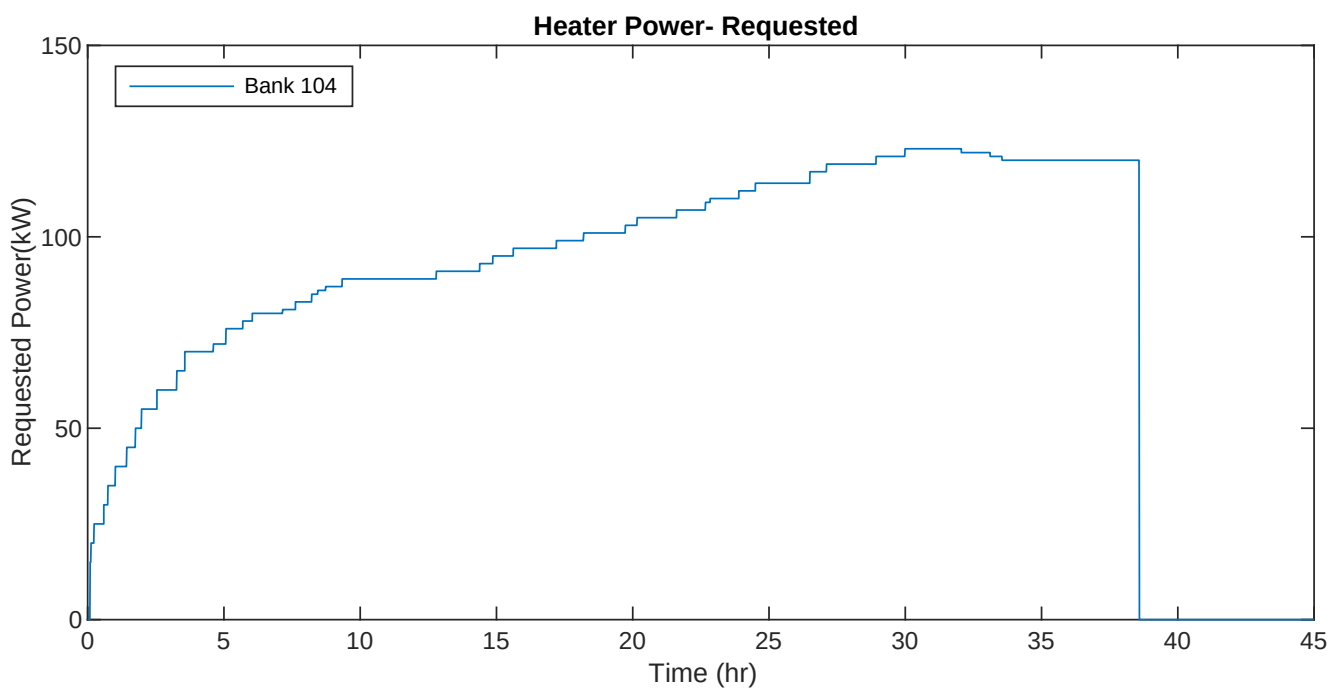

Figure 8.2: Requested heater power output on channel HO-103/104

8.3. Reactor Cavity Cooling System

In the 28th hour of the test, the RCCS pump was started. It operated at a pump speed of 30% for the remainder of the test.

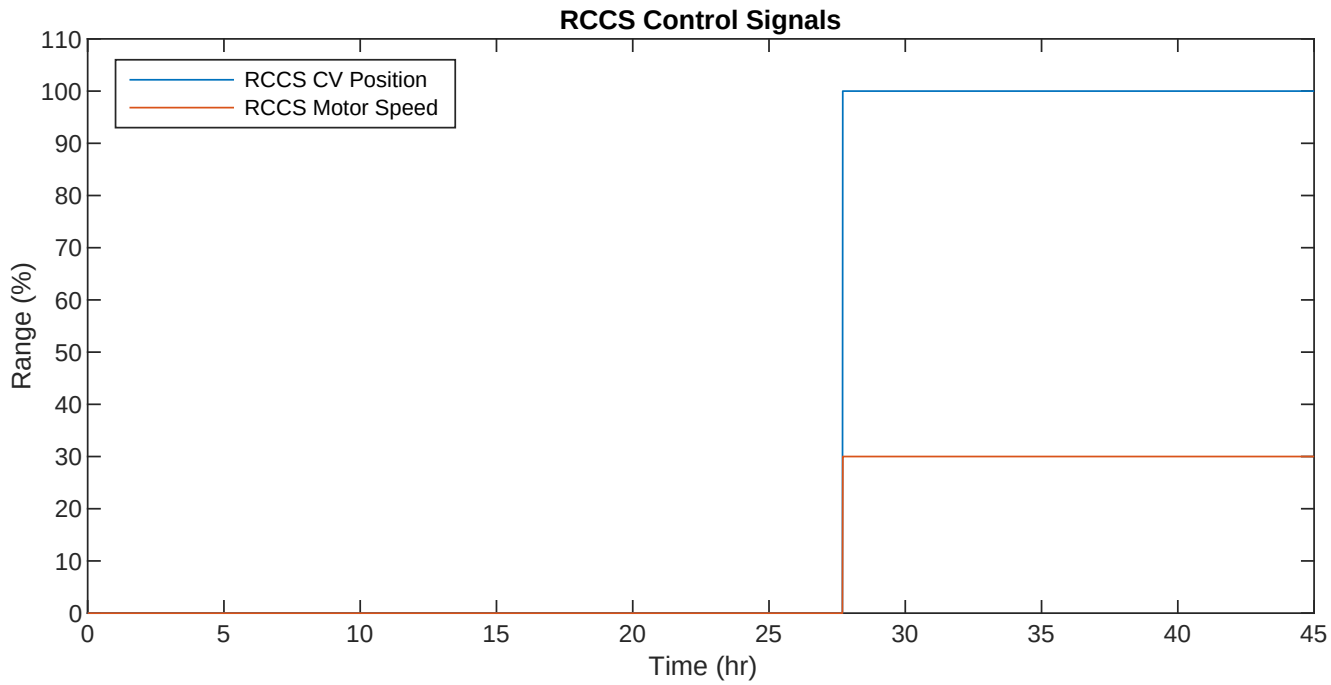

Figure 8.3: RCCS Control signals: MS-9001 and CV-9001

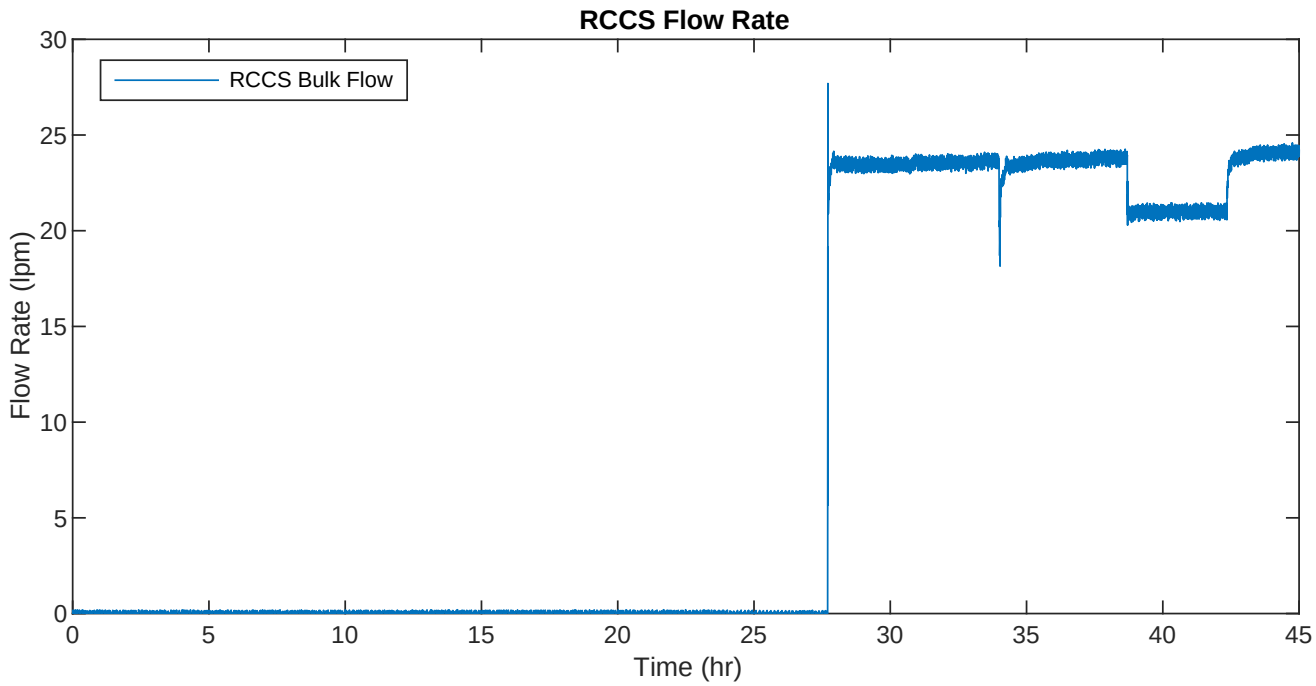

Figure 8.4: RCCS flow rate during the test.

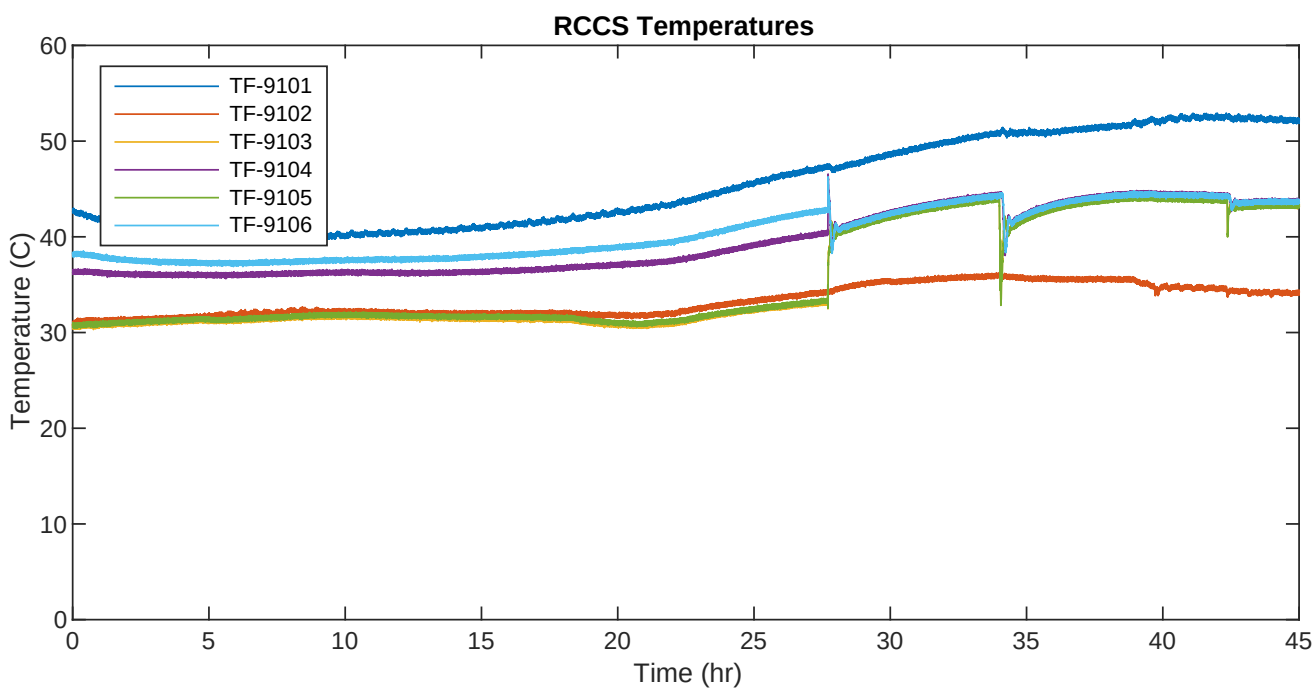

Figure 8.5: Temperatures on the Northeast corner of the RCCS. These are typical of the other three corners.

8.4. Steam Generator Performance

The steam generator was filled to approximately 74% of its volume before the test. During the initial stages of the test the water was heated reaching saturation in the 17th hour. After this time, the pressure in the SG rose steadily as steam was being generated eventually reaching a peak of over 400 kPa. The SG vent valves were operated to lower the SG pressure below 200 kPa. There were two water additions to the SG during the test. One in the 35th and 39th hours after test start.

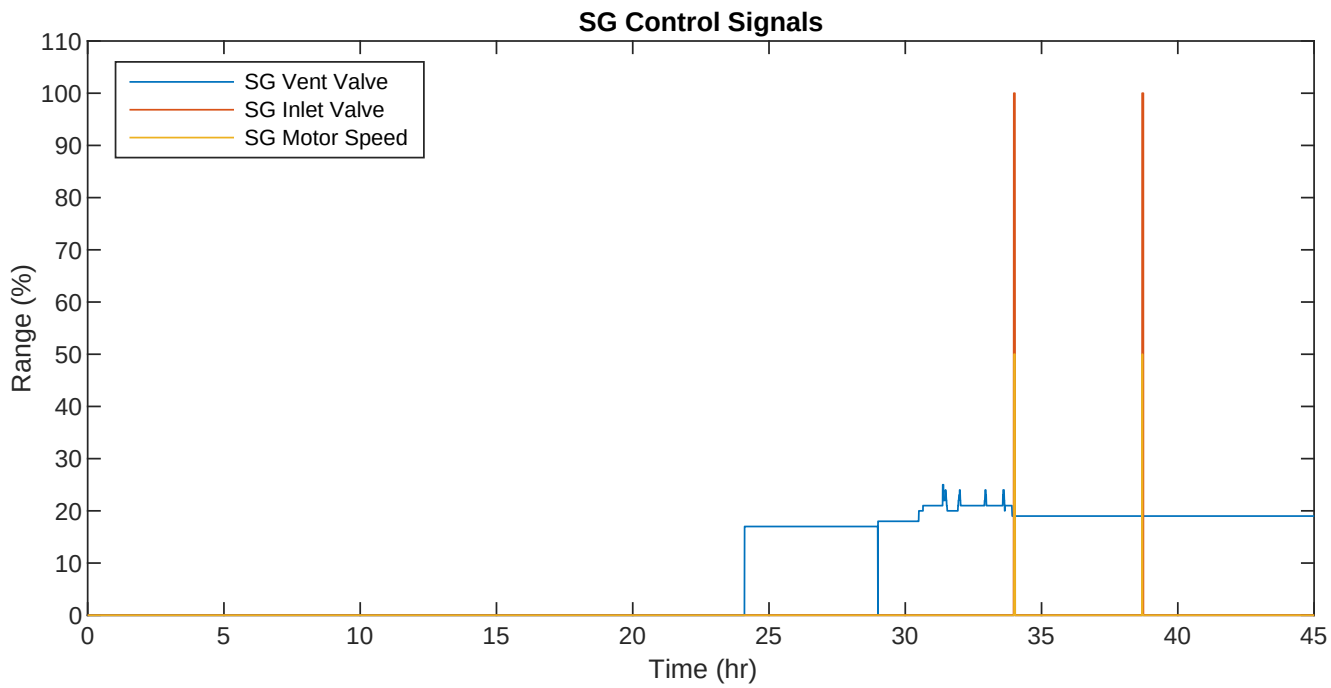

Figure 8.6: Steam Generator control signals: CV-5001 Vent valve position, CV-5002 water inlet valve position, and MS-5001 water inlet pump speed.

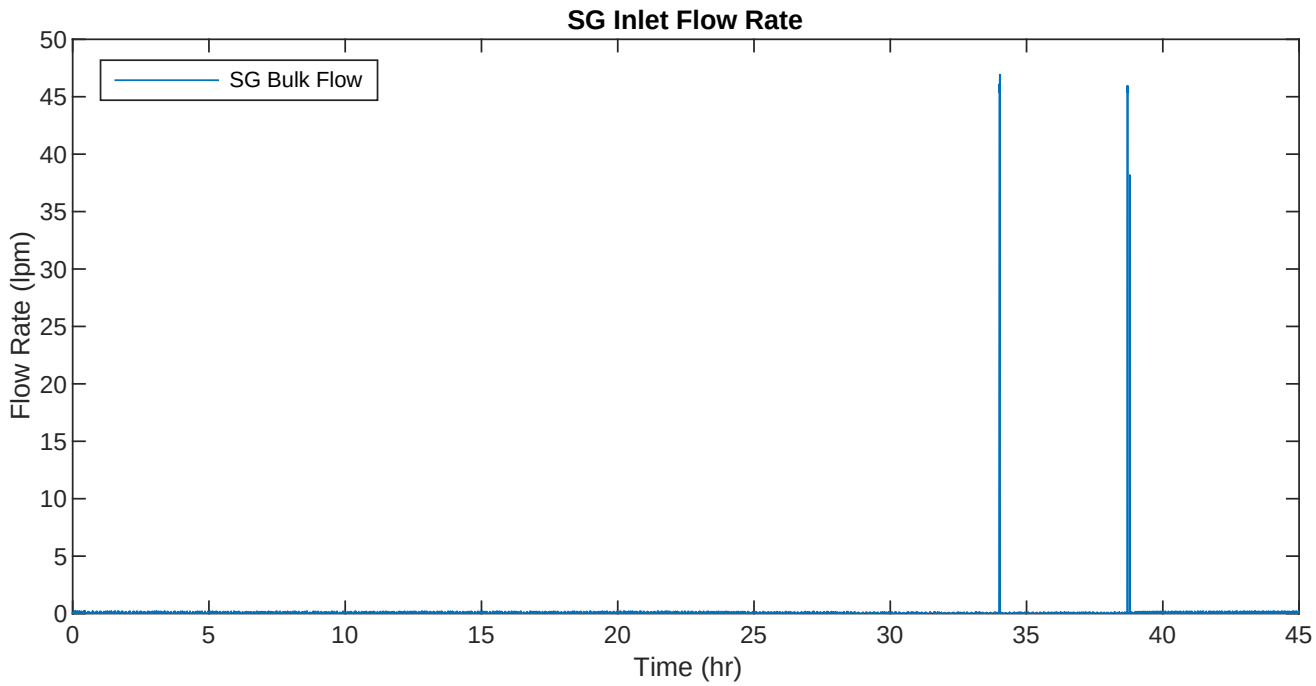

Figure 8.7: Steam Generator inlet flow rate, FT-5001

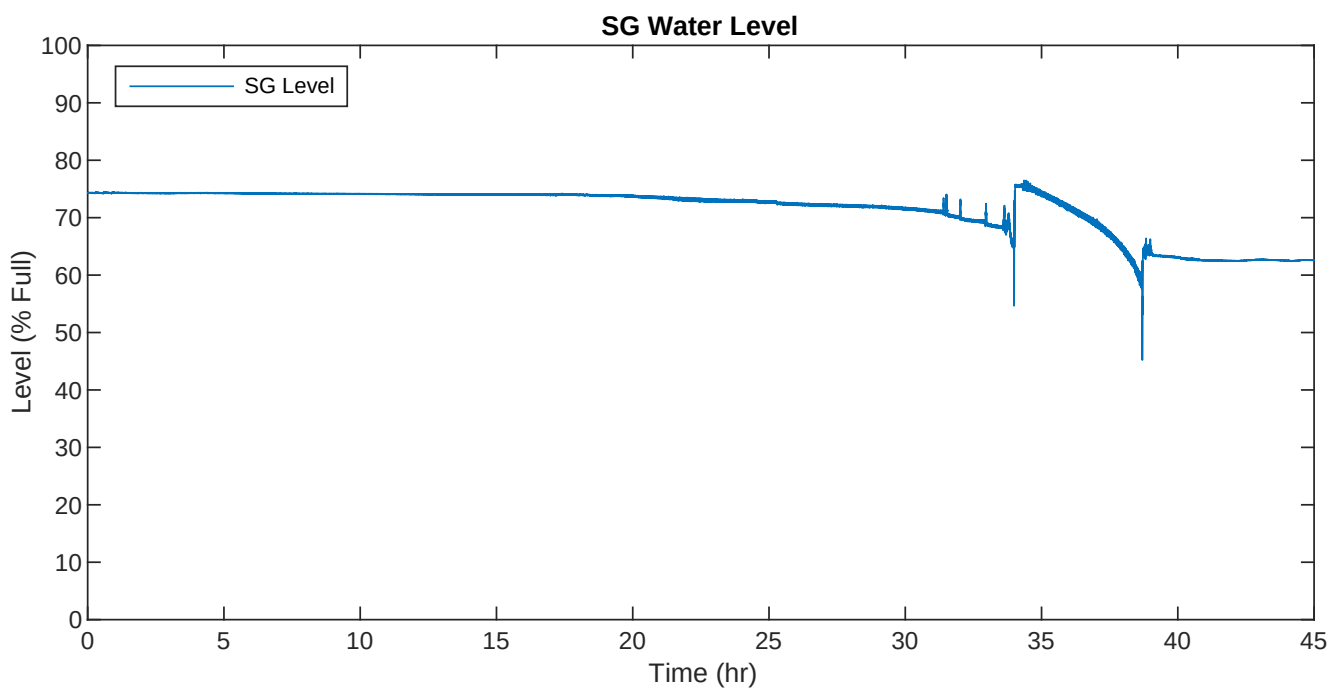

Figure 8.8: Steam Generator Water Level, LF-5002

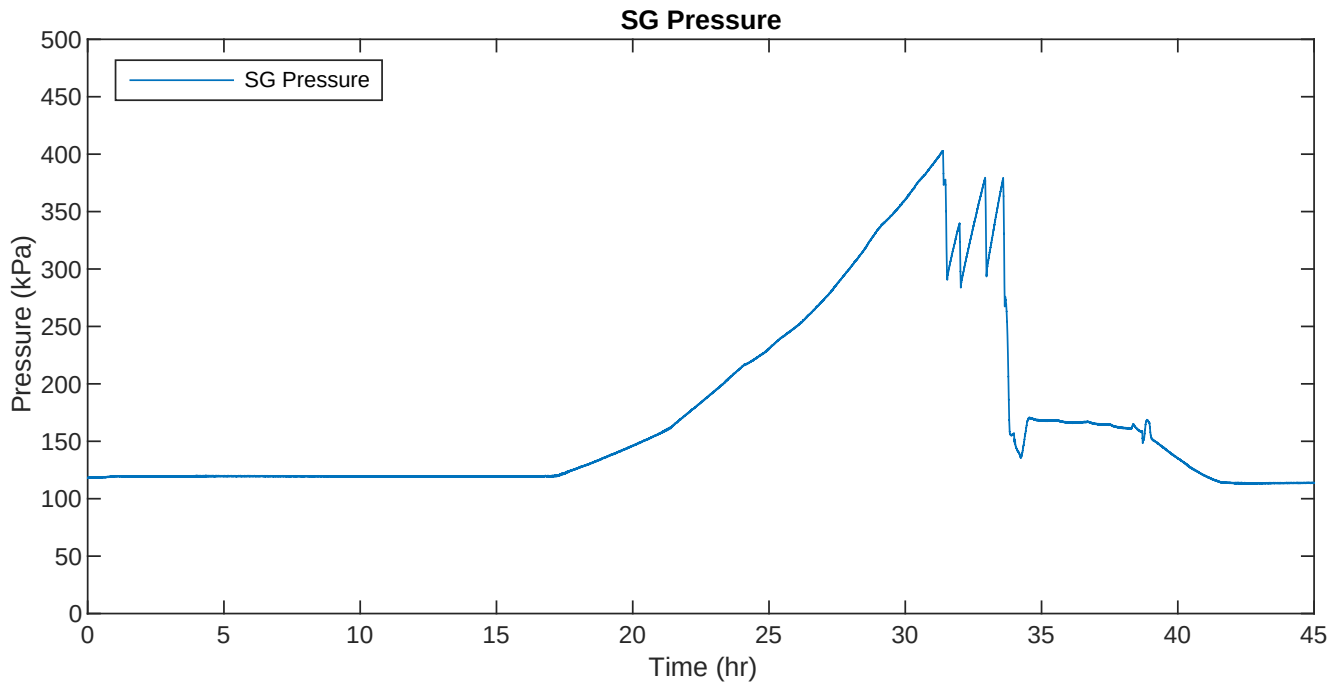

Figure 8.9: Steam Generator Pressure, PT-5001

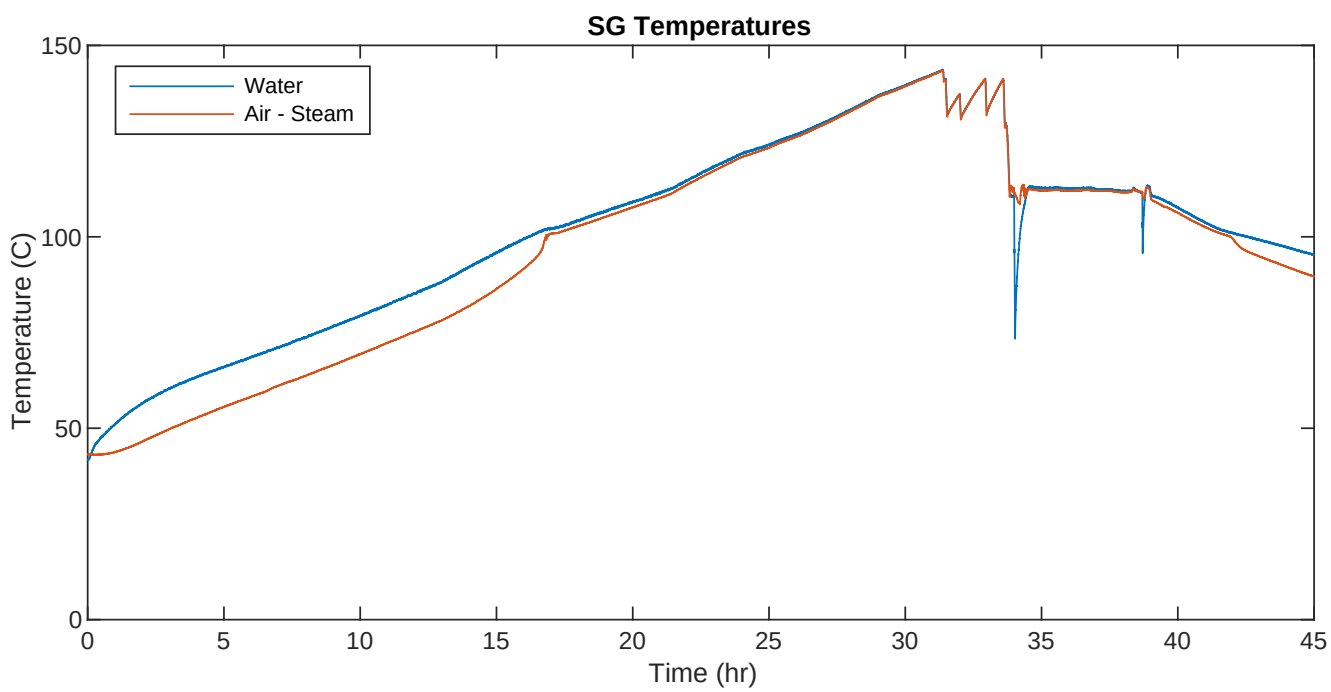

Figure 8.10: Steam Generator Fluid Temperatures, TF-5001 water temperature, TF-5002 air-steam temperature

8.5. Test Results

PG-34 is a test that examines the heat up of the test facility using an asymmetric heater configuration. Figure 8.11 shows the heat up of 3 ceramic core temperatures at 3 axial locations during the performance of PG-32. These thermocouples are located in the primary core sector.

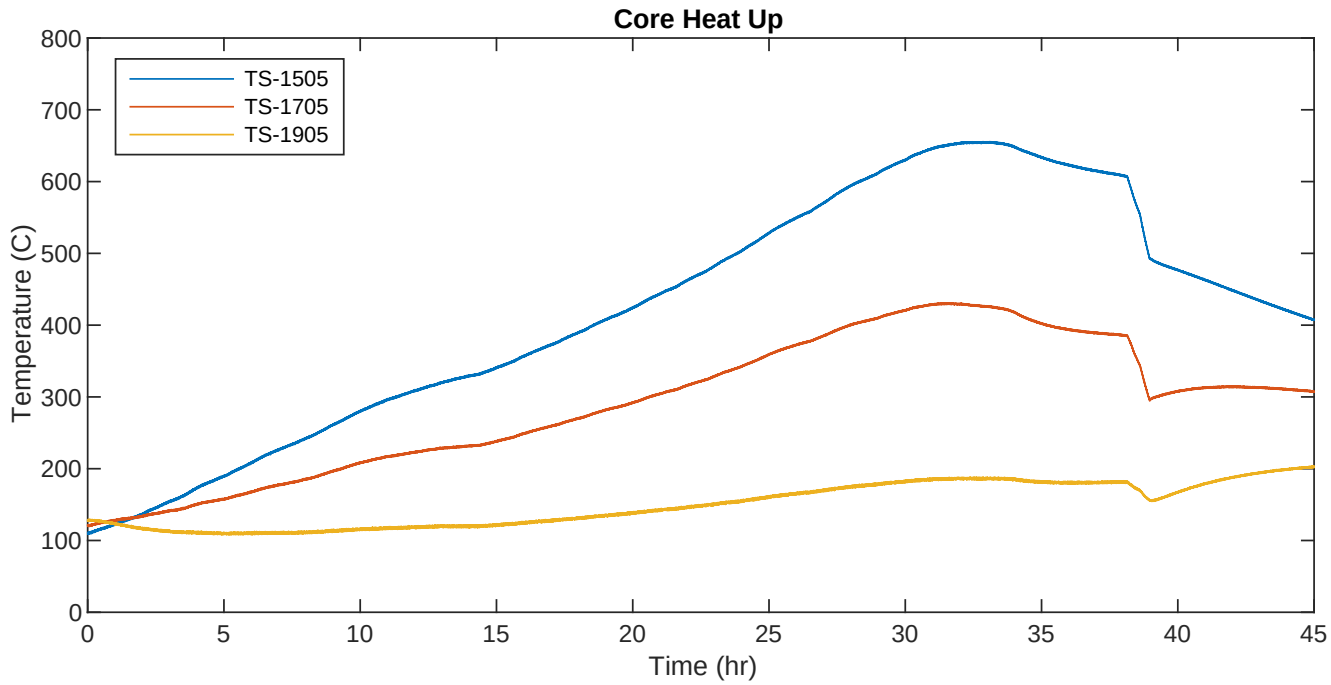

Figure 8.11: Plot of ceramic core temperatures, TS-1505, TS-1705, and TS-1905.

Chapter 9. PG-35 Zero Power Crossover Duct Exchange Flow and Diffusion Test 1

The purpose of this test is to examine exchange flow in the crossover duct and diffusion of gases in an integral test facility scaled to General Atomics' Modular High Temperature Gas Reactor (MHGTR) design.

This test began on 6/3/2019 and was completed on 6/4/2019. This test was started and completed in one session, and there is only one data file. In this report the data set, LockEx1_data, will be presented and discussed.

9.1. Initial Conditions

On June 2, 2019, the HTTF was put into hot standby following the completion of PG-026, which was a DCC test. While the facility was cooling down, a vacuum was placed on the system in order to remove the gases present from the previous test. The primary was then filled with helium and the RCST filled with nitrogen. Approximately 27 hours following the completion of PG-026, PG-035 was initiated by opening the hot leg (SV-3001) and cold leg (SV-6001) break valves. All members of the testing team were certified as HTTF Test Engineers.

The facility conditions at the time of the start of the test are presented in Table 9.1. All pumps were secured and the flow rate was zero in each fluid carrying system at the start of the test.

Table 9.1: Initial conditions for the start of the test.

Primary Loop:	>120 kPa helium
RCSS:	<120 kPa helium
Cooling Water System:	filled with water, ambient pressure
Steam Generator:	>60% water level, ambient pressure
RCCS Tank:	filled with water, ambient pressure
RCCS Panels:	filled with water, ambient pressure

9.2. Heater Operation

Neither the heaters nor the main circulator were operated during this test.

9.3. Reactor Cavity Cooling System

The RCCS was filled for the duration of this test although the RCCS pump was not operated. Figure 9.1 shows representative temperatures in the RCCS during the test.

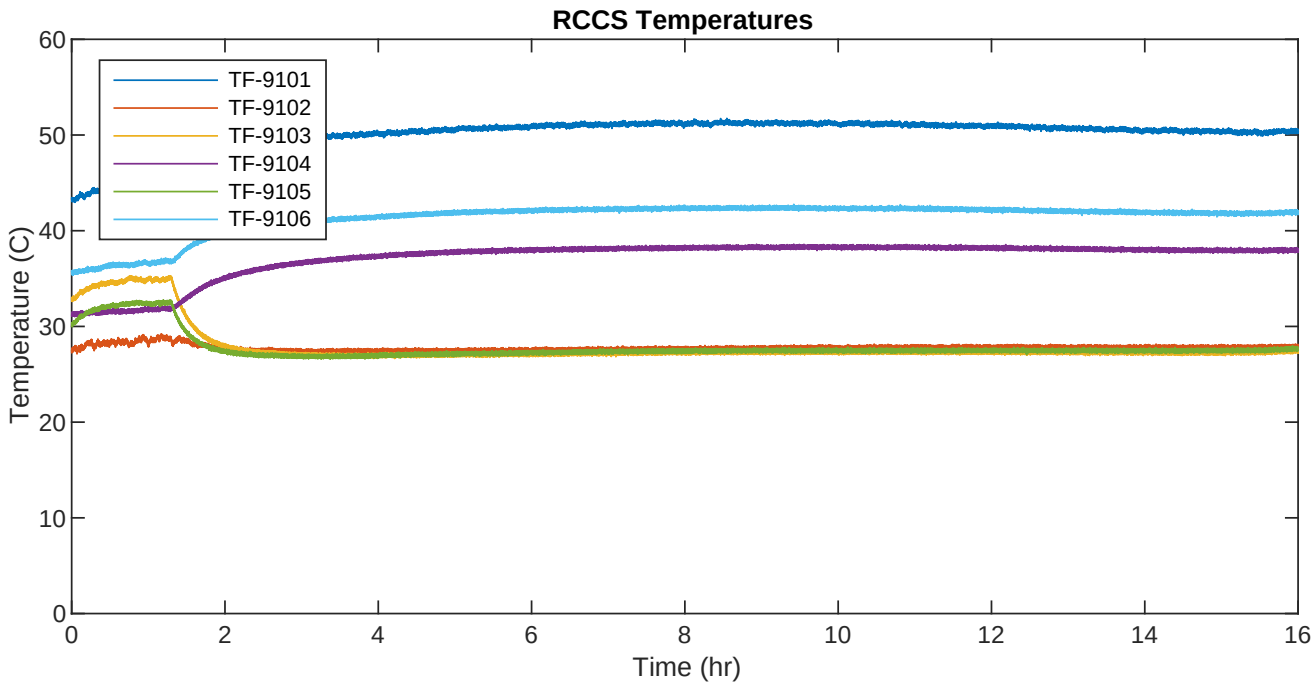

Figure 9.1: Temperatures on the Northeast corner of the RCCS. These are typical of the other three corners.

9.4. Steam Generator Performance

The steam generator remained at approximately 61% level during the duration of the test with a pressure around 115 kPa. The water on the secondary side of the steam generator remained well subcooled. No water was added to the steam generator during the test.

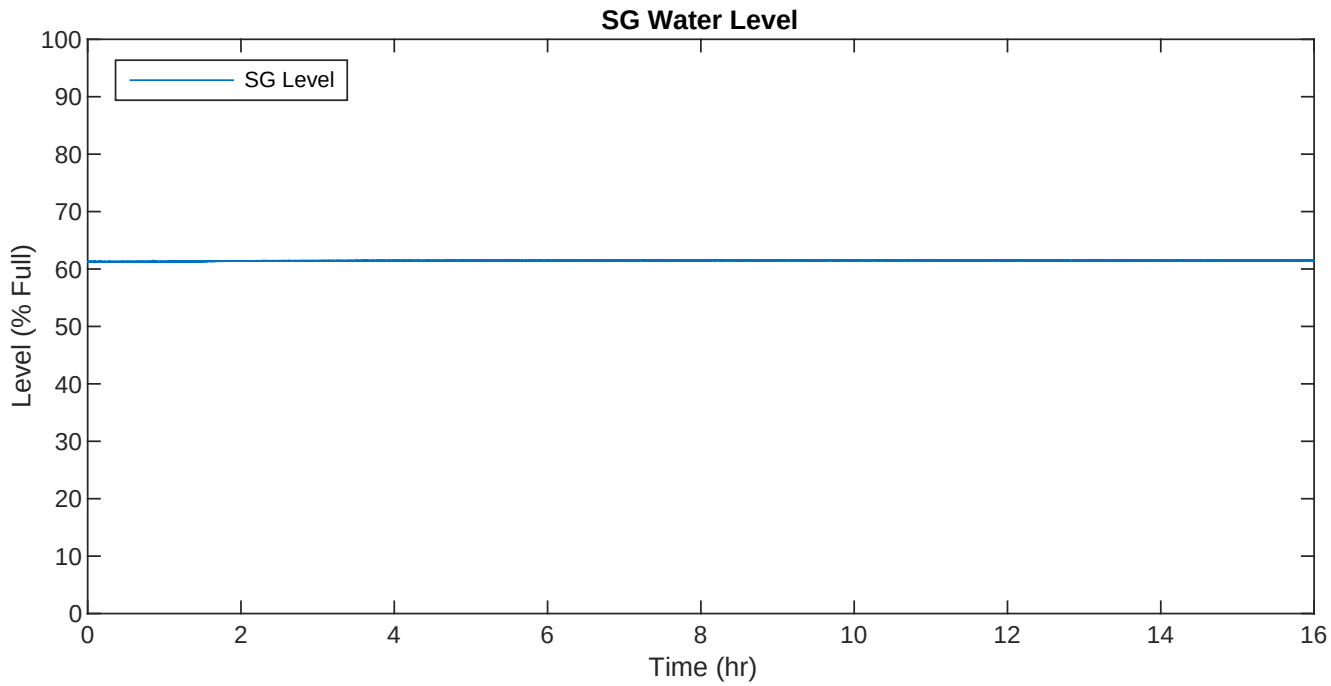

Figure 9.2: Steam Generator Water Level, LF-5002

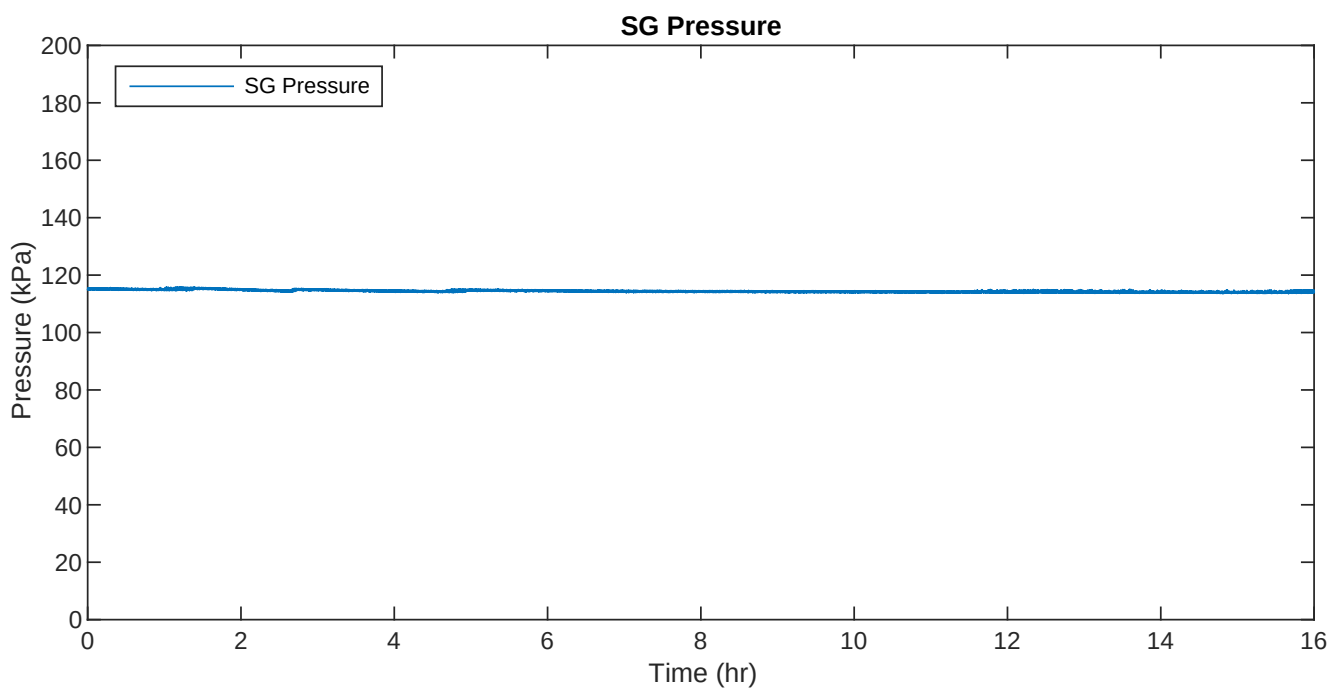

Figure 9.3: Steam Generator Pressure, PT-5001

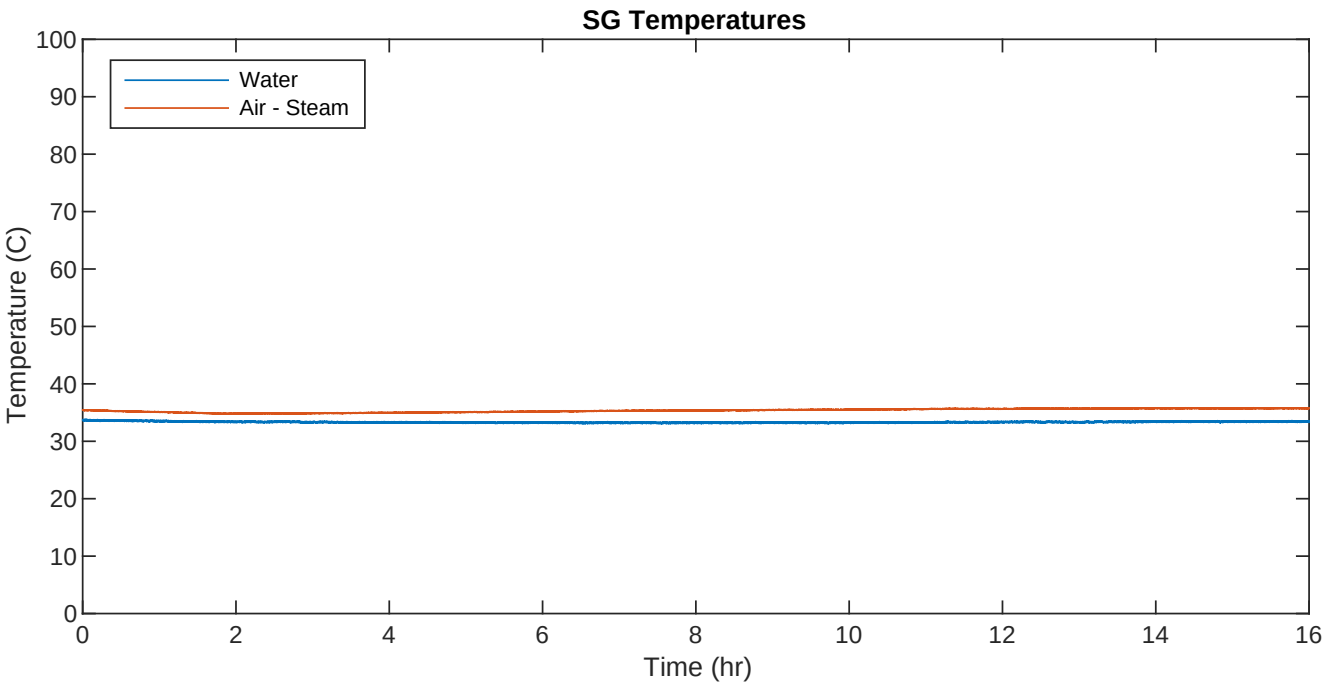

Figure 9.4: Steam Generator Fluid Temperatures, TF-5001 water temperature, TF-5002 air-steam temperature

9.5. Test Results

PG-035 is a test that examines the exchange flow and diffusion in the system loop following a hot and cold leg crossover duct break. Figures 9.5 and 9.6 show gas temperatures in the outlet duct (hot leg) while figure 9.7 shows gas temperatures in the inlet duct (cold leg) during the test.

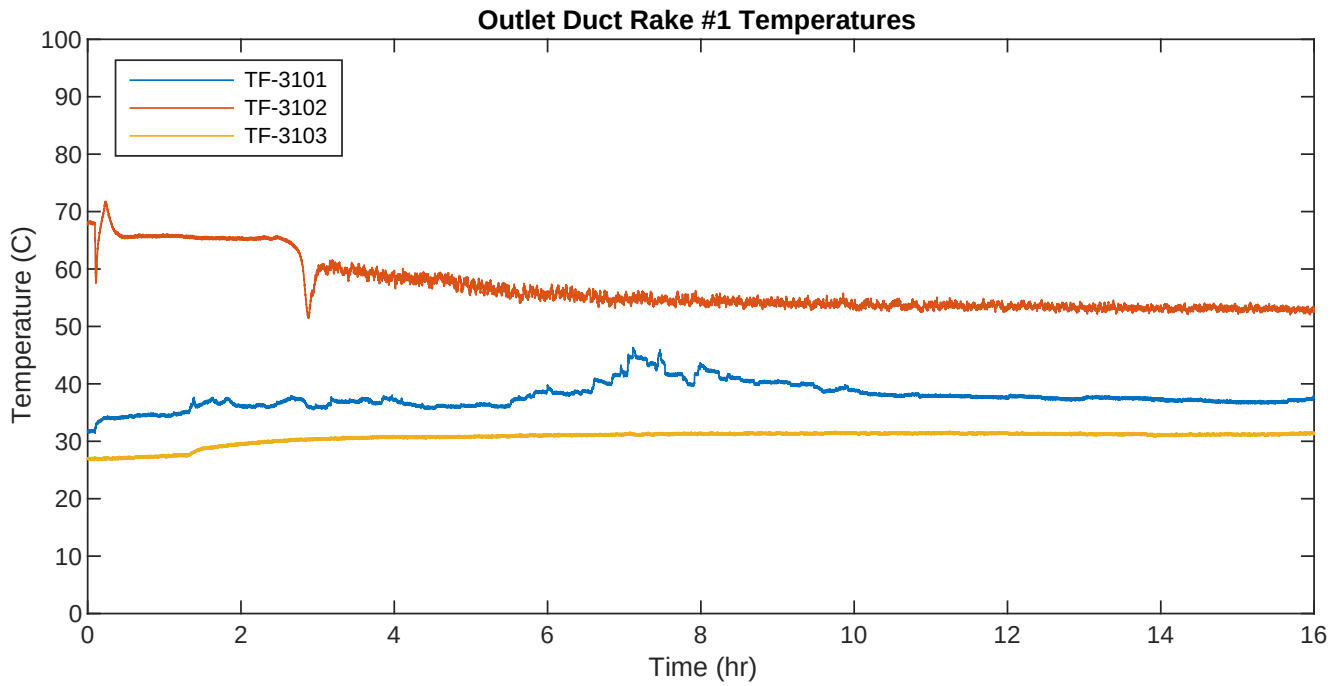

Figure 9.5: Plot of outlet duct rake #1 gas temperatures, TF-3101, TF-3102, and TF-3103.

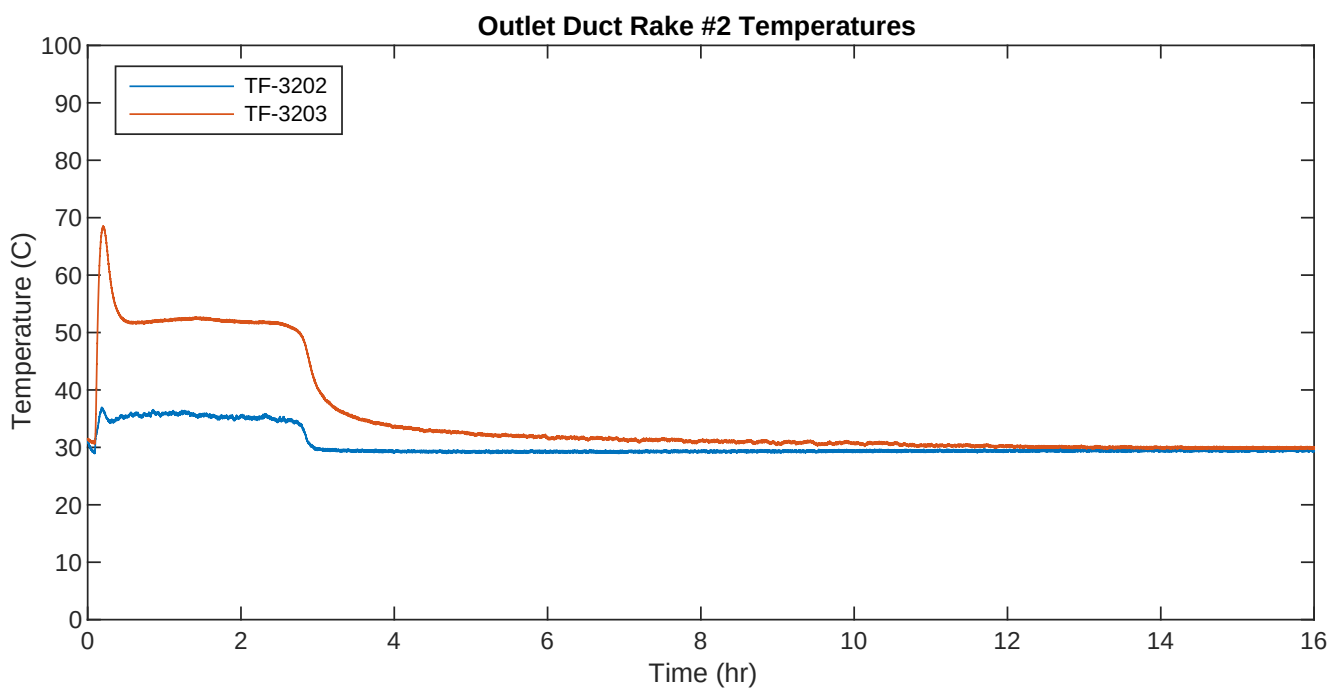

Figure 9.6: Plot of outlet duct rake #2 gas temperatures, TF-3201, TF-3202, and TF-3203.

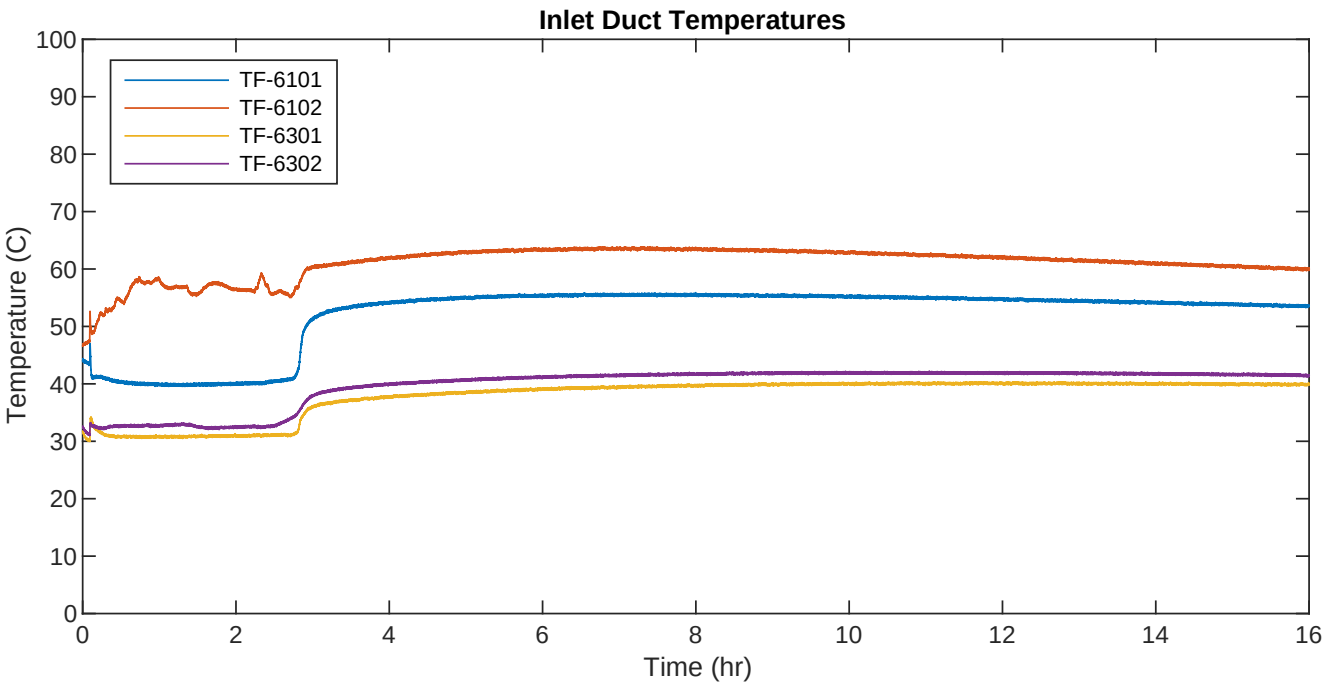

Figure 9.7: Plot of inlet gas temperatures at rakes #1 and #2, TF-6101, TF-6102, TF-6301 and TF-6302.

Chapter 10. Conclusions

During this project, eight tests were completed:

1. PG-28 Low Power (<350kW) Lower Plenum Mixing Test
2. PG-29 Low Power (<350kW) Double Ended Inlet-Outlet Crossover Duct Break, Hybrid Heater
3. PG-32 Low Power (<350kW) Asymmetric Core Heatup
4. PG-30 Low Power (<350kW) Lower Plenum Mixing, Constant Temperature Test
5. PG-31 Low Power (<350kW) Pressure Vessel Bottom Break with Restored Forced Convection Cooling Test
6. PG-33 Zero Power Long Term Cooldown Test
7. PG-34 Low Power (<350kW) Asymmetric Core Heatup Full Hybrid Heater
8. PG-35 Zero Power Crossover Duct Exchange Flow and Diffusion Test 1

In support of these tests, the HTTF Scaling Analysis and the HTTF Instrumentation Plan were revised. A CFD analysis was conducted examining intracore natural circulation during a loss of forced convection event in the HTTF.

Chapter 11. Acknowledgment and Disclaimer

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Appendix A. HTTF Scaling Report Revisions

The revised section 6.3 of the HTTF Scaling Report is included below.

From the critical channel velocity definition, a critical mass flow rate for the core can be developed assuming that channel power is equal to the core average power and that all channels are uniform. This critical mass flow rate is shown in the equation (6-49).

$$\left(\dot{m}_{core}\right)_c = N\rho_{avg,core} d_{channel} \left(\frac{2\dot{q}_{avg,channel}\beta_{avg,core} a_{channel} g}{Cc_{p,avg,core}\mu_{avg,core}} \right)^{1/2} \tag{6-49}$$

The reduction in core mass flow rate once forced convection stops will be governed by equation (5-59) and its non-dimensional version, equation (6-5). The time constant of the initial period of circulator run down and reduction in flow rate is shown in equation (6-50). In this equation, the initial conditions are selected at the period of normal operations, which will occur just prior to the stoppage of forced convection. The ratio of critical mass flow rate to the initial mass flow rate is shown in equation (6-51).

$$\tau_{NO} = \frac{M_{g,system,NO}}{\dot{m}_{core,NO}} = \frac{M_{g,system,NO}}{\rho_{avg,core,NO} w_{avg,core,NO} a_{core}} \tag{6-50}$$

$$\frac{\left(\dot{m}_{core}\right)_c}{\left(\dot{m}_{core}\right)_{NO}} = \frac{N\rho_{avg,core} d_{channel}}{\left(\dot{m}_{core}\right)_{NO}} \left(\frac{2\dot{q}_{avg,channel}\beta_{avg,core} a_{channel} g}{Cc_{p,avg,core}\mu_{avg,core}} \right)^{1/2} \tag{6-51}$$

6.3. Intracore Recirculation

During the PCC event, when forced circulation of the coolant is lost, and the residual flow momentum is ceased, natural circulation takes place in the reactor system. Because the MHTGR is designed with the heat sink (Steam Generator) at a lower elevation than the core, intracore natural circulation is expected. The flow is the one in which the hottest region of the core has the gas flowing upwards, and when the gas enters into the upper plenum it transfers heat to the upper plenum shroud and then flows down through the cooler regions of the core and where it then circulates back into the heated region. The core coolant circulation is the result of buoyancy forces. These forces are the result of the density differences thermally induced by the decay heat transport from the differentially heated channels (ρc>ρh, downward flow in the low power channel) and the heat sink. This heat sink is formed by the upper plenum and core channels. All these create a closed multi-channel thermosiphon loop for the coolant to circulate entirely within it.

Natural circulation in many parallel vertical channels with different heat inputs is quite complicated because the flow rate and direction depend on the time history of the heat input of each channel. It is desirable to know at what point the fluid buoyancy becomes significant (onset of mixed convection) and predict the threshold of flow instabilities. To help identify the main physical phenomena and system operating characteristics, the sequence of physical phenomena following the loss of flow accident in the HTTF can be divided into three phases according to the development of flow conditions:

1. Circulator rundown – cease of forced circulation.
2. The onset of natural circulation and flow reversal.
3. Quasi steady state multi-channel thermosyhponing within the core volume.

As mentioned in the previous section, in the prototype reactor design, the steam generator thermal center is placed below the core thermal center and loop free convection will not occur after circulator failure. For

the purpose of the proposed test, it is assumed that first phase (circulator rundown) will be omitted and immediately after circulator shutdown, the steam generator cold duct valve will be closed to limit the residual coolant flow. This way, the reference condition that precedes the PCC intracore natural circulation will stem from the core flow stagnation. Flow reversal will not occur (flow is stagnant instead of in a downward direction). PCC natural convection similarity criteria are derived from the integrated loop momentum conservation equation. To address the intracore natural convection instead of loop related behavior, new similarity groups are derived below. Note that phase 3 (Quasi steady state multi-channel thermosyhponing within the core volume) involves the upper plenum mixing that is thoroughly described in section 6.4.

According to (Todreas and Kazimi, 1990), at high power to flow ratio, the momentum equation is coupled to the energy equation. The relevant momentum equation is:

$$\rho_n\left(\frac{\partial u_n}{\partial t} + u_n \cdot \nabla u_n\right) = -\nabla P_n + \rho_n g + \mu \nabla^2 u_n \tag{6-52}$$

n - channel number designation

Conservation of mass:

$$\nabla \cdot u_n = 0 \tag{6-53}$$

Conservation of Energy:

$$\rho_n c_p \left(\frac{\partial T_n}{\partial t} + u_n \cdot \nabla T_n\right) = -k \nabla^2 T_n \tag{6-54}$$

Equations are coupled through velocity and are also linked by temperature.
Temperature differences that result in density variations are the driving force for fluid motion. Perturbations in density with respect to the base state causes changes in hydrostatic pressure that can become unstable. The base state for the loss of flow accident with immediate steam generator valve closure can be defined as follows:

- coolant flow in the core channels stagnates: $u_n = 0$,
- coolant density equals density before the initiation of the transient: $\rho = \rho_0$.

Substituting base state into the momentum equation gives:

$$0 = -\nabla P_n + \rho_0 g \tag{6-55}$$

Thus we can express the pressure term as follows:

$$P_n = P_{n_h} + P_{n_d} \tag{6-56}$$

Where:
P_{n_h} - channel hydrostatic pressure that would exist if $\rho=\rho_0$ everywhere in the channel
P_{n_d} - dynamic pressure due to density variation (temperature gradient)
The pressure term can be expressed as follows:

$$\nabla P_n = \nabla P_{n_h} + \nabla P_{n_d} \tag{6-57}$$

$$\nabla P_{n_h} = \rho_0 g \tag{6-58}$$

Substituting above equations to the momentum equation gives:

$$\begin{aligned}\rho_n\left(\frac{\partial u_n}{\partial t} + u_n \cdot \nabla u_n\right) &= -(\nabla P_{n_h} + \nabla P_{n_d}) + \rho_n g + \mu \nabla^2 u_n \\ &= -(\rho_0 g + \nabla P_{n_d}) + \rho_n g + \mu \nabla^2 u_n \\ &= -\nabla P_{n_d} + (\rho_n - \rho_0) g + \mu \nabla^2 u_n\end{aligned} \tag{6-59}$$

The following assumptions can be made:

1) Steady state flow.
2) The plena are fully mixed.
3) No transverse pressure gradients are present in the plenums.
4) Variations in fluid properties with temperature are neglected, except for density
5) Temperature dependence of density is only important in the buoyancy term
6) Density changes linearly with temperature:

$$\rho_n = \rho_0\big(1 - \beta(T_n - T_0)\big) \tag{6-60}$$

where:
T_0 – reference base state channel temperature (immediately before the beginning of the transient),
β – thermal expansion coefficient.

Application of Boussinesq approximation couples momentum and energy equations through the gravity term in the momentum equation.
With the above assumption, the momentum equation can be rearranged as follows:

$$\rho_n\left(\frac{\partial u_n}{\partial t} + u_n \cdot \nabla u_n\right) = -\nabla P_{n_d} + (\rho_0 - \rho_0 \beta (T_n - T_o) - \rho_0) g + \mu \nabla^2 u_n \tag{6-61}$$

$$\rho_n\left(\frac{\partial u_n}{\partial t} + u_n \cdot \nabla u_n\right) = -\nabla P_{n_d} + \rho_0 \beta (T_n - T_o) g + \mu \nabla^2 u_n \tag{6-62}$$

We now introduce the following dimensionless variables:

$$u_n^+ = \frac{u_n}{v_n} \tag{6-63}$$

$$\nabla^+ = L_c \nabla \tag{6-64}$$

$$\nabla^{+^2} = L_c^2 \nabla^2 \tag{6-65}$$

$$t^+ = \frac{t}{L_c/v_n} \tag{6-66}$$

$$P_n^+ = \frac{P}{\mu v_n/L_c} \tag{6-67}$$

$$T_n^+ = \frac{T_n - T_0}{T_P - T_0} = \theta \tag{6-68}$$

where:
v_n – characteristic reference velocity,
T_P – lower plenum temperature for the channel upflow and upper plenum temperature for downflow,
L_c – core length.

The dimensionless momentum-energy equation can be now written as:

$$\rho_0 \frac{v_n^2}{L_c}\left(\frac{\partial v_n^+}{\partial t^+} + v_n^+ \cdot \nabla^+ v_n^+\right) = -\frac{\mu v_n}{L_c^2}\nabla^+ P_n^+ + \rho_0 \beta([\theta(T_\mathrm{P} - T_o) + T_o] - T_o)g + \frac{\mu v_n}{L_c^2}\nabla^{+2} v_n^+ \tag{6-69}$$

$$\left(\frac{\partial v_n^+}{\partial t^+} + v_n^+ \cdot \nabla^+ v_n^+\right) = -\frac{\mu}{\rho_0 v_n L_c}\nabla^+ P_n^+ + \frac{\beta(T_\mathrm{P} - T_o)L_c}{v_n^2}\theta g + \frac{\mu}{\rho_0 v_n L_c}\nabla^{+2} v_n^+ \tag{6-70}$$

Where:

$\frac{1}{Re_n} = \frac{\mu}{\rho_0 v_n L_c}$ is the inverse of the Reynolds number based on the arbitrary reference velocity. The second term on the right hand side of the equation 6-69 is the buoyancy term. While the Reynolds number was used as a dimensionless parameter to characterize the flow in the forced convection analysis, it cannot be applied in the free convection scaling since the reference velocity is not available. If the buoyancy term similarity is to be kept, then the following reference velocity can be defined:

$$v_n = \sqrt{g\beta(T_p - T_0)L_c} \tag{6-71}$$

Substituting the characteristic reference velocity to the dimensionless momentum-energy equation gives:

$$\left(\frac{\partial v_n^+}{\partial t^+} + v_n^+ \cdot \nabla^+ v_n^+\right) = -\frac{\mu}{\rho_0\sqrt{g\beta(T_p - T_0)L_c^3}}\nabla^+ P_n^+ + \theta + \frac{\mu}{\rho_0\sqrt{g\beta(T_p - T_0)L_c^3}}\nabla^{+2} v_n^+ \tag{6-72}$$

Where:

$Gr = \frac{\rho_0^2 g\beta(T_\mathrm{P} - T_o)L_c^3}{\mu^2}$ is a Grashof number.

This gives the following dimensionless coupled momentum-energy equation:

$$\left(\frac{\partial v_n^+}{\partial t^+} + v_n^+ \cdot \nabla^+ v_n^+\right) = -\frac{1}{(Gr)^{1/2}}\nabla^+ P_n^+ + \theta + \frac{1}{(Gr)^{1/2}}\nabla^{+2} v_n^+ \tag{6-73}$$

Or

$$\left(\frac{\partial v_n^+}{\partial t^+} + v_n^+ \cdot \nabla^+ v_n^+\right) = -(\frac{Pr}{Ra})^{1/2}\nabla^+ P_n^+ + \theta + (\frac{Pr}{Ra})^{1/2}\nabla^{+2} v_n^+ \quad (6\text{-}74)$$

Where:

$GrPr = Ra = \frac{\rho_0 \beta (T_P - T_o) L_c^3}{\mu\alpha}$ – Rayleigh number, which expresses the balance between gravitational and viscous forces. Grashof number, being analogous to the Rayleigh number, is a measure of the relation between the buoyancy forces in a nonisothermal flow and forces of molecular viscosity,

$Pr = \frac{\mu}{\rho_0 \alpha}$- Prandtl number that defines the ratio of momentum to thermal diffusion.

Although the buoyancy force will overcome the inertial force and cause a flow reversal in the core for the aggregate gas flow, there may be individual channels for which the flow will not reverse. An appropriately scaled test facility will be able to capture this distribution of flow directions in the core channels. The preference for upflow in each channel of the prototypical plant should be determined and compared against the upflow preference for the test facility core channels. A similar distribution for upflow preference should be maintained between model and prototype core channels.

An upflow preference number can be determined as shown in the following equation. (Todreas and Kazimi, 1990)

$$U_n = \left[\Theta\delta\left(1 - S\right)\right]^{1/2} \quad (6\text{-}75)$$

Using the definitions for *δ, Θ* and S shown in section 6.2, the ratio of upflow preference number between model and prototype can be determined using the following equation.

$$\left(U_{channel}\right)_R = \left(\frac{\left(\beta\mu\right)_{g,channel}}{\left(c_p\rho^2\right)_{g,channel}}\right)_R^{1/2} \left(\frac{\dot{q}_{channel} C\left(1 - S\right)}{a_{channel} d_{channel}^2}\right)_R^{1/2} \quad (6\text{-}76)$$

The following are the similarity criteria and characteristic ratios for the single-phase natural circulation in the core channels during PCC event:

PCC core Grashof number ratio:

$$(\Pi_{Gr,PCC})_R = \left[\frac{\rho_0^2 g \beta (T_P - T_o) L_c^3}{\mu^2}\right]_R \quad (6\text{-}77)$$

PCC core Rayleigh number ratio:

$$(\Pi_{Ra,PCC})_R = \left[\frac{\rho_0 \beta (T_P - T_o) L_c^3}{\mu\alpha}\right]_R \quad (6\text{-}78)$$

PCC core Reynolds number ratio:

$$(\Pi_{Re,PCC})_R = \left[\frac{\rho_0 v_n L_c}{\mu}\right]_R \tag{6-79}$$

PCC core Prandtl number ratio:

$$(\Pi_{Pr,PCC})_R = \left[\frac{\mu}{\rho_0 \alpha}\right]_R \tag{6-80}$$

PCC Time Scale ratio:

$$(t_{PCC})_R = \left[\frac{\rho_0 L_c^2}{\mu}\right]_R \tag{6-81}$$

PCC Temperature ratio:

$$(\theta_{PCC})_R = \left[\frac{T_n - T_0}{T_P - T_0}\right]_R \tag{6-82}$$

PCC Upflow Preference Number ratio:

$$\left(U_{channel}\right)_R = \left(\frac{\left(\beta\mu\right)_{g,channel}}{\left(c_p \rho^2\right)_{g,channel}}\right)_R^{1/2} \left(\frac{\dot{q}_{channel} C\left(1-S\right)}{a_{channel} d_{channel}^2}\right)_R^{1/2} \tag{6-83}$$

6.4. Inlet Plenum Mixing and Heat Transfer

Of importance during the PCC event is the amount of mixing that occurs as hot jets exit the top of the core. Jets may be exiting at different temperatures due to differences in channel powers. There is potential for high temperature gas jets to impinge upon the inlet plenum vessel wall causing significant thermal stress. To effectively model this behavior both the gas jet mixing and the heat transfer to the inlet plenum vessel wall must be modeled accurately. Heat transfer occurs to the upper plenum vessel wall through the hot helium jets impinging on the inner vessel wall surface as well as thermal radiation from the top of the core. Helium is a non participating medium when it comes to radiation heat transfer thus radiation does not affect the gas flow equations. (Bardet 2008) Thermal radiation only affects the boundary condition at the inlet plenum vessel wall.

Since the mixing of gas jets in the inlet plenum is a local phenomenon, a two-dimensional differential form of the conservation equations will be used. Azimuthal symmetry and an azimuthal velocity of zero will be assumed. It will also be assumed that the inlet plenum jets will be vertically oriented. Equations (6-84) and (6-85) show the differential mass and energy equations for a jet mixing in an ambient environment. Equations (6-86) and (6-87) show the general differential momentum equations for the *r* and *z* directions respectively. The pressure gradient term can be solved for by applying equation (6-88) to the quiescent region outside the jet. Substituting equation (6-88) into equation (6-87) modifies the momentum equation for modeling jet injection into an ambient environment as shown in equation (6-89). Figure 6 3 shows a jet mixing in an ambient environment.

Appendix B. HTTF Instrumentation Plan Revisions

The revised chapters 5 and 6 and appendices A and B of the HTTF Instrumentation Plan are included below.

5. UNCERTAINTY

The following sections detail the sources of uncertainty expected from the HTTF Instrumentation Plan.

According to the ASME PTC 19.1-2005 standard for Test Uncertainty [3], measurement error (also called total error) is the difference between a measured value and the true value. The true value, and consequently the total error, is unknown. As such, only the expected limits of a measurement's total error can be estimated, which is a measurement's uncertainty. Uncertainty contributions come from both random error and systematic error sources, which are elaborated upon in the following subsections.

5.1. Random Standard Uncertainty

As part of total error, the random error is the component that varies randomly while measurements are repeated. Sources of random error usually come from environmental conditions, measurement acquisition, test conditions, etc. The standard uncertainty contributed by random error for successively repeated measurements can be estimated from sample statistics. From the ASME Test Uncertainty Standard, the random standard uncertainty quantifies the dispersion of a sample mean. In the HTTF, a typical test consists of measuring multiple transient events for safety and operation purposes. With exceptions like monitoring steady-state conditions, there are few instances where the facility is repeating tests and repeating the same successive measurement. Without the sample statistics taken from repeated measurements, the random standard uncertainty cannot be accurately calculated. The HTTF is not designed for single repeated measurements. It monitors system behaviors during transient events over long durations.

5.2. Systematic Standard Uncertainty

The other component to total error is the systematic error. Systematic error remains constant in repeated measurements, but it is unknown. The sources of systematic error arise from instrument calibrations, measurement techniques, electrical noise, etc. Systematic standard uncertainty is defined as quantifying the dispersion of systematic error associated with the mean. The total systematic uncertainty can be quantified by identifying all systematic error sources, determining the systematic standard uncertainty for each source, and calculating the total systematic standard uncertainty using the uncertainties determined for each source. Failing to identify sources of systematic uncertainty can result in an underestimation of test uncertainty.

For the HTTF, sources of systematic uncertainty include the instrument calibration (i.e. thermocouples, process instruments, etc.), environmental effects on instruments, wiring between the instruments and the chassis modules, module calibration uncertainty and noise, chassis and controller uncertainty, and host computer uncertainty. The following two sections outline the systematic uncertainties expected from the HTTFs instrumentation and DAS system, respectively.

1.3 Calculating HTTF Instrument Channel Uncertainties

The total channel uncertainty u_T is the root-sum-square (RSS) of the random uncertainty (u_p), and systematic uncertainty (u_b).

$$u_T = \left(u_p^2 + u_b^2\right)^{1/2} \tag{1}$$

The systemic uncertainty is the RSS of the instrument uncertainty (u_c) and the DAS uncertainty (u_{DAS}).

$$u_b = \left(u_c^2 + u_{DAS}^2\right)^{1/2}$$

(2)

The instrument and DAS uncertainties are derived from information provided by the instrument and component manufacturers.

The DAS uncertainty consists of three separate components, the NI input module uncertainty (u_{das1}), the master controller uncertainty (u_{das2}), and the master chassis uncertainty (u_{das3}). The total DAS uncertainty is the RSS of these three components.

$$u_{DAS} = \left(u_{das1}^2 + u_{das2}^2 + u_{das3}^2\right)^{1/2}$$

(3)

The systematic uncertainties u_b resulting from this process will fall within the 1-sigma confidence interval specification, given that the uncertainty data provided by the component manufacturers fits the 1-sigma specification. In complying with the HTTF test plan, 2-sigma confidence interval error reporting is required. Thus the 1-sigma uncertainty values calculated based on manufacturer specifications will be doubled to produce the HTTF channel systematic uncertainties.

The instrument manufacturers at times provide a range of possible uncertainties for a given instrument. When necessary, the more conservative values of the range have been used for this analysis.

The total channel uncertainties derived in this analysis are referred to as “0-order uncertainties” as they have been computed solely using the information provided by the instrument manufacturers. For the purposes of this analysis, it is assumed that the 0-order method over-estimates the channel uncertainties, and that approximating the random uncertainties (u_p) to be 0 is warranted given this assumption.

Table 5-1 shows the contribution of the three DAS uncertainty components to the total DAS uncertainty. For the Type-K and Type-R thermocouple channels, u_{das1} is the uncertainty of the NI thermocouple input module. For the GC channel type, u_{das1} is the uncertainty of the NI voltage input module. For the rest of the channels, the u_{das1} uncertainty comes from the NI current input module.

The instrument, DAS, systematic, random, and total HTTF channel uncertainties are shown in Table 5-2. The instrument and DAS uncertainty data was obtained using publicly available data sheets provided by the manufacturers. The manufacturer and model of each component, along with a summary of the information used to from each data sheet, are provided in Appendix B.

Table 5-1: Data Acquisition System Uncertainties.

Instrument Type	Units	u_{das1}	u_{das2}	u_{das3}	u_{DAS}
Thermocouple Type K	C	1.8200	0.1150	0.2300	1.8381
Thermocouple Type R	C	2.1500	0.1450	0.2900	2.1743
Temperature Transducer	C	1.5220	0.0986	0.1972	1.5379
Pressure Transducer Type 1	Mpa	0.0076	0.0001	0.0002	0.0076
Pressure Transducer Type 2	Mpa	0.0076	0.0001	0.0002	0.0076
Level Differential Pressure	psi	0.0381	0.0005	0.0010	0.0381
Differential Pressure Transducer	Mpa	0.0076	0.0001	0.0002	0.0076
Voltage Transducer Type 1	V	2.2830	0.0300	0.0600	2.2840
Voltage Transducer Type 2	V	4.5584	0.0599	0.1198	4.5604
Current Transducer	A	0.2245	0.0030	0.0059	0.2246
Gas Concentration Instrument	frac helium	0.0002	0.0001	0.0002	0.0003
Oxygen Sensor	ppm	76.1000	1.0000	2.0000	76.1328
Frequency Converter	%reading	0.7610	0.0100	0.0200	0.7613
Flow Meter	%reading	0.7610	0.0100	0.0200	0.7613

*** The frequency converter is used to obtain the flow measurement and is included as part of the flow meter channel for Table 5-2.**

Table 5-2: Instrument Channel Type and Associated Uncertainties.

Instrument Type	Units	u_c	u_{DAS}	u_b	u_p	u_T [2σ]
Thermocouple Type K	˚C	From 0˚C to 275˚C: 1.1˚C	1.838	From 0˚C to 275˚C: 2.142˚C	0.000	From 0˚C to 275˚C: 4.284˚C
		From 275˚C to 1250˚C: 0.4% reading		From 275˚C to 1250˚C: $[1.838^2 + (0.4\%\text{reading})^2]^{1/2}$		From 275˚C to 1250˚C: $2*[1.838^2 + (0.4\%\text{reading})^2]1^{/2}$
Thermocouple Type R*	˚C	From 0˚C to 600˚C: 2.4˚C	2.174	From 0˚C to 600˚C: 3.238˚C	0.000	From 0˚C to 600˚C: 6.477˚C
		From 600˚C to 1450˚C: 0.4% reading		From 600˚C to 1450˚C: $[2.174^2 + (0.4\%\text{reading})^2]^{1/2}$		From 600˚C to 1450˚C: $2*[2.174^2 + (0.4\%\text{reading})^2]^{1/2}$
Temperature Transducer	˚C	0.0200	1.5379	1.5380	0.0000	3.0760
Pressure Transducer Type 1	Mpa	0.0025	0.0076	0.0080	0.0000	0.0160
Pressure Transducer Type 2	Mpa	0.0008	0.0076	0.0077	0.0000	0.0153
Level Differential Pressure Sensor	psi	0.0125	0.0381	0.0401	0.0000	0.0801
Differential Pressure Transducer	Mpa	0.0008	0.0076	0.0077	0.0000	0.0153
Voltage Transducer Type 1	V	0.4500	2.2840	2.3270	0.0000	4.6550

Voltage Transducer Type 2	V	2.9950	4.5604	4.5627	0.0000	9.1255
Current Transducer	A	0.1475	0.2246	0.2687	0.0000	0.5374
Gas Concentration Instrument	frac helium	0.0500	0.0003	0.0500	0.0000	0.1000
Oxygen Sensor	ppm	100.0000	76.1328	125.6830	0.0000	251.3659
Flow Meter	%reading	1.0000	1.0766	1.4728	0.0000	2.9457

*** The Type-R thermocouple instrument uncertainty is four times greater than what is listed in the ASTM E230-ANSI MC 96.1 Thermocouple Tolerance Standard. This is done to comply with a NQA-1 quality assurance requirement which states that an accuracy ratio of at least 4:1 must be achieved between the calibration device accuracy and transmitter accuracy. Information pertaining to this requirement can be seen in the OSU HTTF Calibration and Alignment document.**

5.3. Instrument Alignment

All the instruments in the facility produce either an analog voltage or current signal. This signal is sent to the NI input modules to be converted to a digital signal, which is read at the host computer. This digital signal is the raw value that the computer then calculates into a practical engineering unit (i.e. Celsius, Pascals, etc.). Engineering values are computed via a linear equation using the raw digital value as the independent variable. The alignment process is performed to determine the slope of the linear equation for each instrument. Since each instrument has a different field range, the slopes vary between instruments.

The linear equation to calculate the engineering value is shown below:

$$ENGRValue = \frac{UEV - LEV}{URV - LRV}\left(RawInput - LRV\right) + LEV$$

Here, UEV and LEV are the Upper and Lower Engineering values, respectively; URV is the Upper Raw Value; and LRV is the Lower Raw Value. The difference between the UEV and LEV in the numerator of the slope covers the field range of the instrument.

For instruments connected to the NI 9208 modules (i.e. analog current instruments such as PTs, OAs, FTs, etc.) a simulated current device is used to send a signal at the LRV and URV, which are 4 mA and 20 mA, respectively. Alignment effectively scales these signals to match the LEV and UEV for each instrument. In this way, for example, when a PT instrument has a signal of 4 mA, the engineering value value is shown as the LEV.

Once a LRV and URV have been determined in each instrument, the slope can be calculated and an engineering value can be determined. Figure 5-1 shows graphically how signals are computed into the more practical engineering value.

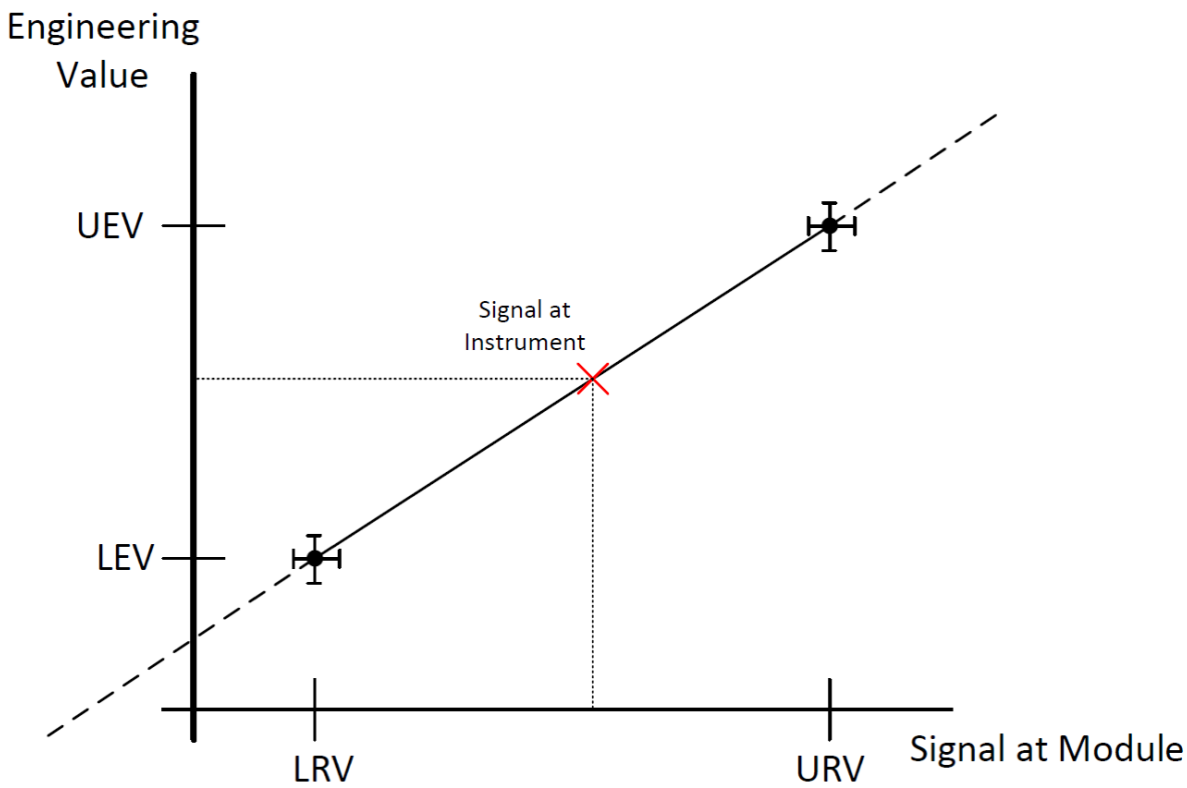

Figure 5-1. Instrument Alignment Signal Process.

However, as can be seen in Figure 5-1, there is also error associated with the URV and the LRV. Although a calibrated signal producer is used during the alignment process, no calibration process is perfect, and there is error associated with them. These errors can be minimized during the calibration, multimeter, and thermocouple calibrator devices, and they are shown as the vertical error bars in Figure 5-1.

Shown by the horizontal error bars, there is also error in the raw value that the host computer sees, and this is in the form of noise. Since there is noise here, a sample size of 60 data points (1 minute at a 1 Hz sampling rate) is taken at the LRV and the URV. Assuming a normal distribution, sampling statistics are applied to this data population, and uncertainty is estimated from this with 95% confidence.

Thermocouples require a thermocouple calibrator, which produces the voltage signal corresponding to a particular temperature in the K- and R-type thermocouples. Thermocouples are tolerance tested for compliance to American Society for Testing and Materials error ratings. Tolerance testing involves measuring the voltage output at at least two temperatures within the range of the thermocouple and confirming that the thermocouple error is within the error from the standard tables.

5.4. Instrument Location Uncertainty

All instruments are verified to be installed in the HTTF within ±⅛” in the x, y and z directions from their published location in this report.

6. DATA QUALIFICATION

The data collected at the HTTF will be used for the design and validation of computer codes that in turn will be used in the design of Nuclear Power Plants and Systems. Therefore, it is of the utmost importance that the data is qualified prior to submission to the program sponsors. The following section outlines the philosophy intended for implementation at the HTTF to qualify the test data prior to submission to program sponsors.

6.1 Test Acceptance Reports

Test results shall be documented and their conformance with test requirements and acceptance criteria shall be evaluated. A Test Acceptance Report (TAR) shall be prepared, independently reviewed, and approved by the Program Manager. The TAR should be issued to the program sponsor (or designated party), within 30 days of successful completion of the test. Each report should include the following information:

9. Description of the test, including initial conditions, environmental conditions, details of the heater, Reactor Cavity Cooling System (RCCS) and steam generator operation, and a general discussion of the test results. Any unexpected results and test procedure changes should be highlighted and discussed.
10. Test Log. This log will be in digital format and will include the recording of all major events that occurred at the test facility during the test.
11. Assessment of the test data in order to ensure that the test met the original intent of the test. The intent of each test should be agreed upon by the HTTF staff and program sponsors prior to the start of each test and documented in the Test Readiness Review Engineering Transmittal. Program sponsors approval of the Test Readiness Review shall be documented via external correspondence.
12. Critical Instrument List. The Critical Instrument List is the minimum set of instruments that must be operable in order to meet the intent of any particular test.
13. Data qualification assessment. The data qualification assessment shall include a table of Instruments listing channel name (channel name associated with each instrument), units (the engineering units associated with each channel), data file (the file name where the data is located), error (the instrumentation uncertainty provided as a 2 sigma value), sampling rate, and qualification of the instrument. The qualification of the instrument should be labeled as “qualified,” “trending,” or “failed”. A discussion of the process to determine instrument qualification is included in Section 6.3. Although the instrument error is included in this table, a detailed development of instrument error for each instrument type will be included in Section 5.
14. Acceptance criteria. The acceptance criteria are those conditions that need to be satisfied in order to meet the intent of any particular test. This shall include a determination that procedures were followed as written and approved and that all of the critical instruments were qualified.
15. Data plots for all collected data.
16. Test data file identification.
17. Completed test procedures.
18. Baseline configuration. The baseline configuration Includes references to the documentation that establish and describe the current configured managed baseline for the High Temperature Test Facilty.
19. Active Change Requests. Active Change Requests are those Change Requests that have been initiated but have not been incorporated into the configuration managed baseline.
20. Calibration records. If an instrument is found to be operating outside of its previously published uncertainty range during calibration, a Discrepancy Action Request will be initiated and appended to any published TARs impacted by this instrument.

If the acceptance criteria are met, the test data and Test Acceptance Report will be provided to the program sponsors. Acceptance of the test data and Test Acceptance Report will be documented by the program sponsors via external correspondence.

If the acceptance criteria for a test are not met, the OSU Program Manager will consult with the program sponsors to determine if the test is acceptable as is, with the non-functioning critical instrument(s) or non-met condition(s), acceptance criteria or prerequisite(s). If the test is determined to be unacceptable, the test shall be deemed unsatisfactory and the test data and Test Acceptance Report will not be provided to the program sponsors. If the test is determined to be acceptable, the test data and Test Acceptance Report will be provided to the program sponsors in accordance with established procedures. The acceptance of the test data and Test Acceptance Report shall be documented by the program sponsors via external correspondence.

6.2 Critical Instrumentation Philosophy

The critical instrumentation at the HTTF is the minimum set of instruments that must be operable in order to meet the intent of any particular test. Thus, the list of critical instruments will vary between tests. The list of critical instruments will be determined prior to each test and approved by the program sponsor through their approval of the Test Readiness Review Engineering Transmittal. In the development of the Critical Instrument List the use of the data will be taken into consideration. Each test procedure must include this list of critical instruments and a process for assessing the operation of these instruments prior to and following the subject test.

The following represents a framework for the critical instrumentation for each type of test expected to be encountered at the HTTF.

6.2.1 Depressurized Conduction Cooldown

For a symmetric Depressurized Conduction Cooldown (DCC) transient instrumentation important to the phenomena being examined includes—

1. Primary Sector thermocouples in Core Blocks #1, #3, #5, #7, and #9, including gas and solid thermocouples but excluding heater thermocouples. Heater thermocouples are important for facility operation but shall not be included as critical instrumentation for the analysis of the transient.
2. Secondary Sector thermocouples in Core Blocks #1, #3, #5, #7, and #9, including gas and solid thermocouples but excluding heater thermocouples.
3. Tertiary Sector thermocouples in Core Blocks #3, #5, and #7, including gas and solid thermocouples but excluding heater thermocouples.
4. Upper Plenum thermocouples.
5. Lower Plenum thermocouples.
6. Core Barrel thermocouples.
7. Upcomer thermocouples.
8. Inner Pressure Vessel thermocouples.
9. Outer Pressure Vessel thermocouples.
10. Inlet Duct thermocouples.
11. Outlet Duct thermocouples.
12. RCCS inlet and outlet panel thermocouples.
13. RCST thermocouples.
14. Cold Leg duct static pressure.
15. RCST static pressure.
16. RCCS feed water flow rate.
17. Core power.

This is a large set of instrumentation and it is unlikely that all instruments will remain operable over the length of a full DCC transient. Some of these instruments like the Primary Sector thermocouples are difficult to maintain once installed and thus it is unlikely that all of the Primary Sector thermocouples will remain operable over an entire testing campaign. Most importantly, the intent of this test can be met

while allowing for the failure of a certain number of instruments. Thus the Critical Instrument List can include a subset of these important instruments as outlined in the following.

1. Primary Sector thermocouples in Core Blocks #1, #3, #5, #7, and #9—all gas and solid thermocouples minus two per Core Block as long as the failed thermocouples are not physically adjacent to one another in the Core Block. If more than two thermocouples are failed in a given Primary Sector, Secondary Sector thermocouples in the same axial level Core Block can be used. If more than two thermocouples are failed in a given Secondary Sector, Tertiary Sector thermocouples in the same axial level Core Block can be used, as applicable.
2. Upper Plenum thermocouples—all gas and surface thermocouples minus eight for the entire Upper Plenum as long as the failed thermocouples are not physically adjacent to one another in the Upper Plenum.
3. Lower Plenum thermocouples—all gas and surface thermocouples minus sixteen for the entire Lower Plenum as long as the failed thermocouples are not physically adjacent to one another in the Lower Plenum.
4. Core Barrel thermocouples—all solid thermocouples minus two for the entire core barrel as long as the failed thermocouples are not physically adjacent to one another on the Core Barrel and the adjacent thermocouples in the Side Reflector and Upcomer are not failed.
5. Upcomer thermocouples—all gas thermocouples minus two for the Upcomer as long as the failed thermocouples are not physically adjacent to one another in the Upcomer and the adjacent thermocouples on the Core Barrel and Pressure Vessel are not failed.
6. Inner Pressure Vessel thermocouples—all solid thermocouples minus two for the inner surface of the Pressure Vessel as long as the failed thermocouples are not physically adjacent to one another on the Pressure Vessel and the adjacent thermocouples in the Upcomer and on the outside surface of the Pressure Vessel are not failed.
7. Outer Pressure Vessel thermocouples—all solid thermocouples minus two for the outer surface of the Pressure Vessel as long as the failed thermocouples are not physically adjacent to one another on the Pressure Vessel and the adjacent thermocouple on the inside surface of the Pressure Vessel is not failed.
8. Inlet Duct thermocouples—all gas thermocouples.
9. Outlet Duct thermocouples—all gas thermocouples.
10. RCCS inlet and outlet panel thermocouples—inlet and outlet thermocouples for all panels.
11. RCST thermocouples—all gas thermocouples.
12. Cold Leg duct static pressure.
13. RCST static pressure.
14. RCCS feed water flow rate.
15. Core power.

For a Depressurized Conduction Cooldown transient asymmetric in heating or RCCS operation the Critical Instrument List would include a different subset of these important instruments as outlined in the following.

1. Primary Sector thermocouples in Core Blocks #1, #3, #5, #7, and #9—all gas and solid thermocouples minus two per Core Block as long as the failed thermocouples are not physically adjacent to one another in the Core Block.
2. Secondary Sector thermocouples in Core Blocks #1, #3, #5, #7, and #9—all gas and solid thermocouples minus two per Core Block as long as the failed thermocouples are not physically adjacent to one another in the Core Block.
3. Tertiary Sector thermocouples in Core Blocks #3, #5, and #7—all gas and solid thermocouples minus two per Core Block as long as the failed thermocouples are not physically adjacent to one another in the Core Block.
4. Upper Plenum thermocouples—all gas and surface thermocouples minus eight for the entire Upper Plenum as long as the failed thermocouples are not physically adjacent to one another in the Upper Plenum.
5. Lower Plenum thermocouples—all gas and surface thermocouples minus sixteen for the entire Lower Plenum as long as the failed thermocouples are not physically adjacent to one another in the Lower Plenum.

6. Core Barrel thermocouples—all solid thermocouples minus two for the entire core barrel as long as the failed thermocouples are not physically adjacent to one another on the Core Barrel and the adjacent thermocouples in the Side Reflector and Upcomer are not failed.
7. Upcomer thermocouples—all gas thermocouples minus two for the Upcomer as long as the failed thermocouples are not physically adjacent to one another in the Upcomer and the adjacent thermocouples on the Core Barrel and Pressure Vessel are not failed.
8. Inner Pressure Vessel thermocouples—all solid thermocouples minus two for the inner surface of the Pressure Vessel as long as the failed thermocouples are not physically adjacent to one another on the Pressure Vessel and the adjacent thermocouples in the Upcomer and on the outside surface of the Pressure Vessel are not failed.
9. Outer Pressure Vessel thermocouples—all solid thermocouples minus two for the outer surface of the Pressure Vessel as long as the failed thermocouples are not physically adjacent to one another on the Pressure Vessel and the adjacent thermocouple on the inside surface of the Pressure Vessel is not failed.
10. Inlet Duct thermocouples—all gas thermocouples.
11. Outlet Duct thermocouples—all gas thermocouples.
12. RCCS inlet and outlet panel thermocouples—inlet and outlet thermocouples for all panels.
13. RCST thermocouples—all gas thermocouples.
14. Cold leg duct static pressure.
15. RCST static pressure.
16. RCCS feed water flow rate.
17. Core power.

6.2.2 Pressurized Conduction Cooldown

For a symmetric Pressurized Conduction Cooldown (PCC) transient instrumentation important to the phenomena being examined includes—

1. Primary Sector thermocouples in Core Blocks #1, #3, #5, #7, and #9, including gas and solid thermocouples but excluding heater thermocouples.
2. Secondary Sector thermocouples in Core Blocks #1, #3, #5, #7, and #9, including gas and solid thermocouples but excluding heater thermocouples.
3. Tertiary Sector thermocouples in Core Blocks #3, #5, and #7, including gas and solid thermocouples but excluding heater thermocouples.
4. Upper Plenum thermocouples.
5. Lower Plenum thermocouples.
6. Core Barrel thermocouples.
7. Upcomer thermocouples.
8. Inner Pressure Vessel thermocouples.
9. Outer Pressure Vessel thermocouples.
10. RCCS inlet and outlet panel thermocouples.
11. Cold leg duct static pressure.
12. RCCS feed water flow rate.
13. Core power.

As for the DCC event, this is a large set of instrumentation and it is unlikely that all instruments will remain operable over the length of a full PCC transient and all of the internal thermocouples will remain operable over an entire testing campaign. The intent of this test can still be met while allowing for the failure of a certain number of instruments. Thus the Critical Instrument List can include a subset of these important instruments as outlined in the following.

1. Primary Sector thermocouples in Core Blocks #1, #3, #5, #7, and #9—all gas and solid thermocouples minus two per Core Block as long as the failed thermocouples are not physically adjacent to one another in the Core Block. If more than two thermocouples are failed in a given Primary Sector, Secondary Sector thermocouples in the same axial level Core Block can be used. If more than two thermocouples are failed in a given Secondary Sector, Tertiary Sector thermocouples in the same axial level Core Block can be used, as applicable.

2. Upper Plenum thermocouples—all gas and surface thermocouples minus eight for the entire Upper Plenum as long as the failed thermocouples are not physically adjacent to one another in the Upper Plenum.
3. Lower Plenum thermocouples—all gas and surface thermocouples minus sixteen for the entire Lower Plenum as long as the failed thermocouples are not physically adjacent to one another in the Lower Plenum.
4. Core Barrel thermocouples—all solid thermocouples minus two for the entire core barrel as long as the failed thermocouples are not physically adjacent to one another on the Core Barrel and the adjacent thermocouples in the Side Reflector and Upcomer are not failed.
5. Upcomer thermocouples—all gas thermocouples minus two for the Upcomer as long as the failed thermocouples are not physically adjacent to one another in the Upcomer and the adjacent thermocouples on the Core Barrel and Pressure Vessel are not failed.
6. Inner Pressure Vessel thermocouples—all solid thermocouples minus two for the inner surface of the Pressure Vessel as long as the failed thermocouples are not physically adjacent to one another on the Pressure Vessel and the adjacent thermocouples in the Upcomer and on the outside surface of the Pressure Vessel are not failed.
7. Outer Pressure Vessel thermocouples—all solid thermocouples minus two for the outer surface of the Pressure Vessel as long as the failed thermocouples are not physically adjacent to one another on the Pressure Vessel and the adjacent thermocouple on the inside surface of the Pressure Vessel is not failed.
8. RCCS inlet and outlet panel thermocouples—inlet and outlet thermocouples for all panels.
9. Cold leg duct static pressure.
10. RCCS feed water flow rate.
11. Core power.

For a Pressurized Conduction Cooldown transient asymmetric in heating or RCCS operation the Critical Instrument List would include a different subset of these important instruments as outlined in the following.

1. Primary Sector thermocouples in Core Blocks #1, #3, #5, #7, and #9—all gas and solid thermocouples minus two per Core Block as long as the failed thermocouples are not physically adjacent to one another in the Core Block.
2. Secondary Sector thermocouples in Core Blocks #1, #3, #5, #7, and #9—all gas and solid thermocouples minus two per Core Block as long as the failed thermocouples are not physically adjacent to one another in the Core Block.
3. Tertiary Sector thermocouples in Core Blocks #3, #5, and #7—all gas and solid thermocouples minus two per Core Block as long as the failed thermocouples are not physically adjacent to one another in the Core Block.
4. Upper Plenum thermocouples—all gas and surface thermocouples minus eight for the entire Upper Plenum as long as the failed thermocouples are not physically adjacent to one another in the Upper Plenum.
5. Lower Plenum thermocouples—all gas and surface thermocouples minus sixteen for the entire Lower Plenum as long as the failed thermocouples are not physically adjacent to one another in the Lower Plenum.
6. Core Barrel thermocouples—all solid thermocouples minus two for the entire core barrel as long as the failed thermocouples are not physically adjacent to one another on the Core Barrel and the adjacent thermocouples in the Side Reflector and Upcomer are not failed.
7. Upcomer thermocouples—all gas thermocouples minus two for the Upcomer as long as the failed thermocouples are not physically adjacent to one another in the Upcomer and the adjacent thermocouple on the Core Barrel and Pressure Vessel are not failed.
8. Inner Pressure Vessel thermocouples—all solid thermocouples minus two for the inner surface of the Pressure Vessel as long as the failed thermocouples are not physically adjacent to one another on the Pressure Vessel and the adjacent thermocouples in the Upcomer and on the outside surface of the Pressure Vessel are not failed.
9. Outer Pressure Vessel thermocouples—all solid thermocouples minus two for the outer surface of the Pressure Vessel as long as the failed thermocouples are not physically adjacent to one another on the Pressure Vessel and the adjacent thermocouples on the inside surface of the Pressure Vessel are not failed.

10. RCCS inlet and outlet panel thermocouples—inlet and outlet thermocouples for all panels.
11. Cold leg duct static pressure.
12. RCCS feed water flow rate.
13. Core power.

6.2.3 Crossover Duct Mixing

For a test examining just the crossover duct mixing portion of the DCC transient, instrumentation important to the phenomena being examined includes—

1. Lower Plenum thermocouples.
2. Inlet Duct thermocouples.
3. Outlet Duct thermocouples.
4. RCST thermocouples.
5. Cold leg duct static pressure.
6. RCST static pressure.

The Lower Plenum thermocouples are difficult to maintain once installed and thus it is unlikely that all of the these thermocouples will remain operable over an entire testing campaign. Thus the Critical Instrument List can include a subset of these important instruments as outlined in the following.

1. Lower Plenum thermocouples—all gas and surface thermocouples minus sixteen for the entire Lower Plenum as long as the failed thermocouples are not physically adjacent to one another in the Lower Plenum.
2. Inlet Duct thermocouples—all gas thermocouples.
3. Outlet Duct thermocouples—all gas thermocouples.
4. RCST thermocouples—all gas thermocouples.
5. Cold leg duct static pressure.
6. RCST static pressure.

6.2.4 Upper Plenum Mixing

For a test examining mixing in the Upper Plenum, instrumentation important to the phenomena being examined includes—

1. Primary Sector thermocouples in Core Block #9—gas thermocouples only.
2. Secondary Sector thermocouples in Core Block #9—gas thermocouples only.
3. Tertiary Sector thermocouples in Core Block #7—gas thermocouples only.
4. Upper Plenum thermocouples.
5. Upcomer thermocouple at axial level #10.
6. Cold leg duct static pressure.
7. Primary loop differential pressures.

The intent of this test can be met while allowing for the failure of a certain number of instruments, which leads to the following Critical Instrument List.

1. Primary Sector thermocouples in Core Block #9—all gas thermocouples minus one.
2. Secondary Sector thermocouples in Core Block #9—all gas thermocouples minus one.
3. Tertiary Sector thermocouples in Core Block #7—all gas thermocouples minus one.
4. Upper Plenum thermocouples—all gas and surface thermocouples minus eight for the entire Upper Plenum as long as the failed thermocouples are not physically adjacent to one another in the Upper Plenum.
5. Upcomer thermocouple at axial level #10.
6. Cold leg duct static pressure.
7. Primary loop differential pressures—all differential pressures along primary loop.

6.2.5 Lower Plenum Mixing

For a test examining mixing in the Lower Plenum, instrumentation important to the phenomena being examined includes—

1. Primary Sector thermocouples in Core Block #1—gas thermocouples only.
2. Secondary Sector thermocouples in Core Block #1—gas thermocouples only.
3. Tertiary Sector thermocouples in Core Block #3—gas thermocouples only.
4. Lower Plenum thermocouples.
5. Outlet Duct thermocouples—rake #1.
6. Cold leg duct static pressure.
7. Primary loop differential pressures.

The intent of this test can be met while allowing for the failure of a certain number of instruments, which leads to the following Critical Instrument List.

1. Primary Sector thermocouples in Core Block #1—all gas thermocouples minus one.
2. Secondary Sector thermocouples in Core Block #1—all gas thermocouples minus one.
3. Tertiary Sector thermocouples in Core Block #3—all gas thermocouples minus one.
4. Lower Plenum thermocouples—all gas and surface thermocouples minus sixteen for the entire Lower Plenum as long as the failed thermocouples are not physically adjacent to one another in the Lower Plenum.
5. Outlet Duct thermocouples—all gas thermocouples in rake #1.
6. Cold leg duct static pressure.
7. Primary loop differential pressures

6.3 Data Qualification

Following each test the HTTF Program Manager will convene a Test Review Board (TRB) to assess the quality of the collected test data. Membership of the TRB shall be at the discretion of the OSU Program Manager but will normally include the HTTF Program Manager, the Facility Operations Manager or Configuration Manager, all Test Engineers for the subject test and a program sponsor representative. The composition of the TRB will likely vary from test to test.

The function of the TRB is to examine the data collected by each of the test critical instruments to determine if each instrument was functioning properly during the test. Each critical instrument will be designated as one of the following—

1. Qualified—instrument appears to be functioning as designed.
2. Trending—instrument measurement appears to be trending in appropriate manner but results indicate that the instrument may be functioning outside of its calculated uncertainty band.
3. Failed—instrument does not appear to be functioning as designed.

Following each test, plots will be created using automated processes for all critical instruments. These critical instrument plots will be used by the TRB in their examination of the test data. Note that this is not an effort to eliminate data that does not conform to preconceived notions on how the test should have acted, but is an exercise to identify any instruments that have failed during the test. All test data regardless of their qualification designation will be provided to the program sponsor. In general, if there is doubt as to whether an instrument is failed, the TRB's default position shall be to include the data as qualified.

For thermocouples, the following will be examined by the TRB to guide its qualification determination for the instrument—

1. Thermocouple operation within the instrument range over the entire test.
2. Noise in the thermocouple data.
3. Thermocouple measurement at ambient conditions.
4. Trend of thermocouple during heat up and cool down.

5. Comparison of thermocouple measurement against thermocouple data expected to be similar.

When comparing thermocouple measurements against thermocouple data expected to be similar, care should be taken to ensure that the comparison data actually represents similar data. Comparison measurements will vary for different thermocouples as outlined in the following examples—

1. Primary sector thermocouple measurements can be compared against Secondary and Tertiary Sector thermocouple measurements at comparable radial and axial locations during symmetric tests (or during a symmetric heat up for an asymmetric test).
2. Solid and surface thermocouples in unheated regions can be examined to ensure that they remain bounded by the measurements in adjacent thermocouples.

For static pressure measurements, the following will be examined by the TRB to guide its qualification determination for the instrument—

1. Static pressure operation within the instrument range over the entire test.
2. Noise in the static pressure data.
3. Static pressure measurement at ambient conditions.
4. Trend of static pressure during gas fill, heat up and cold down.

For differential pressure measurements, the following will be examined by the TRB to guide its qualification determination for the instrument—

1. Differential pressure operation within the instrument range over the entire test.
2. Noise in the differential pressure data.
3. Differential pressure measurement at no flow conditions.
4. Trend of differential pressures during circulator operation.
5. Loop sum of differential pressures.

APPENDIX A: INSTRUMENT IDENTIFICATION

This section provides the instrument identification tags for all instruments, as well as information pertaining to their location. This appendix does not include the process and control instruments, which are listed for reference in Section 3.9 of this report.

Figure 3-5 in the Core Region Instrumentation Section shows all the general instrument locations in the core region and their associated location number. In this section, all core instruments are listed in Table A-1, with their location, type, and ID tag given. Below Table A-1 is a set of images depicting each core instrument's unique location in the core.

Tabel A-1. Core instrument locations.

Location, Location #	Instrument	ID Tag
Lower Reflector #1		
Primary Sector, #1	Thermocouple	TS-1101
Primary Sector, #16	Thermocouple	TS-1102
Lower Reflector #3		
Primary Sector, #1	Thermocouple	TS-1103
Primary Sector, #18	Thermocouple	TS-1104
Primary Sector, #17	Thermocouple	TS-1105
Secondary Sector, #18	Thermocouple	TS-1106
Core Block #1		
Primary Sector, #1	Thermocouple	TS-1107
Primary Sector, #2	Thermocouple	TS-1108
Primary Sector, #5	Thermocouple	TS-1109
Primary Sector, #6	Thermocouple	TF-1110
Primary Sector, #7	Thermocouple	TS-1111
Primary Sector, #8	Thermocouple	TF-1112
Primary Sector, #9	Thermocouple	TS-1113
Primary Sector, #10	Thermocouple	TF-1114
Primary Sector, #13	Thermocouple	TS-1115
Primary Sector, #3	Thermocouple	TS-1116
Primary Sector, #12	Thermocouple	TS-1117

Location, Location #	Instrument	ID Tag
Primary Sector, #15	Thermocouple	TS-1118
Primary Sector, #16	Thermocouple	TS-1119
Primary Sector, #17	Thermocouple	TS-1120
Secondary Sector, #2	Thermocouple	TS-1121
Secondary Sector, #5	Thermocouple	TS-1122
Secondary Sector, #6	Thermocouple	TF-1123
Secondary Sector, #7	Thermocouple	TS-1124
Secondary Sector, #8	Thermocouple	TF-1125
Secondary Sector, #9	Thermocouple	TS-1126
Secondary Sector, #10	Thermocouple	TF-1127
Secondary Sector, #13	Thermocouple	TS-1128
Secondary Sector, #3	Thermocouple	TS-1129
Secondary Sector, #12	Thermocouple	TS-1130
Secondary Sector, #15	Thermocouple	TS-1131
Secondary Sector, #16	Thermocouple	TS-1132
Secondary Sector, #17	Thermocouple	TS-1133
Primary Sector, #4	GCI	GC-1101
Tertiary Sector, #4	GCI	GC-1102
Core Block #2		
Primary Sector, #1	Thermocouple	TS-1201
Primary Sector, #16	Thermocouple	TS-1202
Primary Sector, #11	GCI	GC-1201
Core Block #3		
Primary Sector, #1	Thermocouple	TS-1301
Primary Sector, #2	Thermocouple	TS-1302
Primary Sector, #5	Thermocouple	TS-1303
Primary Sector, #6	Thermocouple	TF-1304
Primary Sector, #7	Thermocouple	TS-1305

Location, Location #	Instrument	ID Tag
Primary Sector, #8	Thermocouple	TF-1306
Primary Sector, #9	Thermocouple	TS-1307
Primary Sector, #10	Thermocouple	TF-1308
Primary Sector, #13	Thermocouple	TS-1309
Primary Sector, #18	Thermocouple	TS-1310
Primary Sector, #3	Thermocouple	TS-1311
Primary Sector, #12	Thermocouple	TS-1312
Primary Sector, #15	Thermocouple	TS-1313
Primary Sector, #16	Thermocouple	TS-1314
Primary Sector, #17	Thermocouple	TS-1315
Secondary Sector, #2	Thermocouple	TS-1316
Secondary Sector, #5	Thermocouple	TS-1317
Secondary Sector, #6	Thermocouple	TF-1318
Secondary Sector, #7	Thermocouple	TS-1319
Secondary Sector, #8	Thermocouple	TF-1320
Secondary Sector, #9	Thermocouple	TS-1321
Secondary Sector, #10	Thermocouple	TF-1322
Secondary Sector, #13	Thermocouple	TS-1323
Secondary Sector, #18	Thermocouple	TS-1324
Secondary Sector, #3	Thermocouple	TS-1325
Secondary Sector, #12	Thermocouple	TS-1326
Secondary Sector, #15	Thermocouple	TS-1327
Secondary Sector, #16	Thermocouple	TS-1328
Secondary Sector, #17	Thermocouple	TS-1329
Tertiary Sector, #2	Thermocouple	TS-1330
Tertiary Sector, #5	Thermocouple	TS-1331
Tertiary Sector, #6	Thermocouple	TF-1332
Tertiary Sector, #7	Thermocouple	TS-1333

Location, Location #	Instrument	ID Tag
Tertiary Sector, #8	Thermocouple	TF-1334
Tertiary Sector, #9	Thermocouple	TS-1335
Tertiary Sector, #10	Thermocouple	TF-1336
Tertiary Sector, #13	Thermocouple	TS-1337
Tertiary Sector, #18	Thermocouple	TS-1338
Tertiary Sector, #3	Thermocouple	TS-1339
Tertiary Sector, #12	Thermocouple	TS-1340
Tertiary Sector, #15	Thermocouple	TS-1341
Tertiary Sector, #16	Thermocouple	TS-1342
Tertiary Sector, #17	Thermocouple	TS-1343
Primary Sector, #4	GCI	GC-1301
Tertiary Sector, #4	GCI	GC-1302
Core Block #4		
Primary Sector, #1	Thermocouple	TS-1401
Primary Sector, #16	Thermocouple	TS-1402
Primary Sector, #11	GCI	GC-1401
Core Block #5		
Primary Sector, #1	Thermocouple	TS-1501
Primary Sector, #2	Thermocouple	TS-1502
Primary Sector, #5	Thermocouple	TS-1503
Primary Sector, #6	Thermocouple	TF-1504
Primary Sector, #7	Thermocouple	TS-1505
Primary Sector, #8	Thermocouple	TF-1506
Primary Sector, #9	Thermocouple	TS-1507
Primary Sector, #10	Thermocouple	TF-1508
Primary Sector, #13	Thermocouple	TS-1509
Primary Sector, #18	Thermocouple	TS-1510
Primary Sector, #3	Thermocouple	TS-1511

Location, Location #	Instrument	ID Tag
Primary Sector, #12	Thermocouple	TS-1512
Primary Sector, #15	Thermocouple	TS-1513
Primary Sector, #16	Thermocouple	TS-1514
Primary Sector, #17	Thermocouple	TS-1515
Secondary Sector, #2	Thermocouple	TS-1516
Secondary Sector, #5	Thermocouple	TS-1517
Secondary Sector, #6	Thermocouple	TF-1518
Secondary Sector, #7	Thermocouple	TS-1519
Secondary Sector, #8	Thermocouple	TF-1520
Secondary Sector, #9	Thermocouple	TS-1521
Secondary Sector, #10	Thermocouple	TF-1522
Secondary Sector, #13	Thermocouple	TS-1523
Secondary Sector, #18	Thermocouple	TS-1524
Secondary Sector, #3	Thermocouple	TS-1525
Secondary Sector, #12	Thermocouple	TS-1526
Secondary Sector, #15	Thermocouple	TS-1527
Secondary Sector, #16	Thermocouple	TS-1528
Secondary Sector, #17	Thermocouple	TS-1529
Tertiary Sector, #2	Thermocouple	TS-1530
Tertiary Sector, #5	Thermocouple	TS-1531
Tertiary Sector, #6	Thermocouple	TF-1532
Tertiary Sector, #7	Thermocouple	TS-1533
Tertiary Sector, #8	Thermocouple	TF-1534
Tertiary Sector, #9	Thermocouple	TS-1535
Tertiary Sector, #10	Thermocouple	TF-1536
Tertiary Sector, #13	Thermocouple	TS-1537
Tertiary Sector, #18	Thermocouple	TS-1538
Tertiary Sector, #3	Thermocouple	TS-1539

Location, Location #	Instrument	ID Tag
Tertiary Sector, #12	Thermocouple	TS-1540
Tertiary Sector, #15	Thermocouple	TS-1541
Tertiary Sector, #16	Thermocouple	TS-1542
Tertiary Sector, #17	Thermocouple	TS-1543
Primary Sector, #4	GCI	GC-1501
Tertiary Sector, #4	GCI	GC-1502
Core Block #6		
Primary Sector, #1	Thermocouple	TS-1601
Primary Sector, #16	Thermocouple	TS-1602
Primary Sector, #11	GCI	GC-1601
Core Block #7		
Primary Sector, #1	Thermocouple	TS-1701
Primary Sector, #2	Thermocouple	TS-1702
Primary Sector, #5	Thermocouple	TS-1703
Primary Sector, #6	Thermocouple	TF-1704
Primary Sector, #7	Thermocouple	TS-1705
Primary Sector, #8	Thermocouple	TF-1706
Primary Sector, #9	Thermocouple	TS-1707
Primary Sector, #10	Thermocouple	TF-1708
Primary Sector, #13	Thermocouple	TS-1709
Primary Sector, #18	Thermocouple	TS-1710
Primary Sector, #3	Thermocouple	TS-1711
Primary Sector, #12	Thermocouple	TS-1712
Primary Sector, #15	Thermocouple	TS-1713
Primary Sector, #16	Thermocouple	TS-1714
Primary Sector, #17	Thermocouple	TS-1715
Secondary Sector, #2	Thermocouple	TS-1716
Secondary Sector, #5	Thermocouple	TS-1717

Location, Location #	Instrument	ID Tag
Secondary Sector, #6	Thermocouple	TF-1718
Secondary Sector, #7	Thermocouple	TS-1719
Secondary Sector, #8	Thermocouple	TF-1720
Secondary Sector, #9	Thermocouple	TS-1721
Secondary Sector, #10	Thermocouple	TF-1722
Secondary Sector, #13	Thermocouple	TS-1723
Secondary Sector, #18	Thermocouple	TS-1724
Secondary Sector, #3	Thermocouple	TS-1725
Secondary Sector, #12	Thermocouple	TS-1726
Secondary Sector, #15	Thermocouple	TS-1727
Secondary Sector, #16	Thermocouple	TS-1728
Secondary Sector, #17	Thermocouple	TS-1729
Tertiary Sector, #2	Thermocouple	TS-1730
Tertiary Sector, #5	Thermocouple	TS-1731
Tertiary Sector, #6	Thermocouple	TF-1732
Tertiary Sector, #7	Thermocouple	TS-1733
Tertiary Sector, #8	Thermocouple	TF-1734
Tertiary Sector, #9	Thermocouple	TS-1735
Tertiary Sector, #10	Thermocouple	TF-1736
Tertiary Sector, #13	Thermocouple	TS-1737
Tertiary Sector, #18	Thermocouple	TS-1738
Tertiary Sector, #3	Thermocouple	TS-1739
Tertiary Sector, #12	Thermocouple	TS-1740
Tertiary Sector, #15	Thermocouple	TS-1741
Tertiary Sector, #16	Thermocouple	TS-1742
Tertiary Sector, #17	Thermocouple	TS-1743
Primary Sector, #4	GCI	GC-1701
Tertiary Sector, #4	GCI	GC-1702

Location, Location #	Instrument	ID Tag
Core Block #8		
Primary Sector, #1	Thermocouple	TS-1801
Primary Sector, #16	Thermocouple	TS-1802
Primary Sector, #11	GCI	GC-1801
Core Block #9		
Primary Sector, #1	Thermocouple	TS-1901
Primary Sector, #2	Thermocouple	TS-1902
Primary Sector, #5	Thermocouple	TS-1903
Primary Sector, #6	Thermocouple	TF-1904
Primary Sector, #7	Thermocouple	TS-1905
Primary Sector, #8	Thermocouple	TF-1906
Primary Sector, #9	Thermocouple	TS-1907
Primary Sector, #10	Thermocouple	TF-1908
Primary Sector, #13	Thermocouple	TS-1909
Primary Sector, #18	Thermocouple	TS-1910
Primary Sector, #3	Thermocouple	TS-1911
Primary Sector, #12	Thermocouple	TS-1912
Primary Sector, #15	Thermocouple	TS-1913
Primary Sector, #16	Thermocouple	TS-1914
Primary Sector, #17	Thermocouple	TS-1915
Secondary Sector, #2	Thermocouple	TS-1916
Secondary Sector, #5	Thermocouple	TS-1917
Secondary Sector, #6	Thermocouple	TF-1918
Secondary Sector, #7	Thermocouple	TS-1919
Secondary Sector, #8	Thermocouple	TF-1920
Secondary Sector, #9	Thermocouple	TS-1921
Secondary Sector, #10	Thermocouple	TF-1922
Secondary Sector, #13	Thermocouple	TS-1923

Location, Location #	Instrument	ID Tag
Secondary Sector, #18	Thermocouple	TS-1924
Secondary Sector, #3	Thermocouple	TS-1925
Secondary Sector, #12	Thermocouple	TS-1926
Secondary Sector, #15	Thermocouple	TS-1927
Secondary Sector, #16	Thermocouple	TS-1928
Secondary Sector, #17	Thermocouple	TS-1929
Primary Sector, #4	GCI	GC-1901
Tertiary Sector, #4	GCI	GC-1902
Core Block #10		
Secondary Sector, #1	Thermocouple	TS-1001
Secondary Sector, #16	Thermocouple	TS-1002
Upper Reflector #2		
Primary Sector, #1	Thermocouple	TS-1003
Primary Sector, #2	Thermocouple	TS-1004
Primary Sector, #5	Thermocouple	TS-1005
Primary Sector, #6	Thermocouple	TF-1006
Primary Sector, #7	Thermocouple	TS-1007
Primary Sector, #8	Thermocouple	TF-1008
Primary Sector, #9	Thermocouple	TS-1009
Primary Sector, #10	Thermocouple	TF-1010
Primary Sector, #13	Thermocouple	TS-1011
Primary Sector, #18	Thermocouple	TS-1012
Primary Sector, #11	GCI	GC-1001

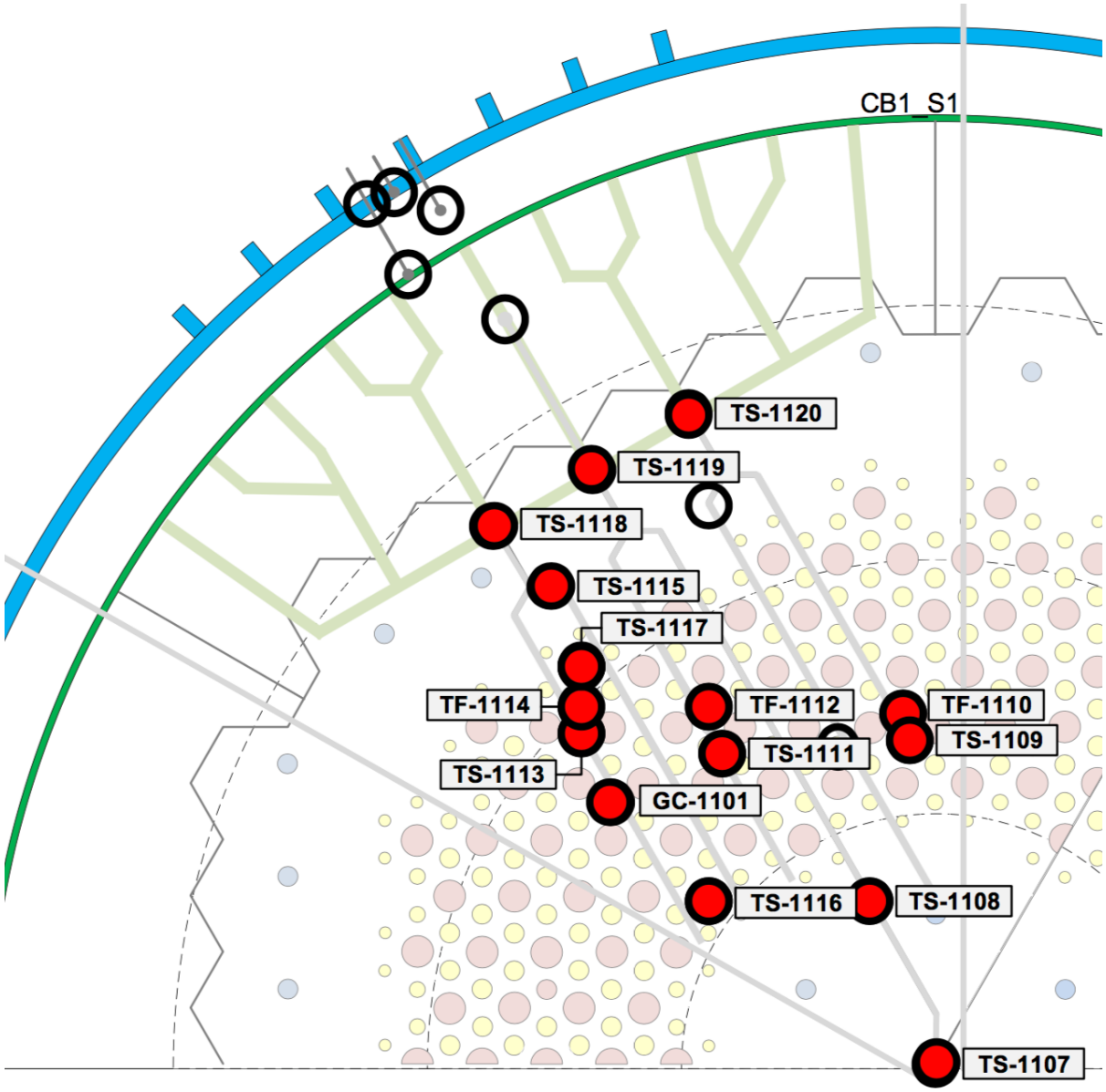

Figure A-1. Instrument locations for Core Block 1, Sector 1.

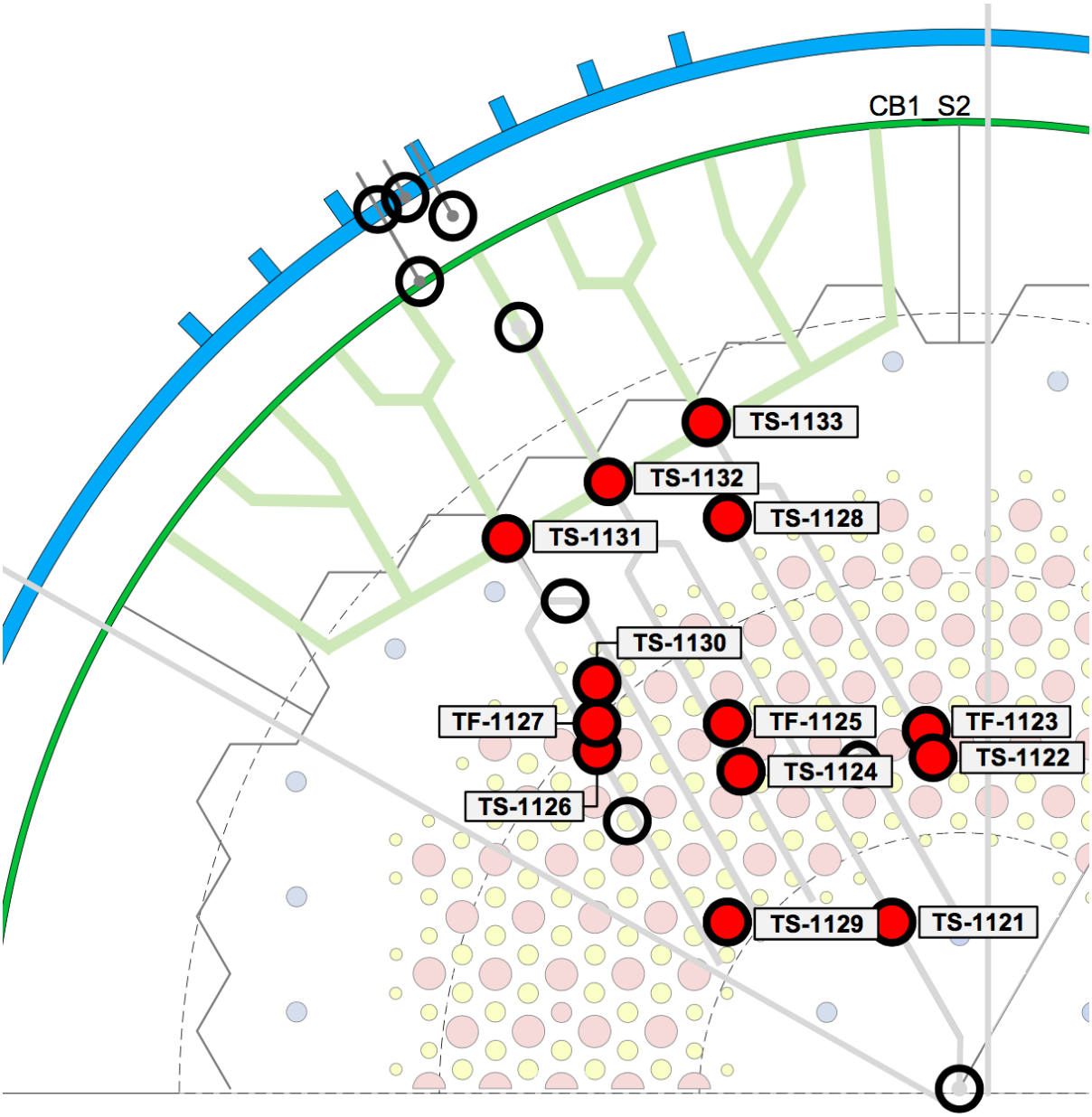

Figure A-2. Instrument locations for Core Block 1, Sector 2.

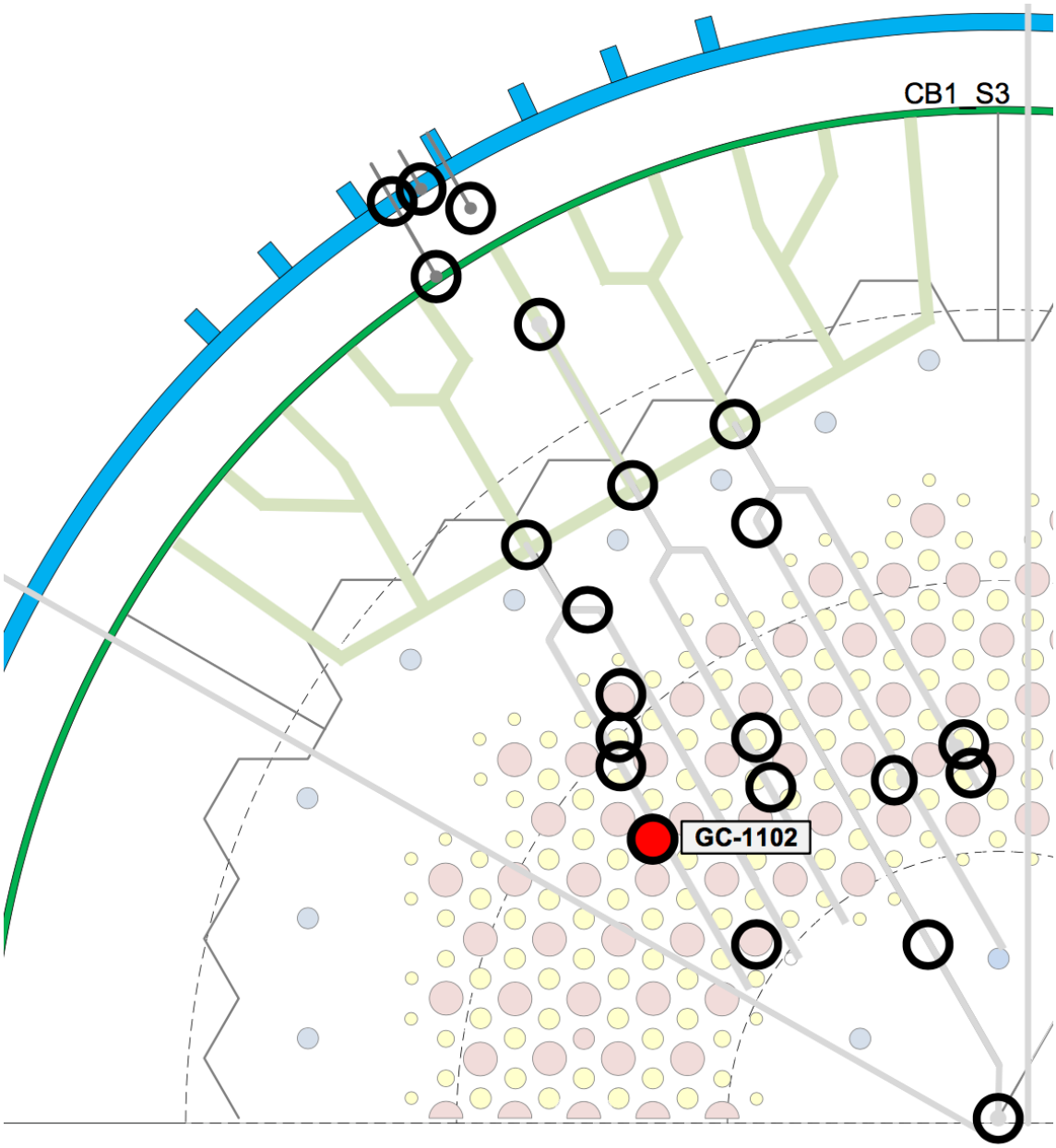

Figure A-3. Instrument locations for Core Block 1, Sector 3.

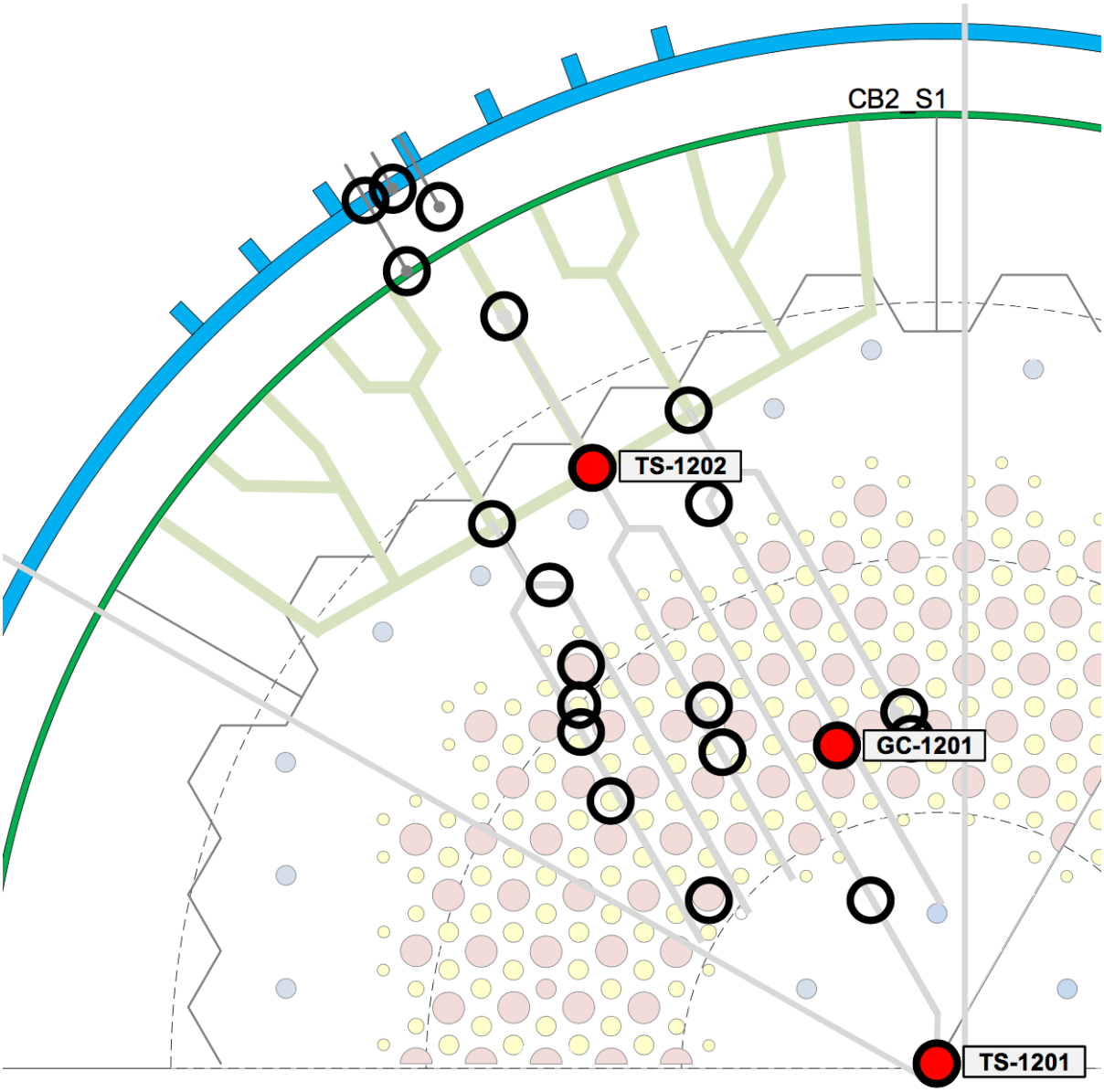

Figure A-4. Instrument locations for Core Block 2, Sector 1.

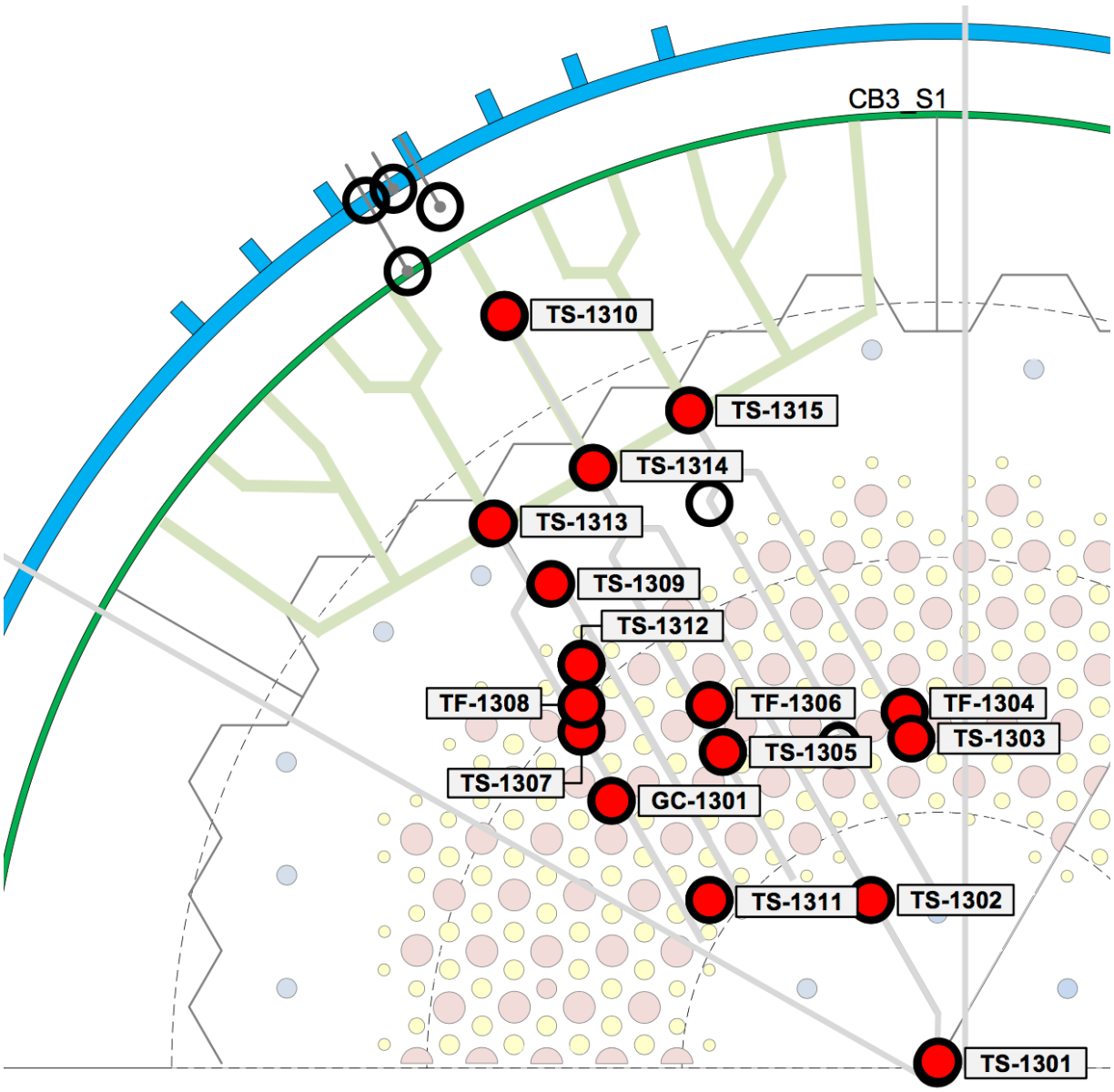

Figure A-5. Instrument locations for Core Block 3, Sector 1.

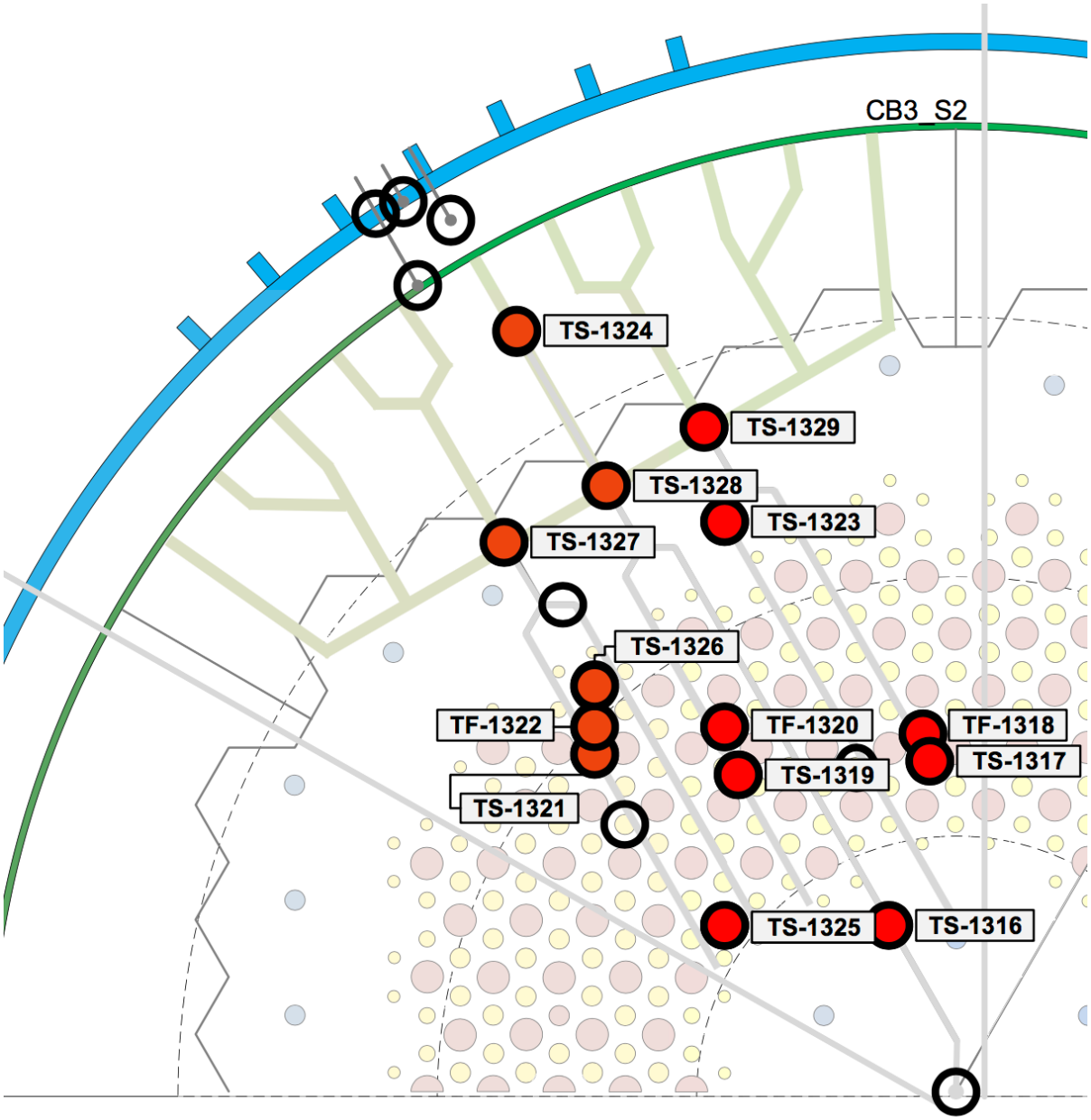

Figure A-6. Instrument locations for Core Block 3, Sector 2.

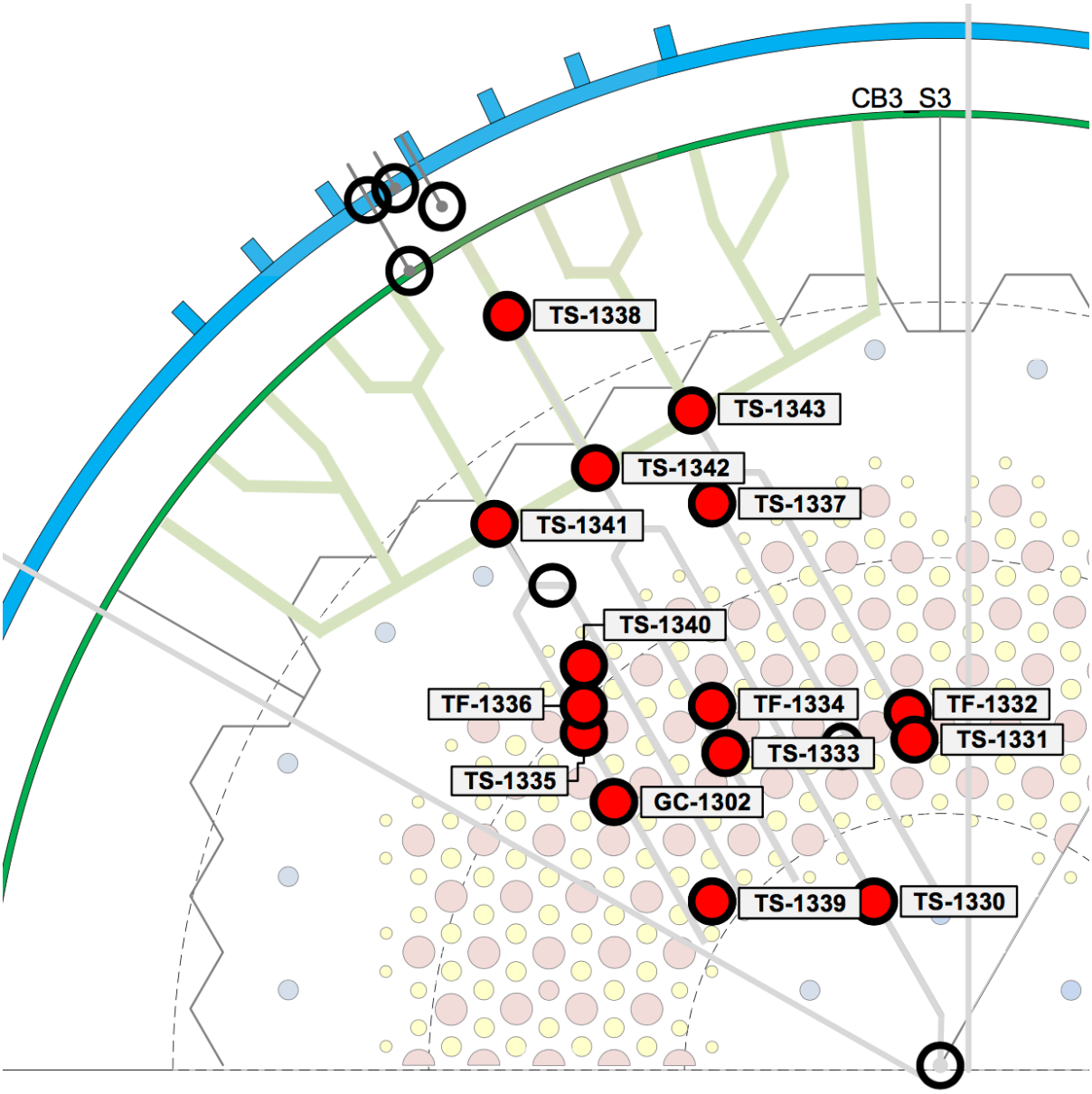

Figure A-7. Instrument locations for Core Block 3, Sector 3.

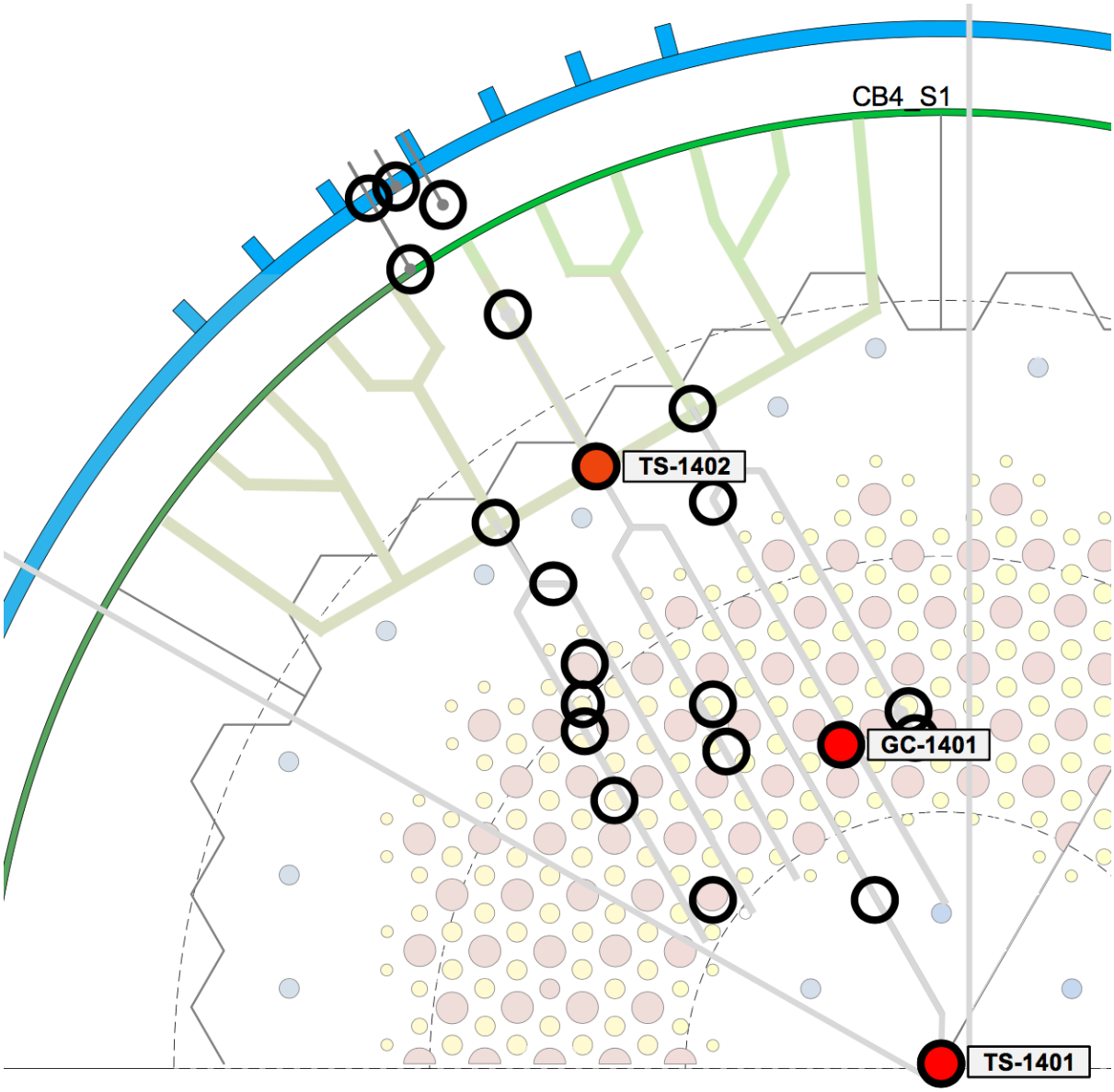

Figure A-8. Instrument locations for Core Block 4, Sector 1.

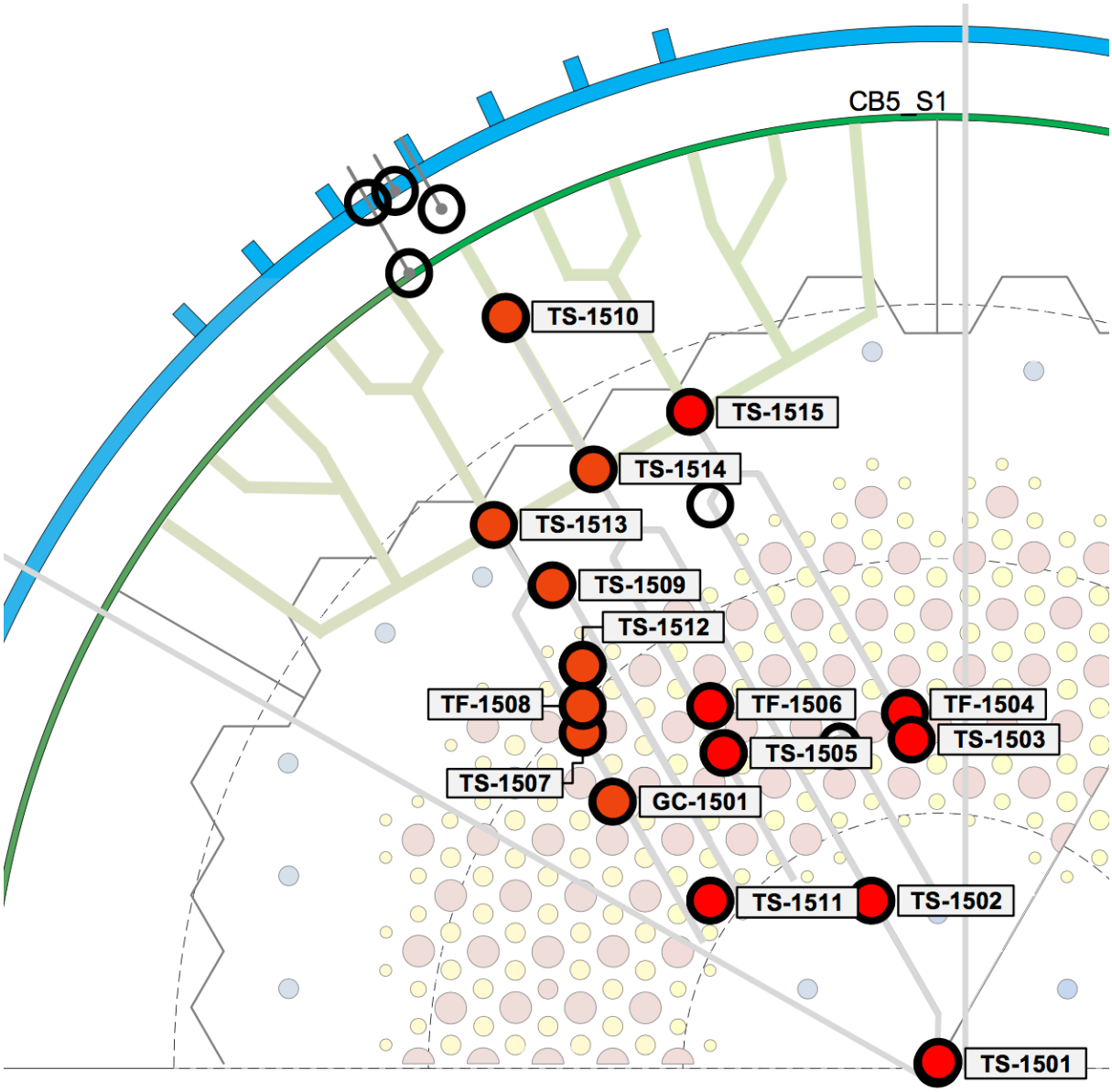

Figure A-9. Instrument locations for Core Block 5, Sector 1.

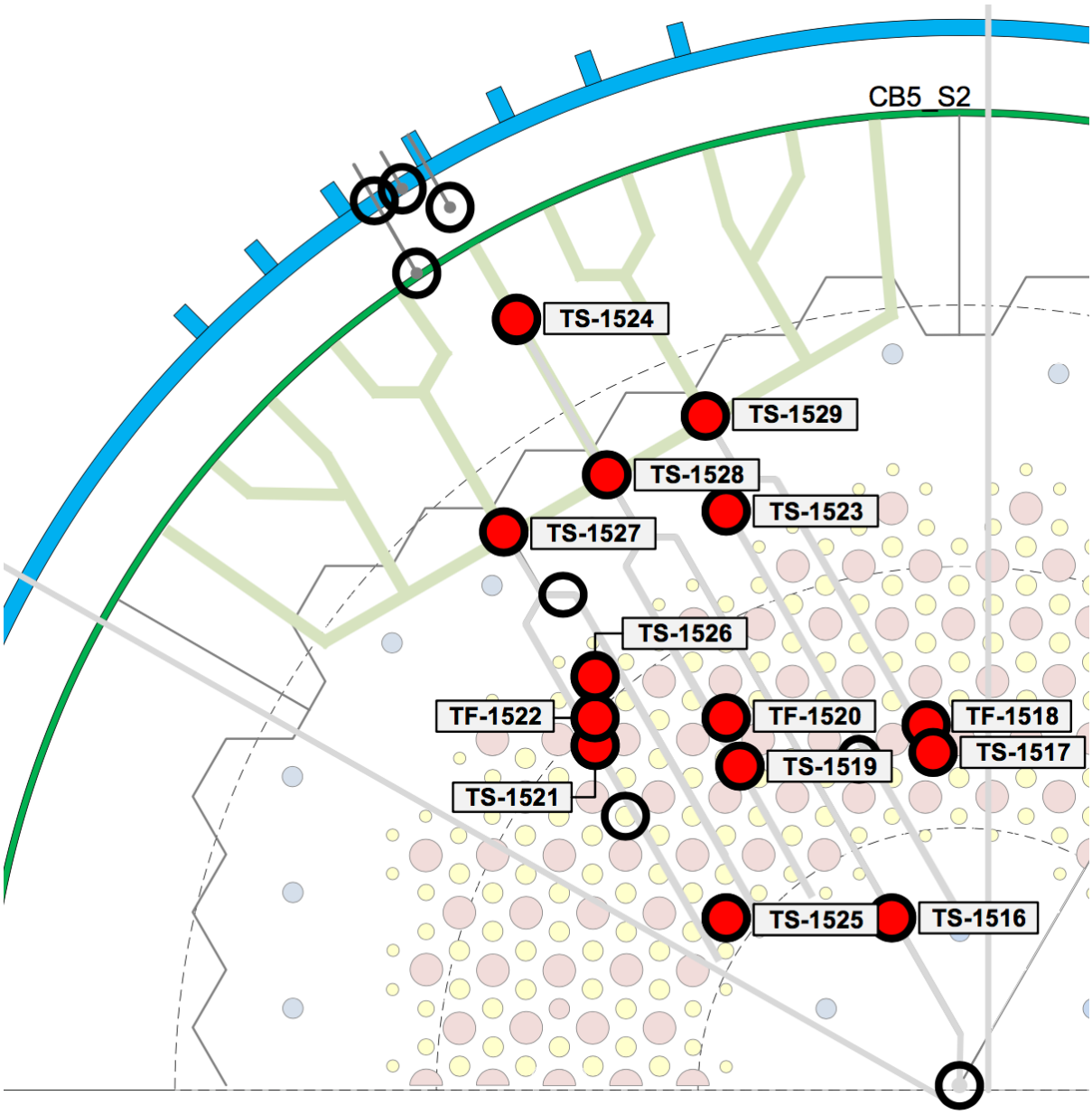

Figure A-10. Instrument locations for Core Block 5, Sector 2.

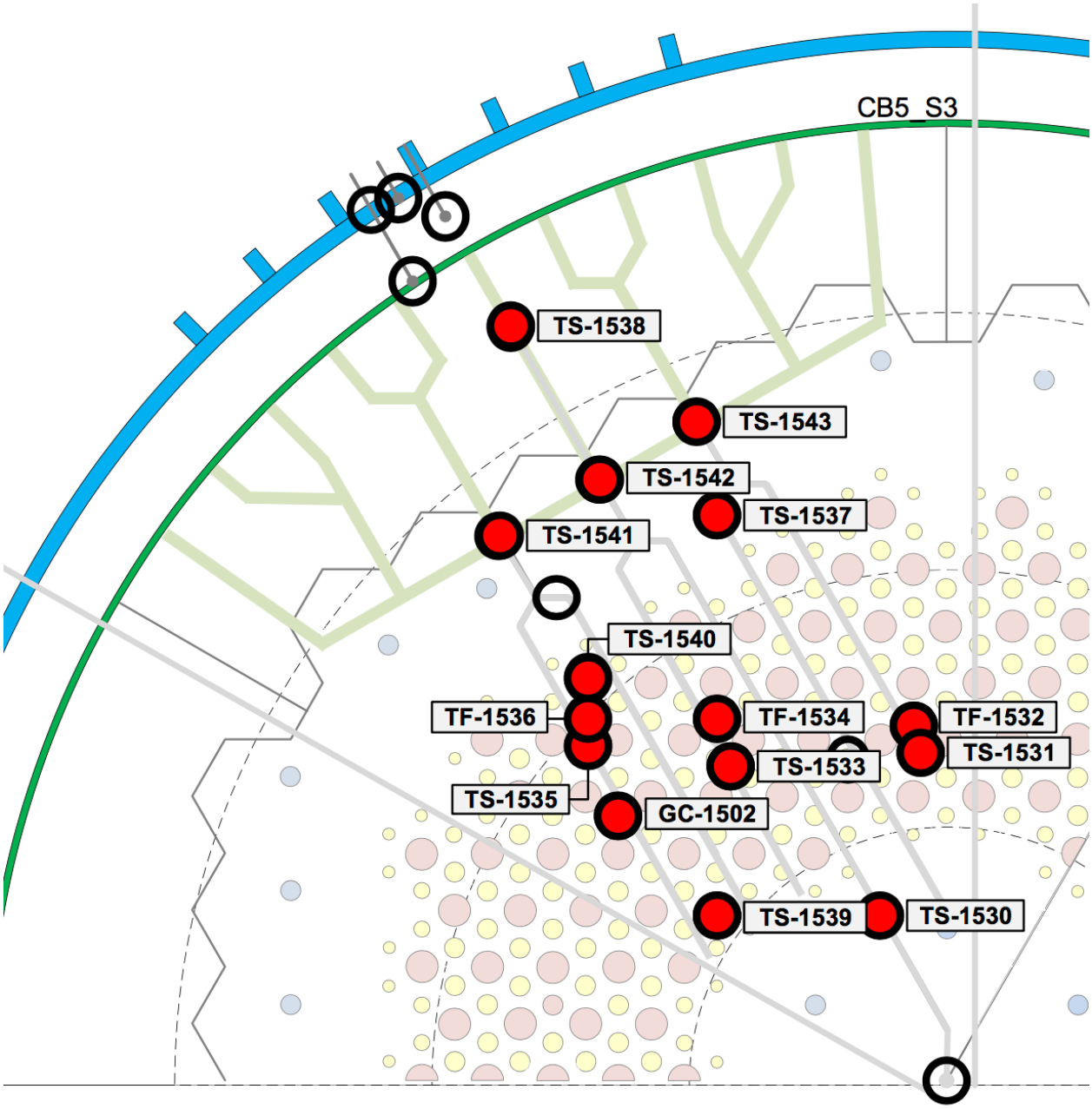

Figure A-11. Instrument locations for Core Block 5, Sector 3.

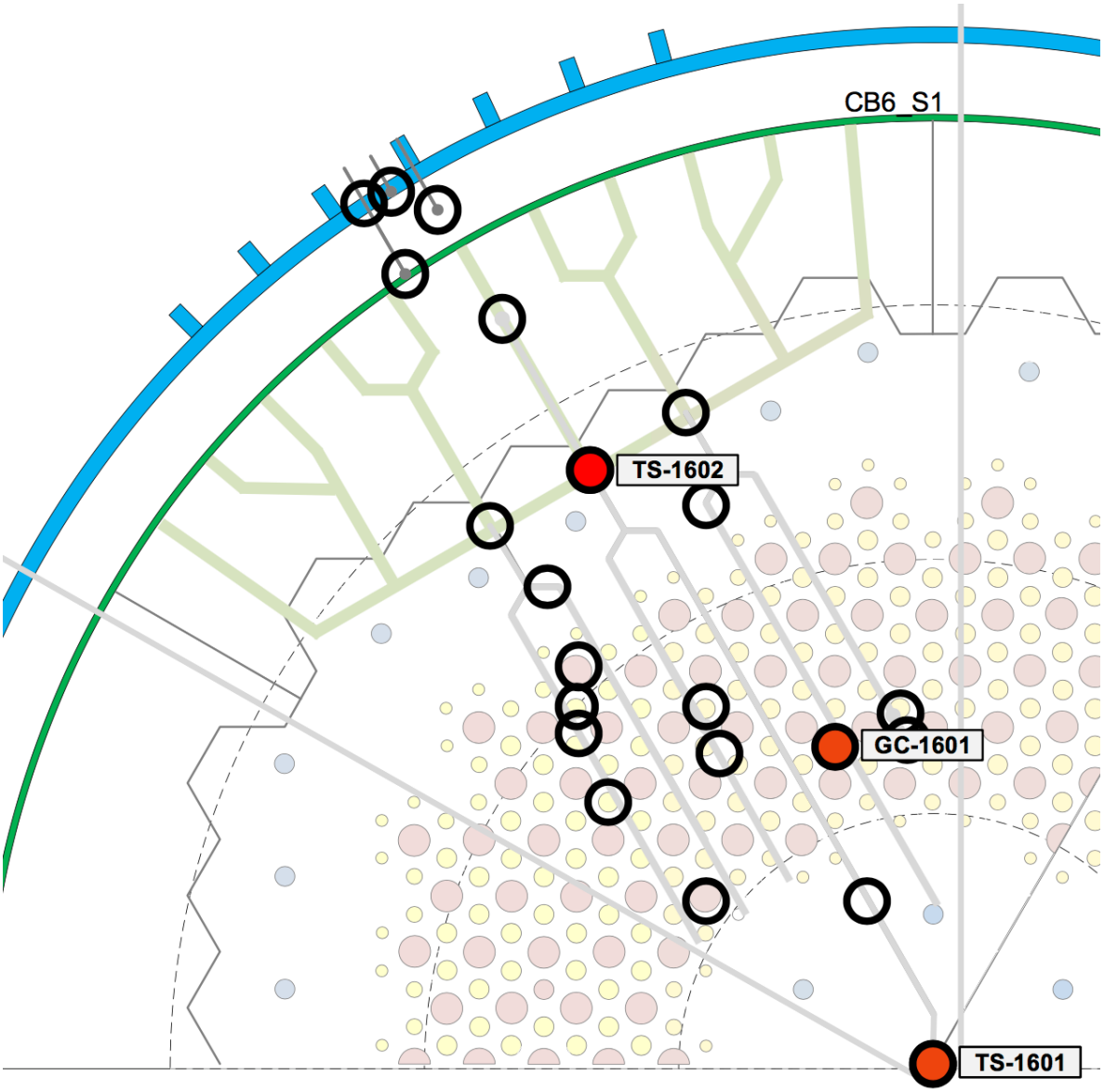

Figure A-12. Instrument locations for Core Block 6, Sector 1.

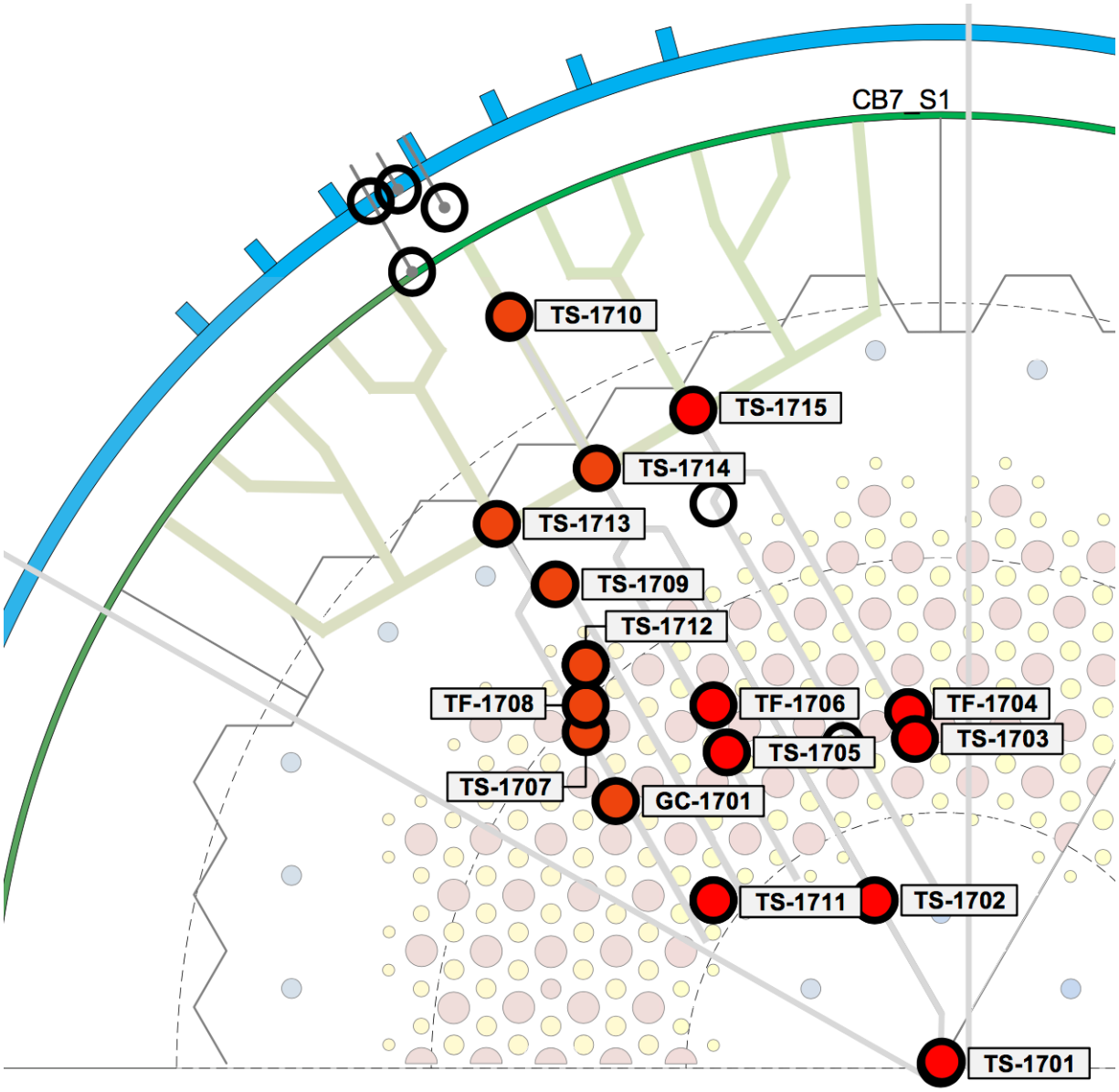

Figure A-13. Instrument locations for Core Block 7, Sector 1.

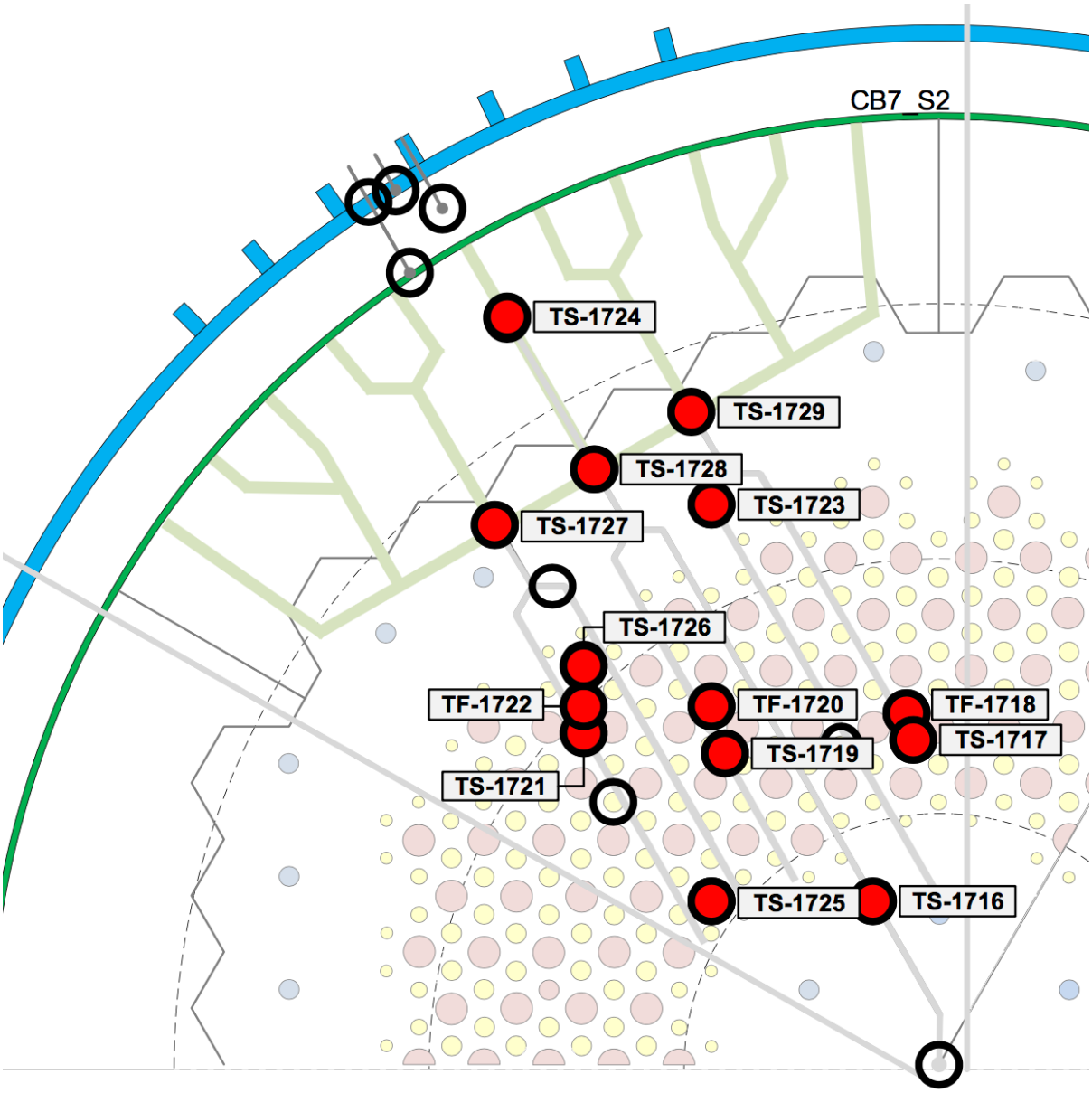

Figure A-14. Instrument locations for Core Block 7, Sector 2.

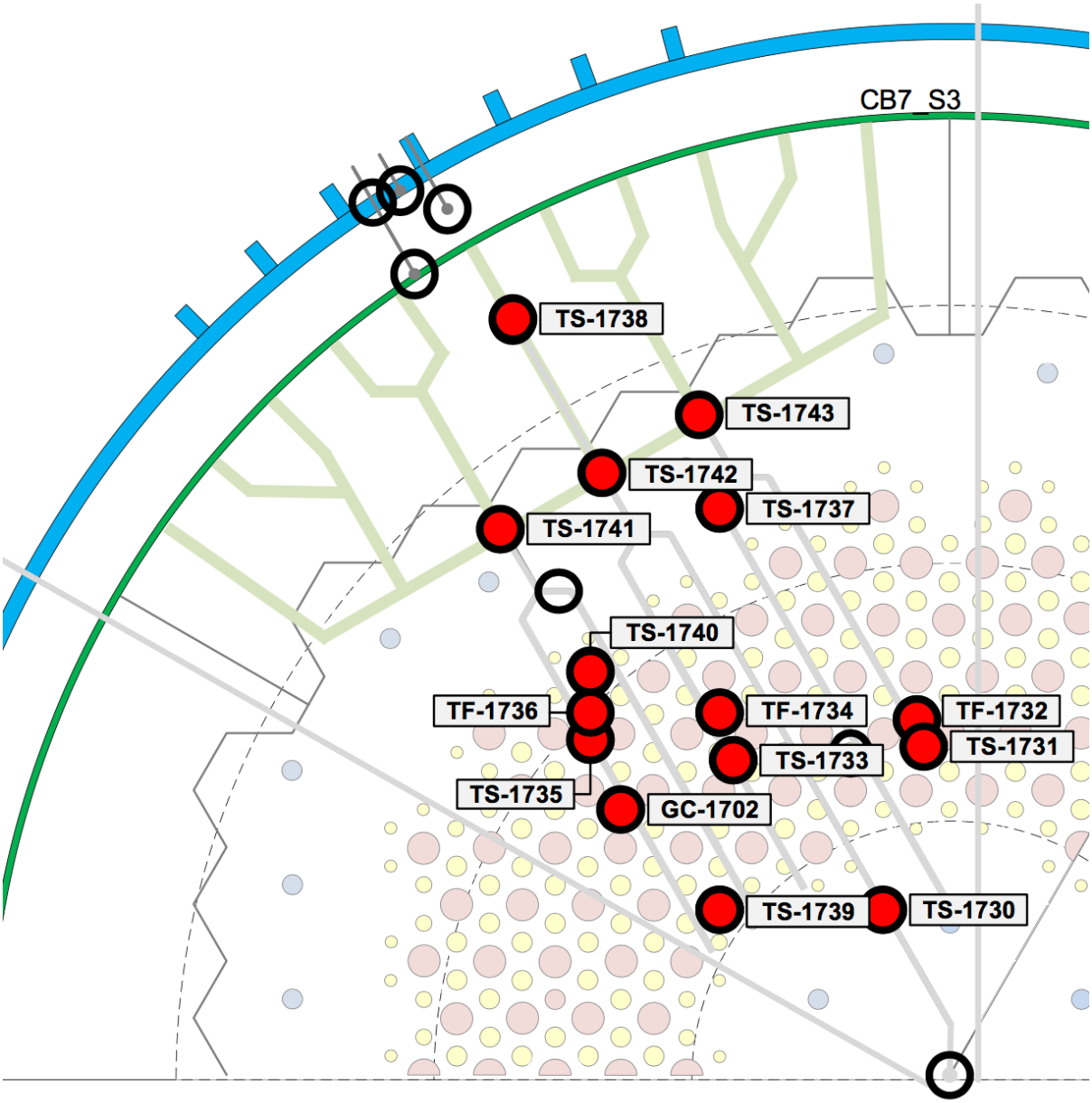

Figure A-15. Instrument locations for Core Block 7, Sector 3.

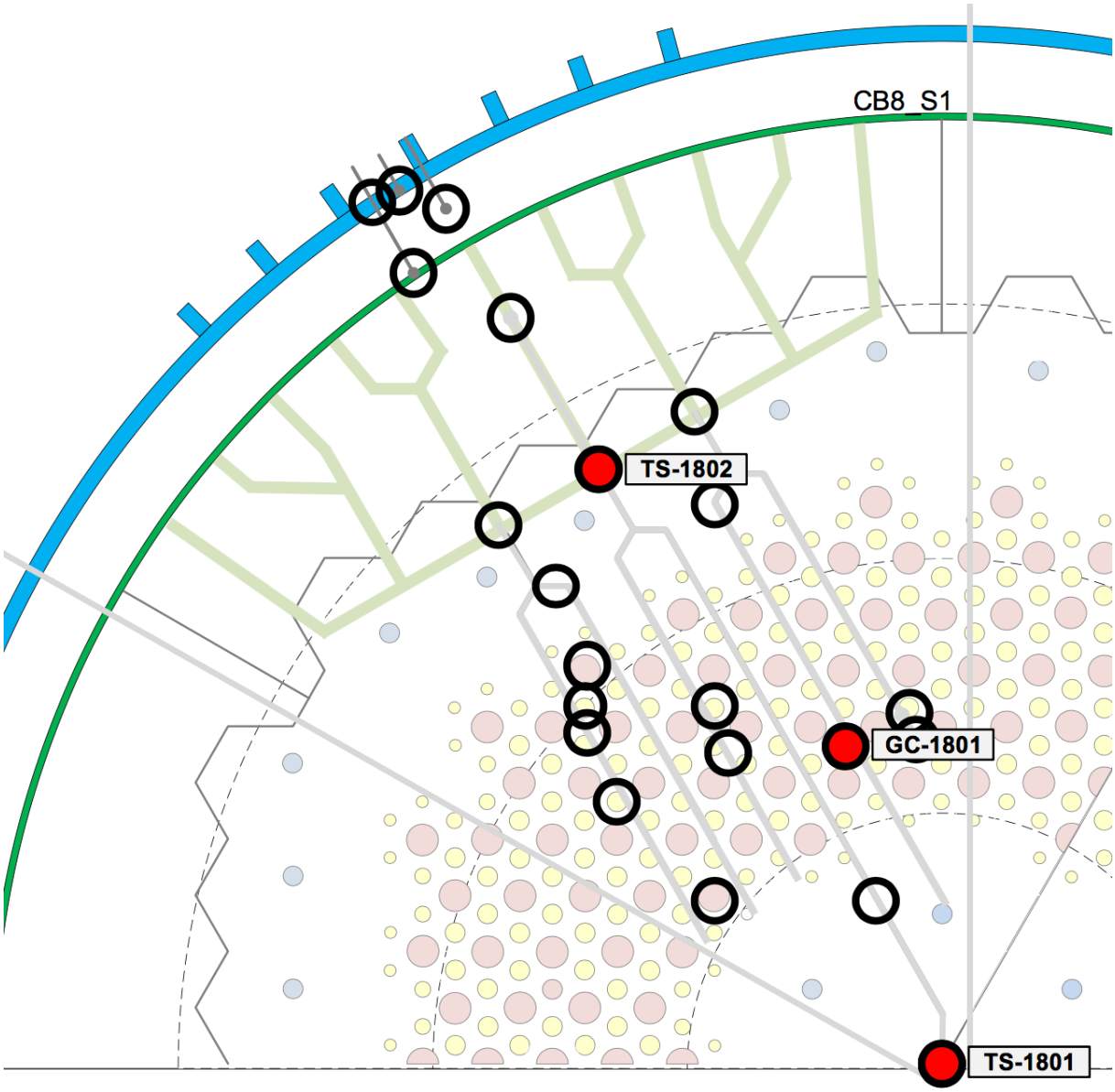

Figure A-16. Instrument locations for Core Block 8, Sector 1.

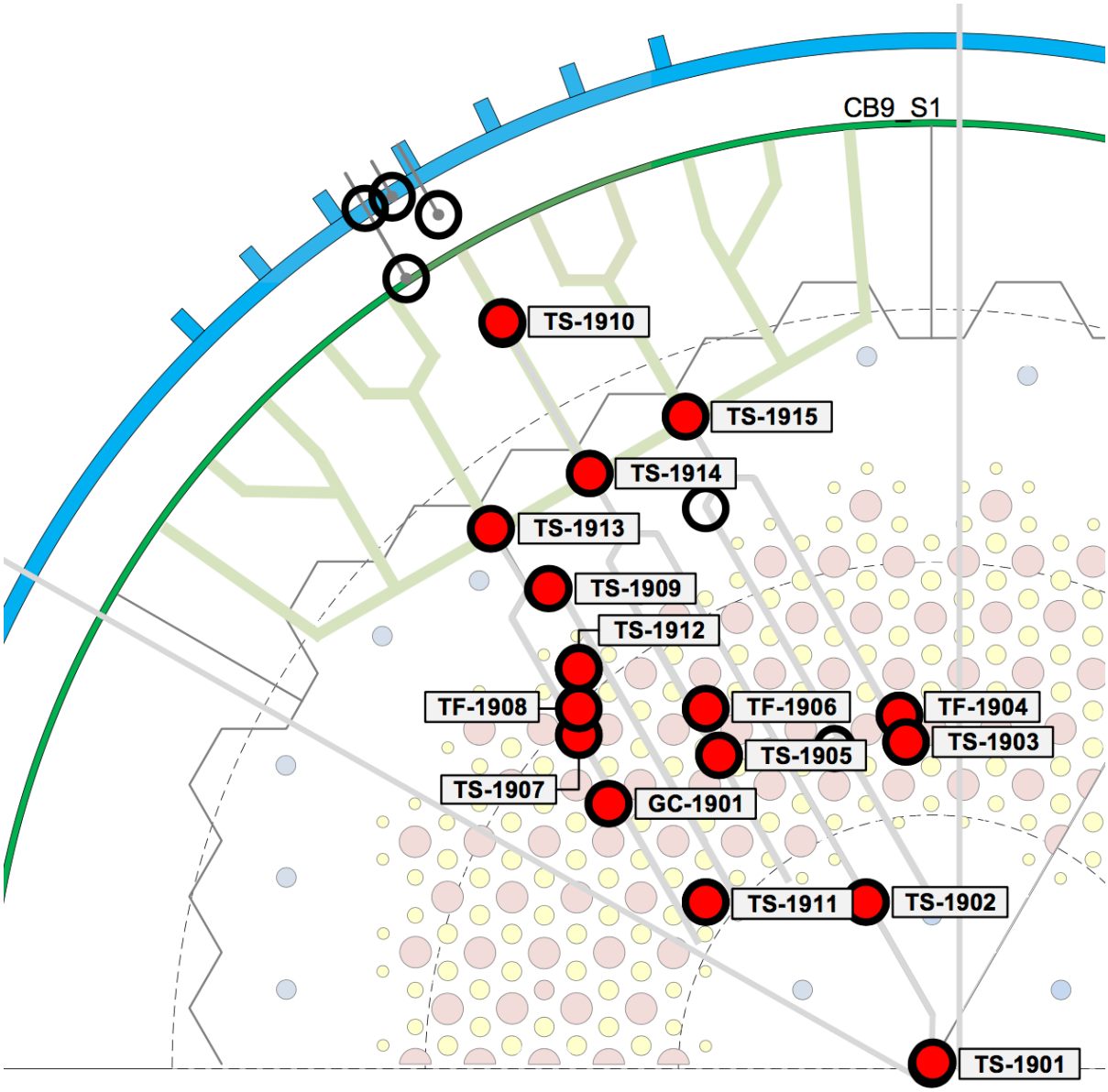

Figure A-17. Instrument locations for Core Block 9, Sector 1.

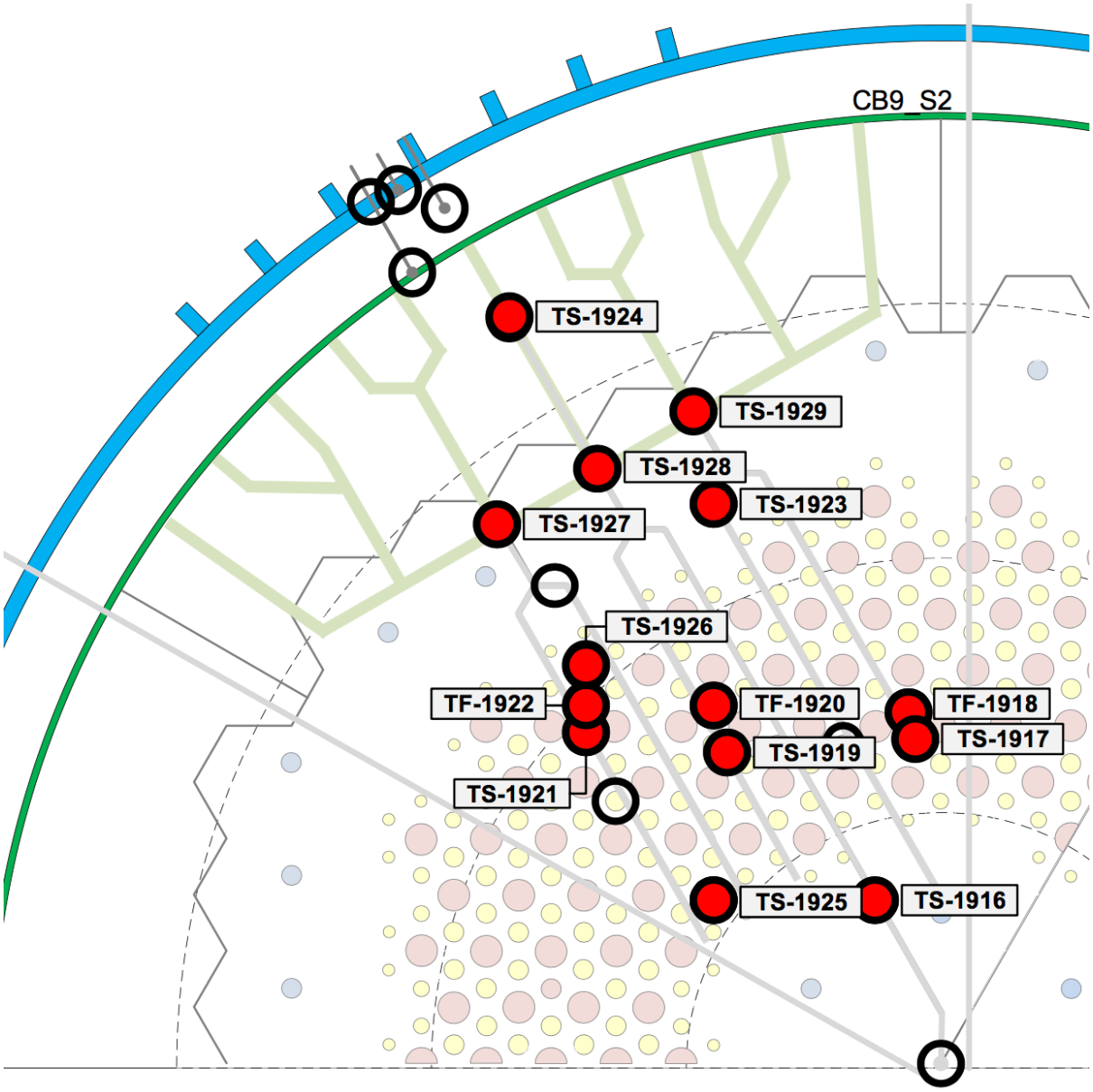

Figure A-18. Instrument locations for Core Block 9, Sector 2.

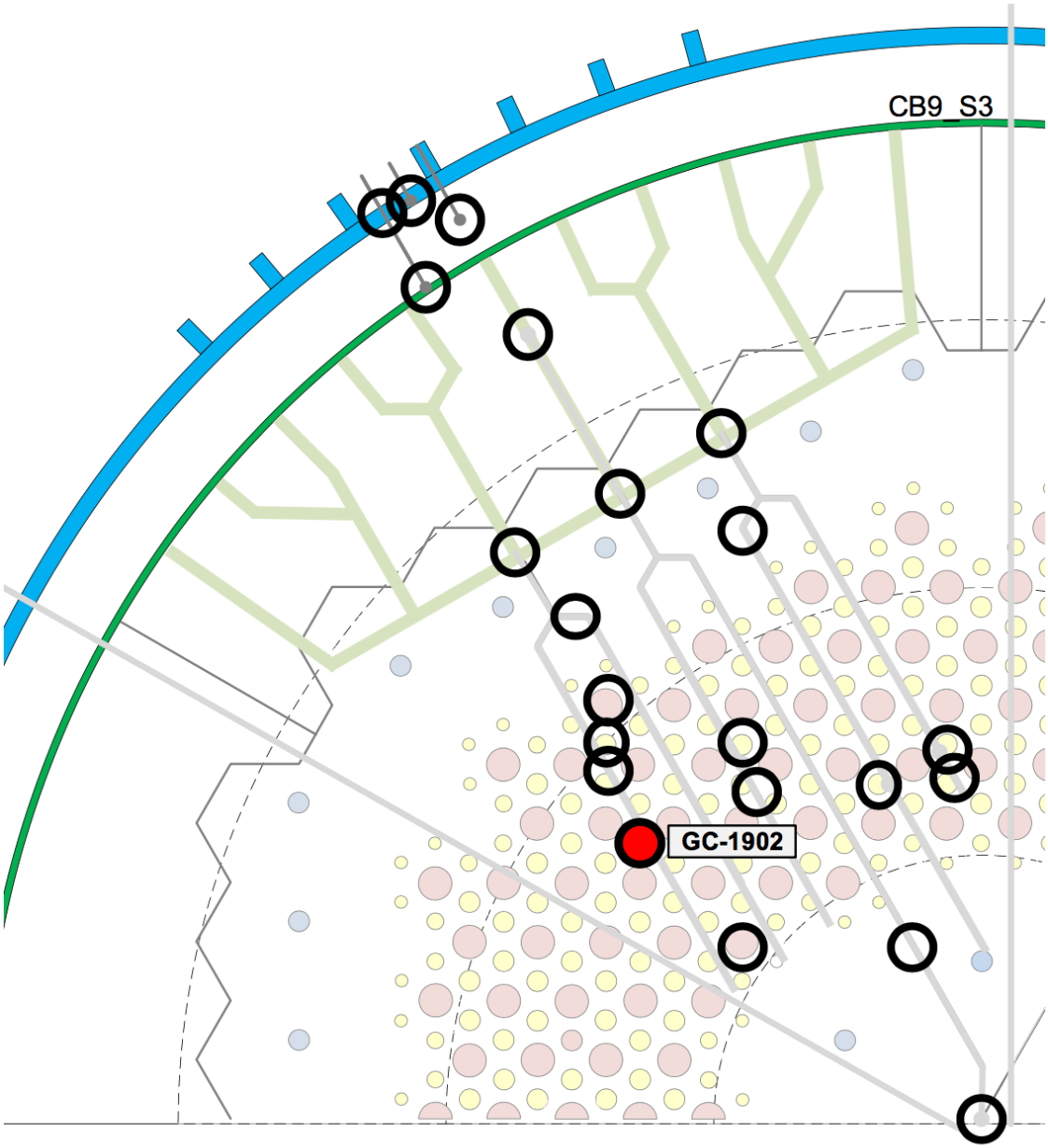

Figure A-19. Instrument locations for Core Block 9, Sector 3.

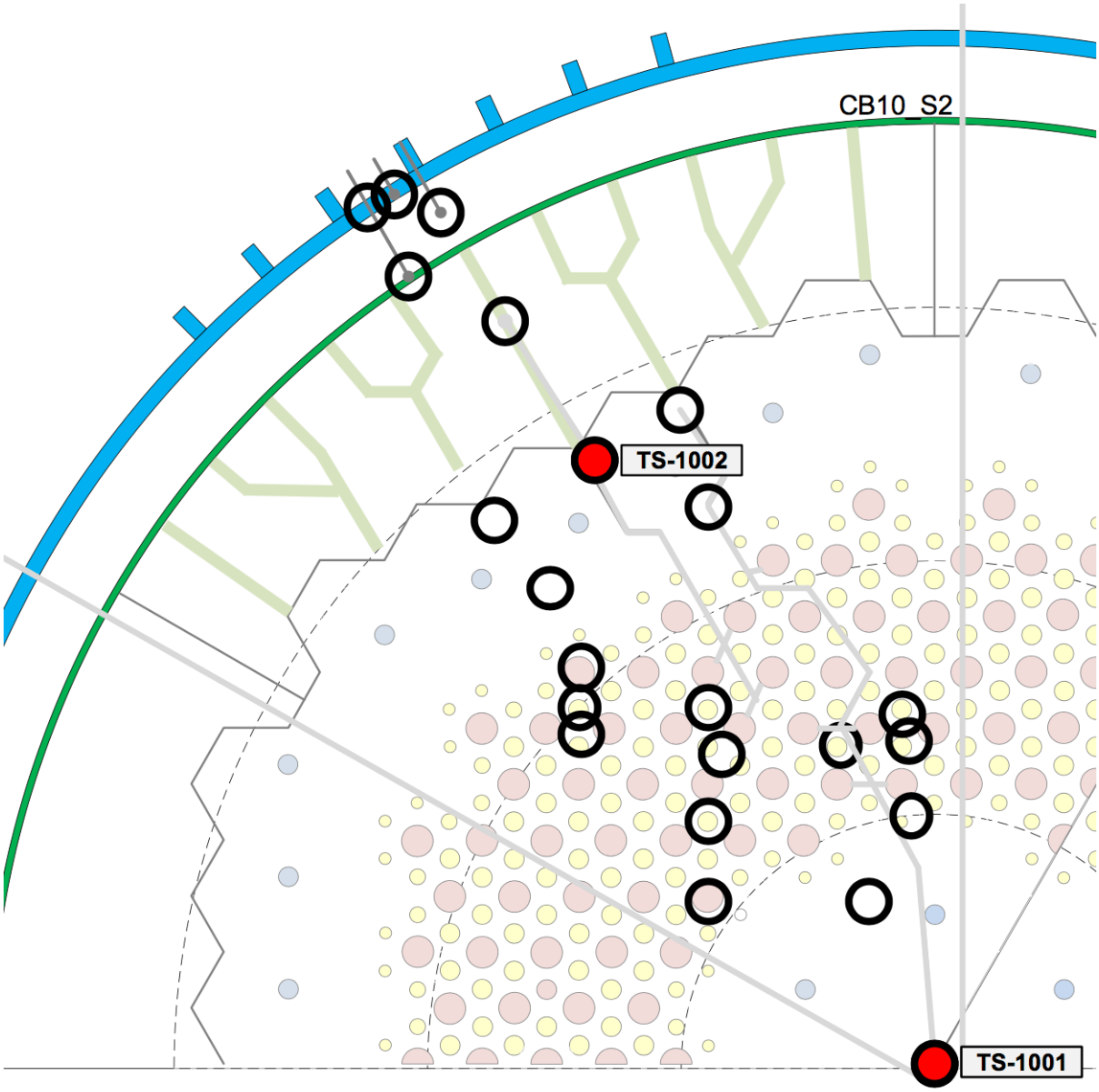

Figure A-20. Instrument locations for Core Block 10, Sector 2.

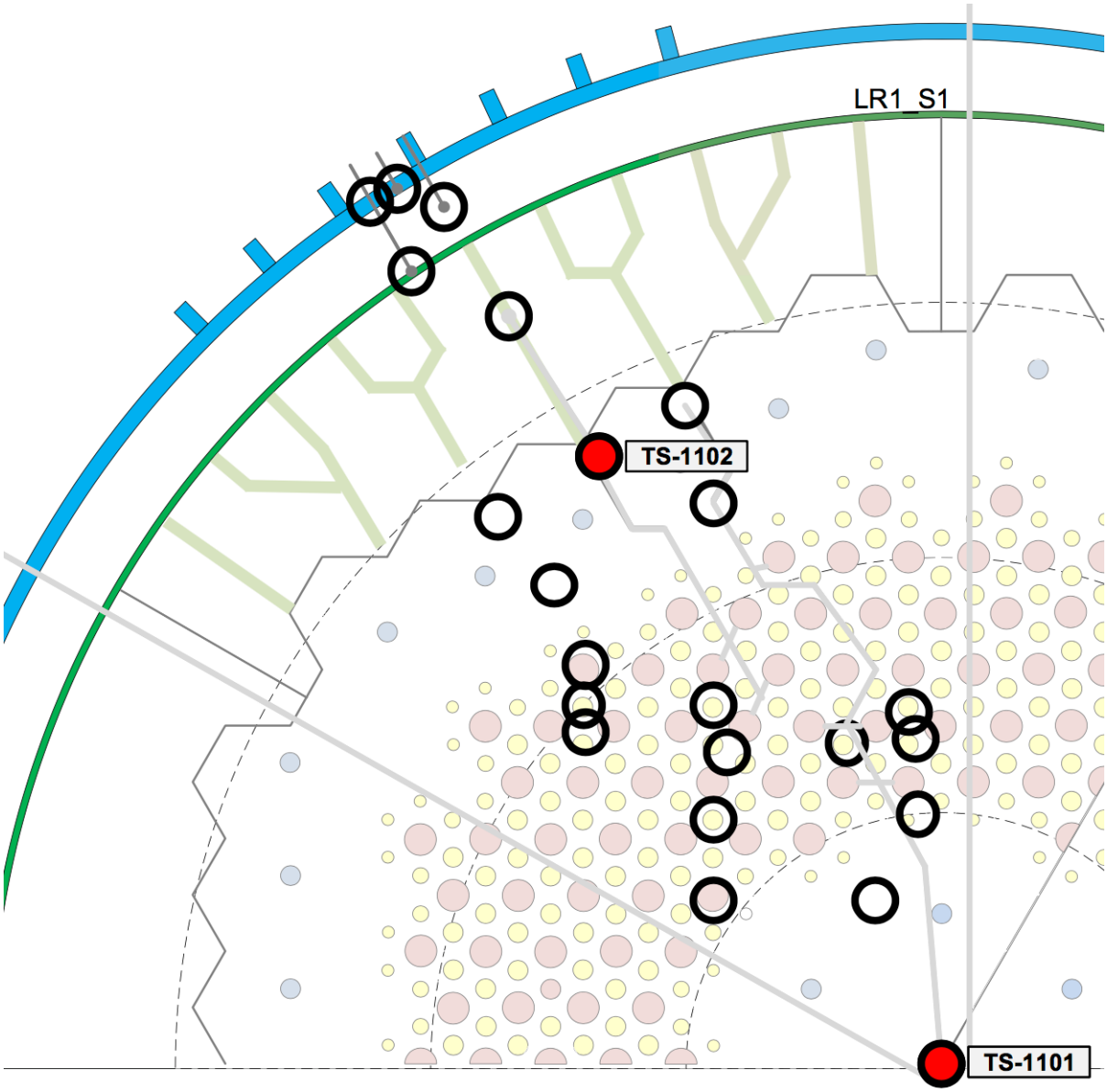

Figure A-21. Instrument locations for Lower Reflector 1, Sector 1.

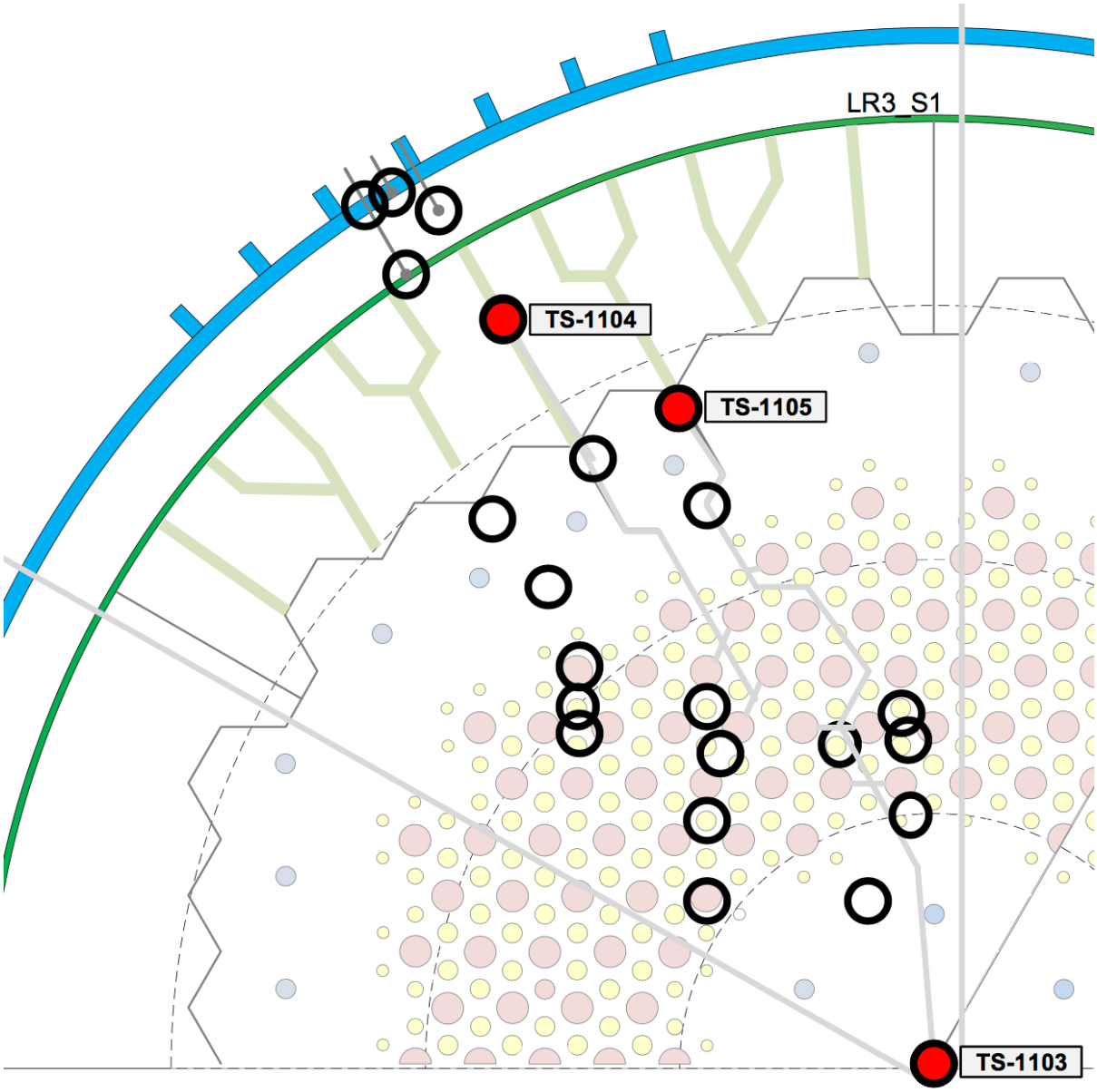

Figure A-22. Instrument locations for Lower Reflector 3, Sector 1.

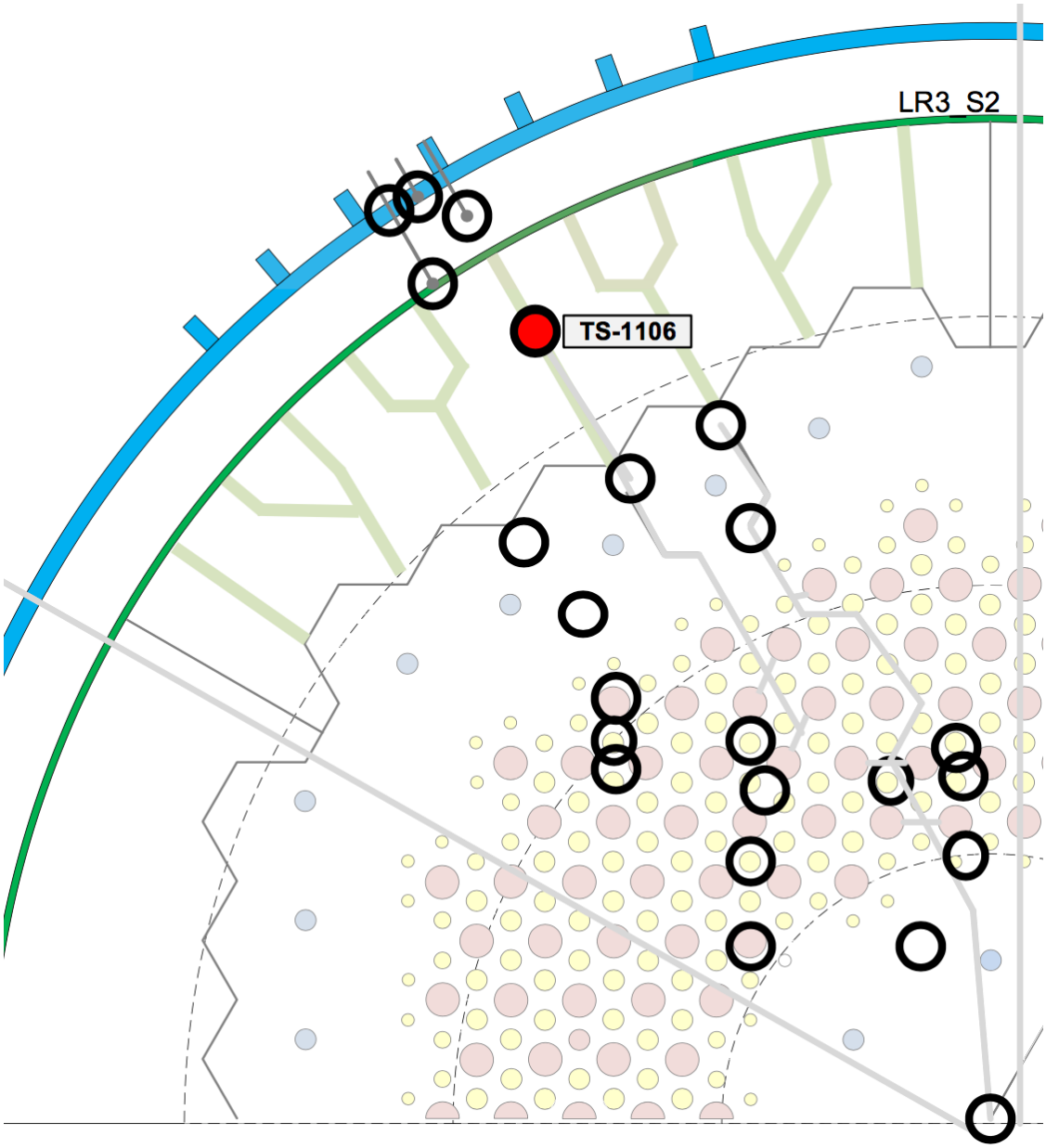

Figure A-23. Instrument locations for Lower Reflector 3, Sector 2.

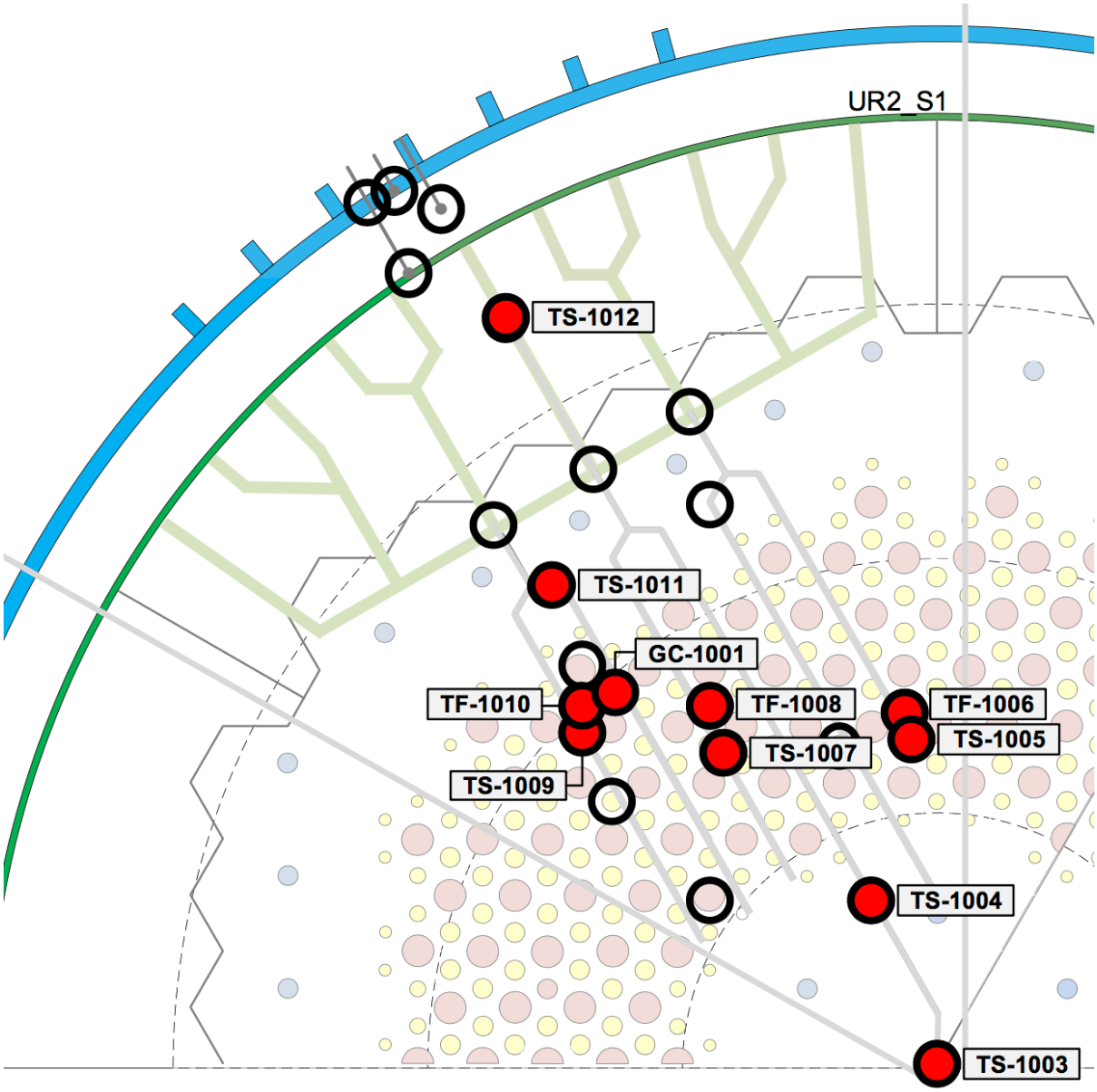

Figure A-24. Instrument locations for Upper Reflector 2, Sector 1.

Table A-2 outlines the locations and associated instrument tag numbers for instrumentation located in the lower plenum and head. The following figure can be used with Table A-2 to specify the physical location of each instrument in the lower plenum.

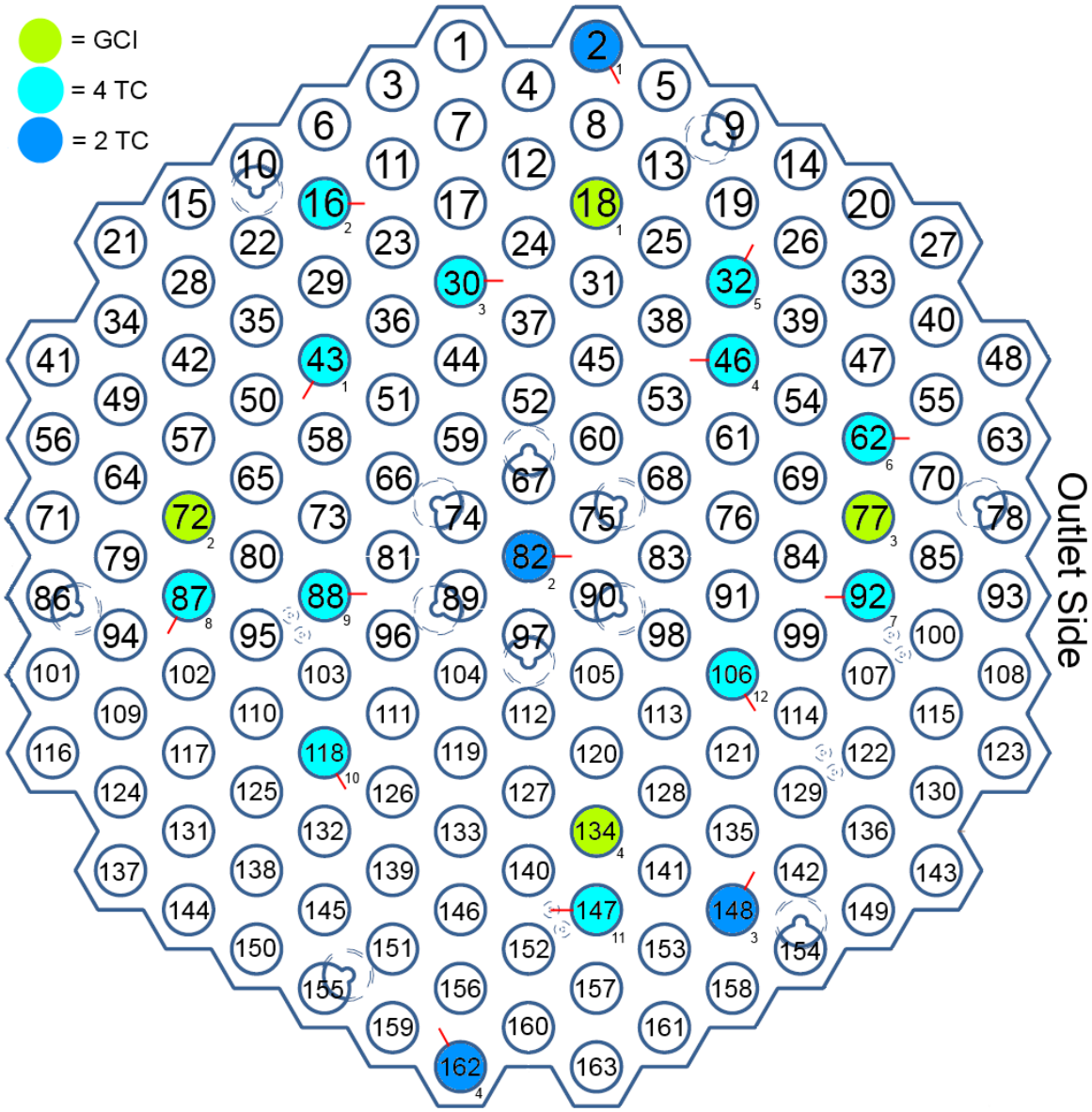

Figure A-25. Positional designations for lower plenum instrumentation.

Table A-2. Lower plenum instrument locations.

Location	Instrument	ID Tag
Post 2, upper	Thermocouple	TF-2301
Post 2, lower	Thermocouple	TF-2201
Post 16, gas inlet	Thermocouple	TF-2402
Post 16, upper	Thermocouple	TF-2302
Post 16, lower	Thermocouple	TF-2202
Post 16, floor	Thermocouple	TS-2102
Post 30, gas inlet	Thermocouple	TF-2403
Post 30, upper	Thermocouple	TF-2303
Post 30, lower	Thermocouple	TF-2203
Post 30, floor	Thermocouple	TS-2103
Post 32, gas inlet	Thermocouple	TF-2404
Post 32, upper	Thermocouple	TF-2304
Post 32, lower	Thermocouple	TF-2204
Post 32, floor	Thermocouple	TS-2104
Post 43, gas inlet	Thermocouple	TF-2405
Post 43, upper	Thermocouple	TF-2305
Post 43, lower	Thermocouple	TF-2205
Post 43, floor	Thermocouple	TS-2105
Post 46, gas inlet	Thermocouple	TF-2406
Post 46, upper	Thermocouple	TF-2306
Post 46, lower	Thermocouple	TF-2206
Post 46, floor	Thermocouple	TS-2106
Post 62, gas inlet	Thermocouple	TF-2407
Post 62, upper	Thermocouple	TF-2307
Post 62, lower	Thermocouple	TF-2207
Post 62, floor	Thermocouple	TS-2107
Post 82, upper	Thermocouple	TF-2308

Location	Instrument	ID Tag
Post 82, lower	Thermocouple	TF-2208
Post 87, gas inlet	Thermocouple	TF-2409
Post 87, upper	Thermocouple	TF-2309
Post 87, lower	Thermocouple	TF-2209
Post 87, floor	Thermocouple	TS-2109
Post 88, gas inlet	Thermocouple	TF-2410
Post 88, upper	Thermocouple	TF-2310
Post 88, lower	Thermocouple	TF-2210
Post 88, floor	Thermocouple	TS-2110
Post 92, gas inlet	Thermocouple	TF-2411
Post 92, upper	Thermocouple	TF-2311
Post 92, lower	Thermocouple	TF-2211
Post 92, floor	Thermocouple	TS-2111
Post 106, gas inlet	Thermocouple	TF-2412
Post 106, upper	Thermocouple	TF-2312
Post 106, lower	Thermocouple	TF-2212
Post 106, floor	Thermocouple	TS-2112
Post 118, gas inlet	Thermocouple	TF-2413
Post 118, upper	Thermocouple	TF-2313
Post 118, lower	Thermocouple	TF-2213
Post 118, floor	Thermocouple	TS-2113
Post 147, gas inlet	Thermocouple	TF-2414
Post 147, upper	Thermocouple	TF-2314
Post 147, lower	Thermocouple	TF-2214
Post 147, floor	Thermocouple	TS-2114
Post 148, upper	Thermocouple	TF-2315
Post 148, lower	Thermocouple	TF-2215
Post 162, upper	Thermocouple	TF-2316

Location	Instrument	ID Tag
Post 162, lower	Thermocouple	TF-2216
Gas detectors		
Post 18, upper	GCI	GC-2301
Post 18, lower	GCI	GC-2201
Post 72, upper	GCI	GC-2302
Post 72, lower	GCI	GC-2202
Post 77, upper	GCI	GC-2303
Post 77, lower	GCI	GC-2203
Post 134, upper	GCI	GC-2304
Post 134, lower	GCI	GC-2204
Miscellaneous		
Side reflector, 1	Thermocouple	TS-2501
Side reflector, 2	Thermocouple	TS-2502
Lower head, 1	Thermocouple	TS-2601
Lower head, 2	Thermocouple	TS-2602
MCSS, 1	Thermocouple	TS-2701
MCSS, 2	Thermocouple	TS-2702
Lower break, 1	Thermocouple	TF-2801
Lower break, 2	Thermocouple	TF-2802
Lower break	GCI	GC-2801

Table A-3 outlines the locations and associated instrument tag numbers for instrumentation located in the upper plenum and head. The following figure can be used with Table A-3 to specify the physical location of each instrument in the upper plenum.

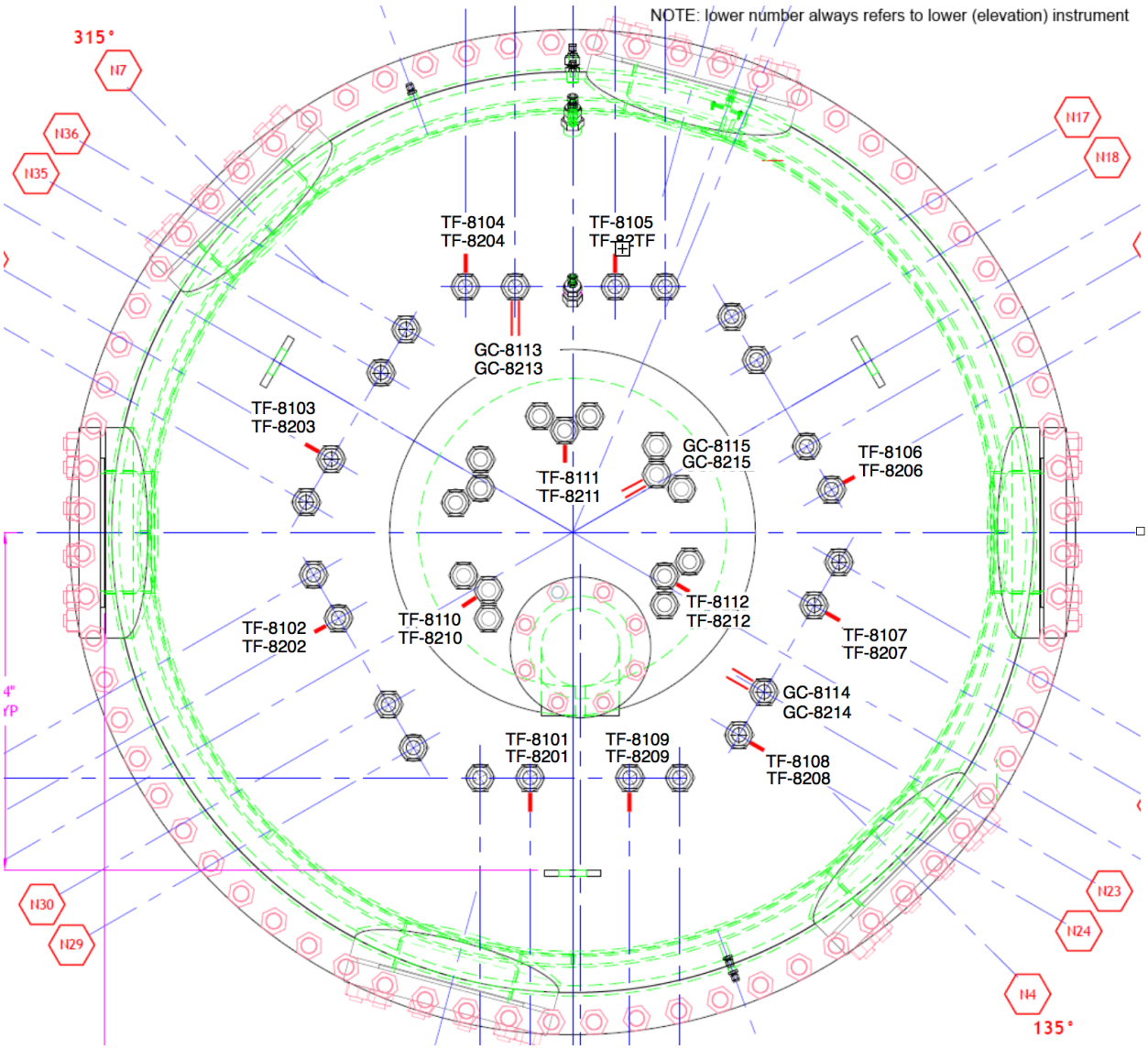

Figure A-26. Positional designations for upper plenum instrumentation.

Table A-3. Upper plenum instrument locations.

Location	Instrument	ID Tag
Upper plenum gas TCs		
Control Rod Drive 1, upper	Thermocouple	TF-8201
Control Rod Drive 1, lower	Thermocouple	TF-8101
Control Rod Drive 2, upper	Thermocouple	TF-8202
Control Rod Drive 2, lower	Thermocouple	TF-8102
Control Rod Drive 3, upper	Thermocouple	TF-8203
Control Rod Drive 3, lower	Thermocouple	TF-8103
Control Rod Drive 4, upper	Thermocouple	TF-8204
Control Rod Drive 4, lower	Thermocouple	TF-8104
Control Rod Drive 5, upper	Thermocouple	TF-8205
Control Rod Drive 5, lower	Thermocouple	TF-8105
Control Rod Drive 6, upper	Thermocouple	TF-8206
Control Rod Drive 6, lower	Thermocouple	TF-8106
Control Rod Drive 7, upper	Thermocouple	TF-8207
Control Rod Drive 7, lower	Thermocouple	TF-8107
Control Rod Drive 8, upper	Thermocouple	TF-8208
Control Rod Drive 8, lower	Thermocouple	TF-8108
Control Rod Drive 9, upper	Thermocouple	TF-8209
Control Rod Drive 9, lower	Thermocouple	TF-8109
Control Rod Drive 10, upper	Thermocouple	TF-8210
Control Rod Drive 10, lower	Thermocouple	TF-8110
Control Rod Drive 11, upper	Thermocouple	TF-8211
Control Rod Drive 11, lower	Thermocouple	TF-8111
Control Rod Drive 12, upper	Thermocouple	TF-8212
Control Rod Drive 12, lower	Thermocouple	TF-8112
Upper plenum shroud TCs		
H=33%	Thermocouple	TS-8113

Location	Instrument	ID Tag
H=66%	Thermocouple	TS-8213
Top	Thermocouple	TS-8013
Upper plenum vessel TCs		
H=33%	Thermocouple	TS-8114
H=66%	Thermocouple	TS-8214
Top	Thermocouple	TS-8014
Control rod drive break		
Upper break, lower	Thermocouple	TF-8015
Upper break, upper	Thermocouple	TF-8016
Gas detectors		
Control Rod Drive 13, H=33%	GCI	GC-8113
Control Rod Drive 13, H=66%	GCI	GC-8213
Control Rod Drive 14, H=33%	GCI	GC-8114
Control Rod Drive 14, H=66%	GCI	GC-8214
Control Rod Drive 15, H=33%	GCI	GC-8115
Control Rod Drive 15, H=66%	GCI	GC-8215
Upper break	GCI	GC-8001

Tables A-4, A-5, A-6 and A-7 outline the locations and associated instrument tag numbers for the remaining facility instrumentation. The position of these instruments is discussed in the body of this instrumentation plan.

Table A-4. Cylindrical sections instrument locations.

Location	Instrument	ID Tag
Outer core barrel		
Primary Sector, Lower Reflector #3	Thermocouple	TS-7101
Primary Sector, Core Block #3	Thermocouple	TS-7102
Primary Sector, Core Block #5	Thermocouple	TS-7103
Primary Sector, Core Block #7	Thermocouple	TS-7104
Primary Sector, Core Block #10	Thermocouple	TS-7105
Upcomer		
Primary Sector, Lower Reflector #3	Thermocouple	TF-7201
Primary Sector, Core Block #3	Thermocouple	TF-7202
Primary Sector, Core Block #5	Thermocouple	TF-7203
Primary Sector, Core Block #7	Thermocouple	TF-7204
Primary Sector, Core Block #10	Thermocouple	TF-7205
Primary Sector, Lower Reflector #3	GCI	GC-7201
Primary Sector, Core Block #4	GCI	GC-7202
Primary Sector, Core Block #6	GCI	GC-7203
Primary Sector, Core Block #10	GCI	GC-7204
Inner RPV		
Primary Sector, Core Block #3	Thermocouple	TS-7301
Primary Sector, Core Block #5	Thermocouple	TS-7302
Primary Sector, Core Block #7	Thermocouple	TS-7303
Outer RPV		
Primary Sector, Lower Reflector #3	Thermocouple	TS-7401
Primary Sector, Core Block #3	Thermocouple	TS-7402
Primary Sector, Core Block #5	Thermocouple	TS-7403
Primary Sector, Core Block #7	Thermocouple	TS-7404
Primary Sector, Core Block #10	Thermocouple	TS-7405

Table A-5. Crossover duct instrument locations.

Location	Instrument	ID Tag
Outlet ducts		
Rake #1, lower	Thermocouple	TF-3101
Rake #1, middle	Thermocouple	TF-3102
Rake #1, upper	Thermocouple	TF-3103
Rake #2, lower	Thermocouple	TF-3201
Rake #2, middle	Thermocouple	TF-3202
Rake #2, upper	Thermocouple	TF-3203
Rake #1, lower	GCI	GC-3101
Rake #1, middle	GCI	GC-3102
Rake #1, upper	GCI	GC-3103
Rake #2, lower	GCI	GC-3201
Rake #2, middle	GCI	GC-3202
Rake #2, upper	GCI	GC-3203
Inlet ducts		
Rake #1, lower	Thermocouple	TF-6101
Rake #1, upper	Thermocouple	TF-6102
Rake #3, lower	Thermocouple	TF-6301
Rake #3, upper	Thermocouple	TF-6302
Rake #1, lower	GCI	GC-6101
Rake #1, middle	GCI	GC-6102
Rake #3, lower	GCI	GC-6301
Rake #3, upper	GCI	GC-6302

Table A-6. RCST ans RCCS instrument locations.

Location	Instrument	ID Tag
RCST		
Low	Thermocouple	TF-4101
Lower Middle	Thermocouple	TF-4201
Middle	Thermocouple	TF-4301
High	Thermocouple	TF-4401
Low	GCI	GC-4101
Middle	GCI	GC-4301
High	GCI	GC-4401
RCCS		
Ceiling, 1	Thermocouple	TF-9101
Ceiling, 2	Thermocouple	TF-9201
Ceiling, 3	Thermocouple	TF-9301
Ceiling, 4	Thermocouple	TF-9401
Cavity floor, 1	Thermocouple	TF-9102
Cavity floor, 2	Thermocouple	TF-9202
Cavity floor, 3	Thermocouple	TF-9302
Cavity floor, 4	Thermocouple	TF-9402
Column 1 Inlet	Thermocouple	TF-9103
Column 1 Outlet	Thermocouple	TF-9104
Column 2 Inlet	Thermocouple	TF-9105
Column 2 Outlet	Thermocouple	TF-9106
Column 3 Inlet	Thermocouple	TF-9203
Column 3 Outlet	Thermocouple	TF-9204
Column 4 Inlet	Thermocouple	TF-9205
Column 4 Outlet	Thermocouple	TF-9206
Column 5 Inlet	Thermocouple	TF-9303
Column 5 Outlet	Thermocouple	TF-9304

Location	Instrument	ID Tag
Column 6 Inlet	Thermocouple	TF-9305
Column 6 Outlet	Thermocouple	TF-9306
Column 7 Inlet	Thermocouple	TF-9403
Column 7 Outlet	Thermocouple	TF-9404
Column 8 Inlet	Thermocouple	TF-9405
Column 8 Outlet	Thermocouple	TF-9406

Table A-7. Pressure.

Location	Instrument	ID Tag
Core	Differential Pressure	DP-1001
Upcomer	Differential Pressure	DP-7201
Upper plenum	Differential Pressure	DP-8001
Lower plenum	Differential Pressure	DP-2001
MCSS	Differential Pressure	DP-2701
Hot leg	Differential Pressure	DP-3001
Cold leg	Static Pressure	PT-6001
RCST	Static Pressure	PT-4001
RCCS	Differential Pressure	DP-9001

Table A-8. Miscellaneous

Location	Instrument	ID Tag
Spare Channels		
Spare Channel 1	-	TF-0001
Spare Channel 2	-	TF-0002
Spare Channel 3	-	TF-0003
Spare Channel 4	-	TF-0004

APPENDIX B: INSTRUMENT MANUFACTURER INFORMATION

Table B-1 provides the manufacturer and model of the instrumentation used on the HTTF. All information used in this uncertainty analysis was acquired from the manufacturer's publicly available data sheet.

Table B-1: HTTF Instrument Manufacturer and Model Details.

Component	Manufacturer	Model	Uncertainty Information from Data Sheet
Thermocouple Type K	—	—	From 0 to 275C: 1.1C. From 275C to 1250C: 0.4% reading
Thermocouple Type R	—	—	From 0 to 600C: 0.6C From 600C to 1450C: 0.1% reading
Temperature Transducer	INOR	APAQ-LC	0.1% of span
Pressure Transducer Type 1	OMEGA	PX209	0.25% full scale (including linearity, hysteresis and repeatability)
Pressure Transducer Type 2	OMEGA	PX409	±0.08% BSL maximum (BSL = best straight line)
Level Differential Pressure Sensor	OMEGA	PX2300-5DI	±0.25% RSS FS at constant temperature (includes linearity, repeatability and hysteresis)
Differential Pressure Transducer	OMEGA	PX429	±0.08% BSL Includes Linearity, Hysteresis, and Repeatability
Voltage Transducer Type 1	OMEGA	ACT-SV	±0.1% (for 5 to 120% of span) typical; ±0.15% max
Voltage Transducer Type 2	CR Magnetics	CR4560	0.5% span
Current Transducer	CR Magnetics	CR4460	0.5% span
Gas Concentration Instrument	Oregon State University	N/A	5% span assumed

Oxygen Sensor	General Electric	O2X1 IS	+/- 1% of span at calibration point
Frequency Converter	Blancett	B220-873	Accuracy of frequency measurement is ±0.1% of reading
Flow Meter	Blancett	B111-110	1% of reading
Analog Current Input Module	National Instruments	NI 9208	Rss of gain/offset: 0.761 %reading*
Analog Voltage Input Module	National Instruments	NI 9205	174 µV accuracy at full scale
Master Controller	National Instruments	NI cRIO-9114	100ppm max (0.01%)
Master Chassis	National Instruments	NI cRIO-9024	35ppm - 200ppm (0.0035 - 0.02%)

***Due to the instrument uncertainties being a function of the instrument span, %span is used here instead of %reading to allow a total channel uncertainty calculation. This results in a conservative estimate.**