ANL-ART-175

RCCS Testing with the Water-Based NSTF

Year-1 Single-Phase Results

Nuclear Science and Engineering Division

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Executive Summary

Under support from the Department of Energy (DOE) and the Office of Advanced Reactor Technologies (ART), a large scale test facility has been constructed to generate validation data for passive decay heat removal systems of advanced reactors. Located at Argonne National Laboratory, the Natural convection Shutdown heat removal Test Facility (NSTF) reflects key features of a ½ scale, water-based, Reactor Cavity Cooling System (RCCS). This report serves as a summary of the single-phase testing results obtained during the programs first year of matrix testing. An introduction to the high-level program objectives is first presented, followed by a brief summary of facility design, instrumentation, and control systems. Details of the NQA-1 driven test method are included, which govern the programs quality assurance requirements and provide a background for the testing strategy and procedures.

Checkout activities, including verification of gross system mass and energy balances, heat loss quantification, and isothermal facility characterization, were performed early in the first year and results presented in this report. These tests have identified relevant facility characteristics such as K-factors, frictional pressure losses, parasitic heat loss rates, and transient heating response. Results are then presented from four accepted matrix tests where the facility established a steady-state, single-phase mode of flow operation. All matrix tests were performed with an identical top-level procedure: first initiating a heater power ramp to target levels, and then holding power levels constant until the facilities structural members and network piping reached thermal equilibrium. Upon obtaining stable thermal and hydraulic conditions, active cooling was initiated off of the bulk storage tank to maintain constant riser inlet temperatures of 30°C. This steady-state period was then held for a minimum required duration, at which point the heaters were ramped down and test concluded.

The two baseline tests completed reflect conditions prototypic to the full scale plant at both normal operation, and design basis Depressurized Loss of Forced Cooling (DLOFC) conditions. These parameters are defined by full RCCS decay heat loads of 1.4 MW_t and 2.1 MW_t, which translate to NSTF scale thermal power levels of 34.4 kW_t and 51.6 kW_t, respectively. Two additional tests were also conducted, which repeated baseline cases but included modification by single parameter variations in decay heat load, or heater power, at 700 kW_t, and 2.8 MW_t. Finally, a scoping test was performed to demonstrate the facilities ability to operate in a two-phase mode of operation. The facility successfully operated for a 3-hour period at this mode, reaching peak inventory temperatures of 105°C and condensing approximately 50 gallons of boil-off inventory. The testing parameters for this demonstration were based off the design basis DLOFC condition, and will be the reference for new baseline cases as the program moves forward with two-phase matrix testing.

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1. Introduction

The Natural convection Shutdown heat removal Test Facility (NSTF) at Argonne National Laboratory (Argonne) is a multi-disciplinary program that centers on supporting a single, large scale thermal hydraulics test facility. The program was first initiated in 2005, with a purpose of generating validation data in support of the Next Generation Nuclear Plant (NGNP), and comprises both experimental testing activities and analytical / computational support. The program operates under support from the Department of Energy (DOE) Office of Advanced Reactor Technologies (ART), and has maintained compliance with NQA-1 2008 with 2009a in both administrative and technical portions of program activities.

Efforts early in the program focused on design and scaling activities [1] which led to a primary purpose of constructing and operating an experimental testing facility to study the behavior and performance of air-based Reactor Cavity Cooling System (RCCS) concepts [2][3]. Between 2010 and 2016 the program examined one concept design using air-based cooling, completing over 2,250 hours of active test operations and 16 successful test runs. Details of the air-based program, including design basis, testing results, and project conclusions, can be found in previously published reports [4].

Following completion of the air-based objectives, the program transitioned to an alternative design concept and began efforts to convert the facility to water-based cooling. Details of the design bases for the conceptual prototype, along with scaling and preparation tasks can be found in earlier reports [5][6]. A design report of the current, as-built, water-based facility, along with new program requirements and testing plan, can similarly be found in previous reports [7].

1.1. QA requirements

The research and development activities of this experimental program are under the control of an NQA-1 compliant quality assurance program plan (QAPP). The program is based on the requirements set forth in the American Society of Mechanical Engineers (ASME) NQA-1-2008 (with 1a 2009 addenda) Quality Assurance (QA) requirements for nuclear facility applications [8]. It is consistent with QA plans adopted by Argonne [9], the Nuclear Science and Engineering (NSE) division within the Energy and Global Security directorate [10], and the QAPP for the NGNP at the Idaho National Laboratory (INL) including INL PLN-2690 [11] and 10 CFR Part 50, App. B [12]. These guidelines have been established to provide reliable, reproducible, and timely data on the effects of the reactor cavity cooling system on the heat removal from the reactor vessel wall. Assessments, both internal and formal external audits, have been, and will continue to be, conducted on a regular basis through the entirety of the water-based testing program.

1.2. Design and review basis

The water-based NSTF was designed primarily to align with major features of the Framatome (formerly AREVA) 625 MW_t SC-HTGR RCCS. The full scale concept is housed entirely within the reactor containment building, Figure 1, and intended to operate continuously during normal operation with active cooling off the water tanks to maintain nominal inventory temperatures of 30°C. During accident transients, where active cooling is no longer available, the inventory begins a gradual rise in temperature, eventually reaching saturation conditions with loss of inventory through boil-off to the atmosphere [14]. The inputs and observations details of this full scale design were provided by a technical report released to the DOE [15]. They include information pertaining to the geometry of the concrete containment, heat removal requirements for the RCCS, and preliminary dimensions of the cooling panels.

Several key aspects of NSTF, such as geometry and dimensions of the riser tube – cooling fin test section, heated plate – test section set back distance, etc., were determined with direct involvement from industry partners. Others areas, such as layout of the network piping and volume of the inventory storage tank, were not selected for optimal RCCS performance, but instead to serve as a representative yet bounding configuration for future implementation into a full scale design. Flexibility remained a driving philosophy through the overall design process, ensuring the facility can accommodate future alternations and support a wide breadth of available testing parameters.

The test facility retains aspects common to the general RCCS concept and thus suitable for providing relevant information to other reactor vendors, supporting the DOE vision of aiding US vendors in design choices of future reactor concepts. Lastly, the NSTF also retains aspects common to a fundamental boiling water thermosiphon, thus is well poised to provide necessary experimental data to advance basic understanding of natural circulation phenomena and contribute to computer code validation.

(Figure 1 has been deleted)

Figure 1: Conceptual layout of single SC-HTGR module [13]

2. Facility Description

2.1. Instrumentation

A suite of sensors within the water NSTF allow measurement of pertinent thermal hydraulic behavior during both single- and two-phase mode of operations. Instruments have been selected to minimize disturbance of the natural circulation flow. The instrumentation suite is diverse enough to quantify both integral and local behaviors across the full extent of the system components. To address the high priority system measurements, e.g. thermal and mass balance, both temperature and flow measurements utilize sensors that are minimally intrusive and exhibit very low uncertainty. Details of each sensor are provided in the following sections, with a high level summary provided in Table 1, a facility diagram of installed locations in Figure 2, and complete details in in previous reports [7].

Table 1: Overview of water NSTF instrumentation suite

Measurement	Sensor Type	Location	Qty.	Mfg.	Model	Range
Flow rate	Magnetic	Inlet header	x1	Krohne	Optiflux 4000	±5 kg/s
Flow rate	Magnetic	Inlet riser	x8	Krohne	Optiflux 4000	±1 kg/s
Static head	Strain	Inlet header	x1	Rosemount	3051S	0 – 10 bar
Steam pressure	Strain	Gas space	x1	Rosemount	3051S	0 – 2 bar_{abs}
ΔP	Strain	Chimney	x2	Rosemount	3051S	±6 kPa
ΔP	Strain	Risers	x3	Rosemount	3051S	±62 kPa
Liquid level	Strain	Tank	x1	Rosemount	3051S	0 – 3 m
Void fraction	Optical	Chimney	x2	RBI	Twin-tip	0 – 100%
Void fraction	γ-Density	Chimney	x1	ThermoFisher	DensityPRO	0 – 100%
Temperature	RTD	Fluid	x4	Omega	UP, 1/10 DIN	0 – 250°C
Temperature	T-type TC	Fluid	x128	ARi	T-31N	0 – 400°C
Temperature	K-type TC	Test section	x24	ARi	T-31N	0 – 600°C
Temperature	K-type TC	Structures	x286	ARi	Silica 20AWG	0 – 600°C
Temperature	DTS	Test section	x20	LUNA	ODiSI-A	0 – 300°C
Water pH	pH Meter	Inlet header	x1	Emerson	RBI 547	0 – 14 pH
TrDO O_2	Amperometric	Inlet header	x1	Emerson	499A	0.1ppb –20ppm
Conductivity	Insertion	Inlet header	x1	Sensorex	CS675HTTC	10-2000 μS/cm

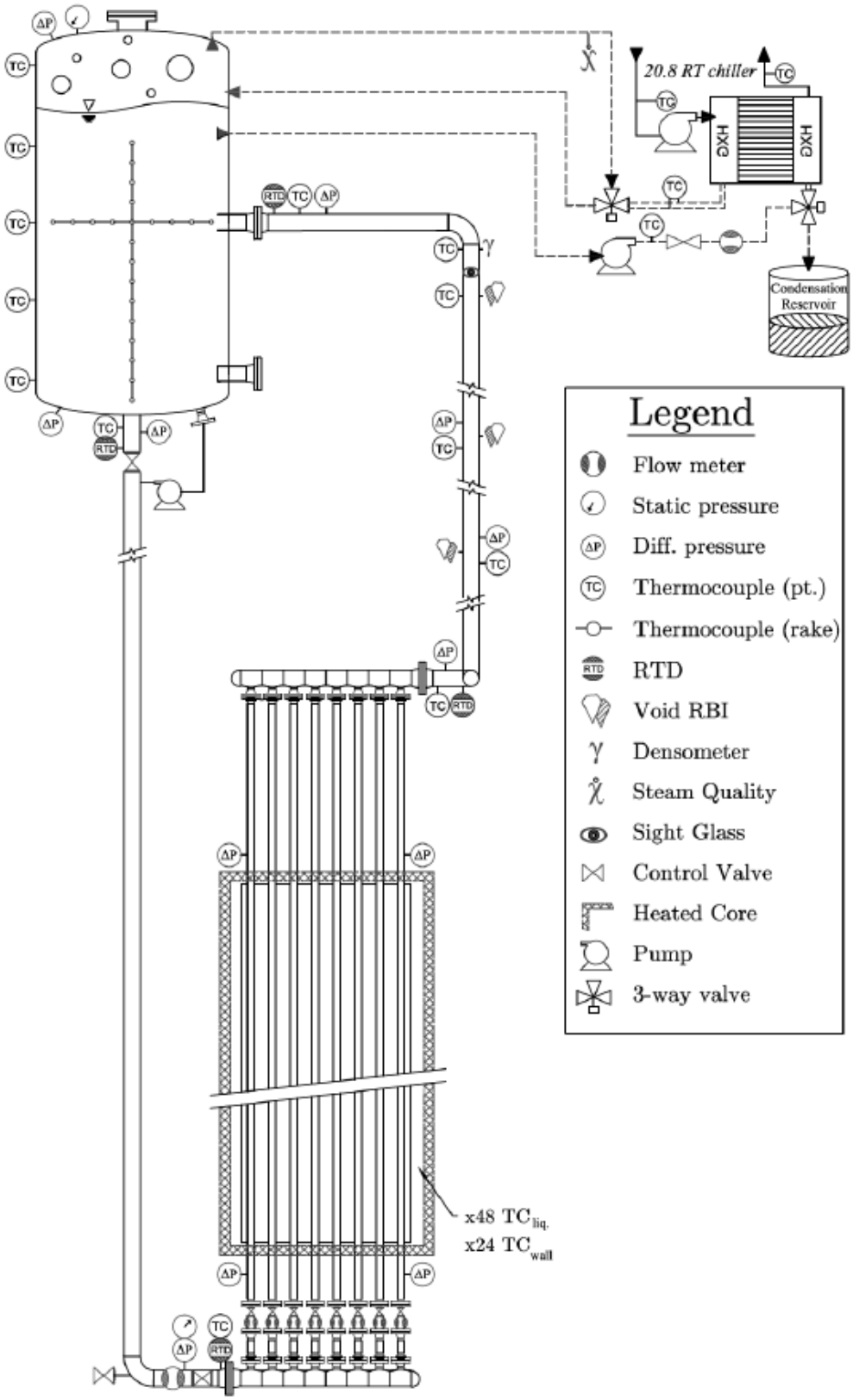

Figure 2: Overview of instrumentation locations on water NSTF

2.2. Water quality

For a boiling water test loop there are three common concerns: corrosion, scale formation, and biological fouling. Corrosion (e.g. red rust on steel components and white rust on galvanized surfaces) may affect the longevity of system components. Scale, typically a calcium or magnesium based build-up, not only reduces heat transfer and system efficiency, but also may lead to under deposit corrosion. If scale is not controlled, it may continue building on critical components, and severely impact thermal performance. Biological fouling, which is usually due to slime and algae formations, may reduce heat transfer, promote corrosion, and harbor pathogens such as Legionella.

To ensure acceptable NSTF water inventory performance, quality, water chemistry and cleanliness need to be maintained, with target metrics summarized in Table 2. The bounds are determined assuming a concentrated "solution" in condensate from boil-off test case, in which ~ 1,000 gallons of water boils down to ~ 20 gallons.

Table 2: NSTF water quality requirements

Property	Limit
pH	5.0 to 9.5
Total Dissolved Solids	50 ppm
Conductivity	20 µS/cm
Total Alkalinity	12 ppm
Total Hardness	15 ppm
Chlorides	15 ppm
Sulfates	15 ppm
Silica	3 ppm

To ensure the functionality and performance of the water NSTF, high purity deionized water is used in the system. The deionized water is generated from city water source by an in-house deionizing system, which is permanently installed in the NSTF laboratory (Building 308 high bay). The deionizing system consists of four resin tanks in serial and is capable of generating approximately 3,000 gallons of low conductivity, high resistivity inventory. After the inventory is generated, it is initially stored in a stainless steel holding tank located in the laboratory pit. A continuous circulation loop with filter and UV sterilizer is implemented in the holding tank to prevent algae growth. In addition, regular sampling and measurement of pertinent quality parameters is performed to ensure the water quality. For each test, after the inventory is transferred to the NSTF loop, re-sampling and measurement of water quality parameters is performed. New water will be made if the prescribed quality limits are exceeded. On average, a single batch is used for 2 – 3 tests.

To measure the water quality parameters, handheld type meters from Hanna Instruments and OAKTON are used, as illustrated in Figure 3. A list of the used meters can be found in Table 3. It should be noted that, only the conductivity meter is for data quality, while the others are not.

Figure 3: Handheld meters from Hanna Instruments (left) and OAKTON (right)

Table 3: List of handheld meters used for NSTF water quality measurement

Manufacturer	Model #	Quality Parameter	Data Quality?
Hanna Instr.	HI775	Total alkalinity	No
Hanna Instr.	HI96735C	Total hardness	
Hanna Instr.	HI96753C	Chloride	
Hanna Instr.	HI96751C	Sulfate	
Hanna Instr.	HI96705C	Silica (low range)	
Hanna Instr.	HI770	Silica (high range)	
Hanna Instr.	HI96734C	Free/total chlorine	
OAKTON	pHTestr 30	pH	
OAKTON	Con 150	Conductivity/TDS	Yes

In addition to the above handheld type meters, continuous online monitoring of the quality metrics of conductivity, pH, and trace dissolved oxygen has also been implemented in the water NSTF via two water quality meters, Emerson RBI 547 and 499A TrDo, Table 4. Both are installed along the network piping prior to the inlet header, and fed directly into the data acquisition for online monitoring. Dissolved oxygen levels will be reduced (if deemed necessary) by bubbling argon through the filled piping system at regular intervals. Finally, exposure of free surfaces is limited to minimum required duration to prevent exposure to ambient air.

Table 4: Water quality sensor specifications

Manufacturer	**Emerson**	**Emerson**
Model	RBI 547	499A TrDO
Measurement	pH	Trace dissolved oxygen
Range	0 - 14 pH	0.1 ppb - 20 ppm
Max. Temp	130°C	50°C
Max. Pressure	276 kPa	65 psig
Accuracy	±0.01 pH	<20 ppb: ±1ppb >20 ppb: ±5% MV
Stability	n/a	<4% / 60 d
Response Time	5 sec	<20 sec

2.3. Test control systems

Eleven control valves of varying types are placed throughout the test loop and serve to adjust the flow resistance or create alternative flow configurations, Table 5. For valves located along the path of natural circulation, only full-bore valves are used, ensuring that when fully open they provide no added resistance that would otherwise affect the loop's form loss coefficient.

Two valves are located along the primary network piping, one at the outlet of the tank, and a second prior to the inlet header. The tank outlet valve allows on or off service, and is used to isolate the tank from the remaining loop during maintenance activities. Additionally, it can be used to create a by-pass loop for forced circulation during characterization activities. The header inlet valve is of the proportional type and allows for precise control of the loss coefficient along the primary flow path. Both valves are of the full-bore type, driven by pneumatic pressure, controlled with a 4-20mA signal, and equipped with positioning indicators to confirm intended position.

At the inlet of the riser tubes, eight valves, also of the full-bore ball valve type, provide the ability to close off individual riser tubes. These valves are of the manual type and must be adjusted by experiment personnel. Currently, another eight valves of exactly the same type are being installed into the outlet of the riser tubes, to encompass the capability of simulating single riser tube blockage in the water NSTF. Finally, within the heat removal network, a globe-style valve with bolted bonnet and interchangeable C_v valve is used. Since this loop will be driven by a pump, a full-bore requirement was not necessary and instead a globe-style valve could be used. The valve was selected for maximum precision in adjusting the flow rate across the heat exchanger, allowing for a high level of granularity in adjustment, Figure 4.

Table 5: Control and throttle valve specifications

	Inlet Throttle	**Tank Shutoff**	**Riser Shutoff**	**HXG Throttle**
Manufacturer	Jamesbury	Flow-Tite	Valpres	Badger Meter
Model	Series 9150	Model F150	Series 720016	Series 9000
Size	4.0in	4.0in	1.5in	1.0in
Type	Full Port Ball	Full Port Ball	Full Port Ball	Globe
Range	0 - 100%	On / off	On / off	0 - 100%
Controller	Neles ND9103	Asco WT8551	manual	Neles ND9103
NTSF Count	x1	x1	x8	x1

Figure 4: HXG throttle valve (Badger Globe) mated to Krohne EM flow meter

To maintain a constant temperature of system inventory during steady-state test conditions, as well as serve as the heat sink for steam condensation during two-phase transients, a heat removal network is installed as part of the overall test assembly.

Components include heat exchanger, multiple water pumps, shut-off and diverter valves, etc. The proposed layout of this separate network will support reconfiguration by adjustment of only valves, allowing seamless transition from single-phase to two-phase modes of facility operation. The piping layouts for both configurations are shown in Figure 5 and Figure 6.

A plate type compact heat exchanger by Standard Xchange Brazepak heat exchanger, model BP422-080, Figure 7, is installed and serves as both single-phase heat transfer for liquid to liquid, and as steam condensations for liquid to steam. The heat exchanger contains 80 plates, has a total heat transfer area of 82.8 ft^2, and is rated to 110 kW (380,000 BTU/hr). The ultimate means for heat rejection from the test assembly is from a chiller, model NQR20 from ThermalCare. The unit has a cooling capacity of 20.8 refrigeration ton (RT), approximately 70.3 kW_t, and features a remote air-cooled condenser mounted outside the laboratory space. In single-phase modes, cold water will be returned to the water tank through a sparger, Figure 8, while in two-phase modes, condensate liquid will be removed and stored within a condensation reservoir.

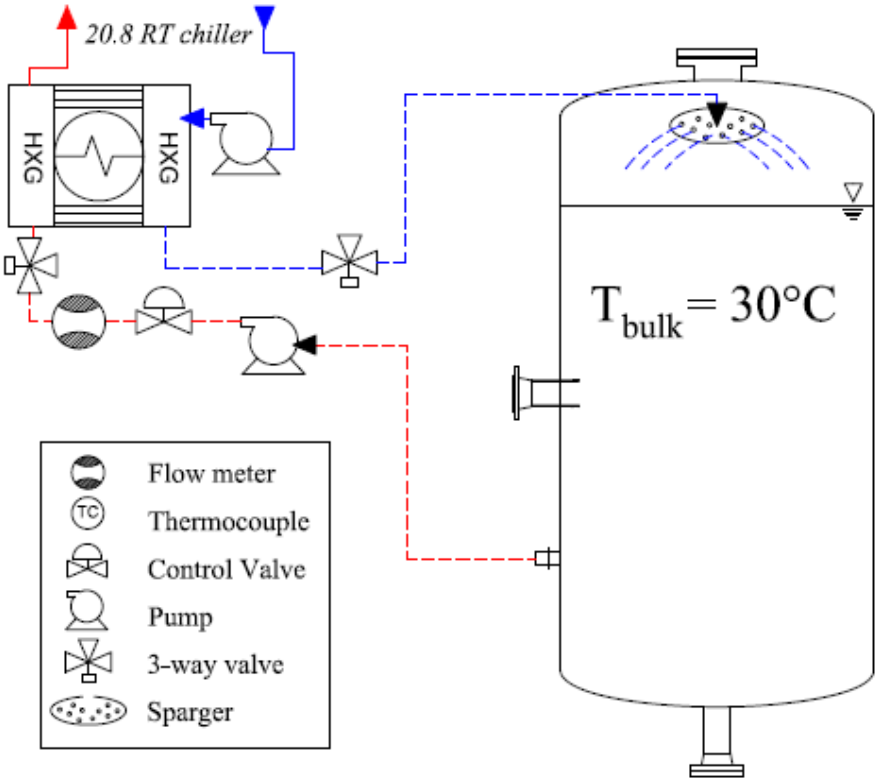

Figure 5: Heat removal network, configured for single-phase liquid cooling

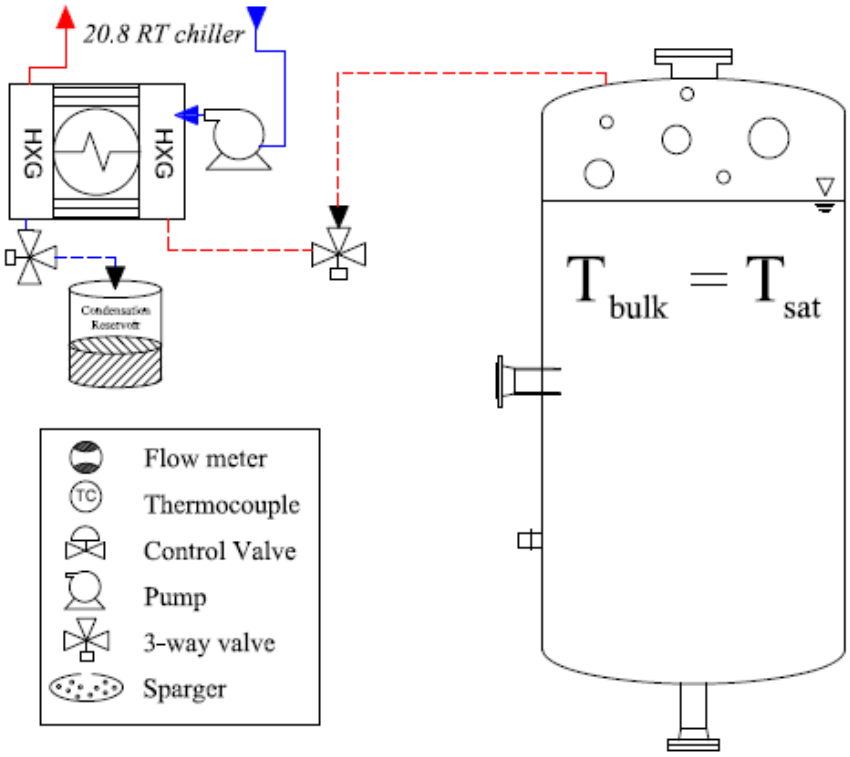

Figure 6: Heat removal network, configured for two-phase steam condensation

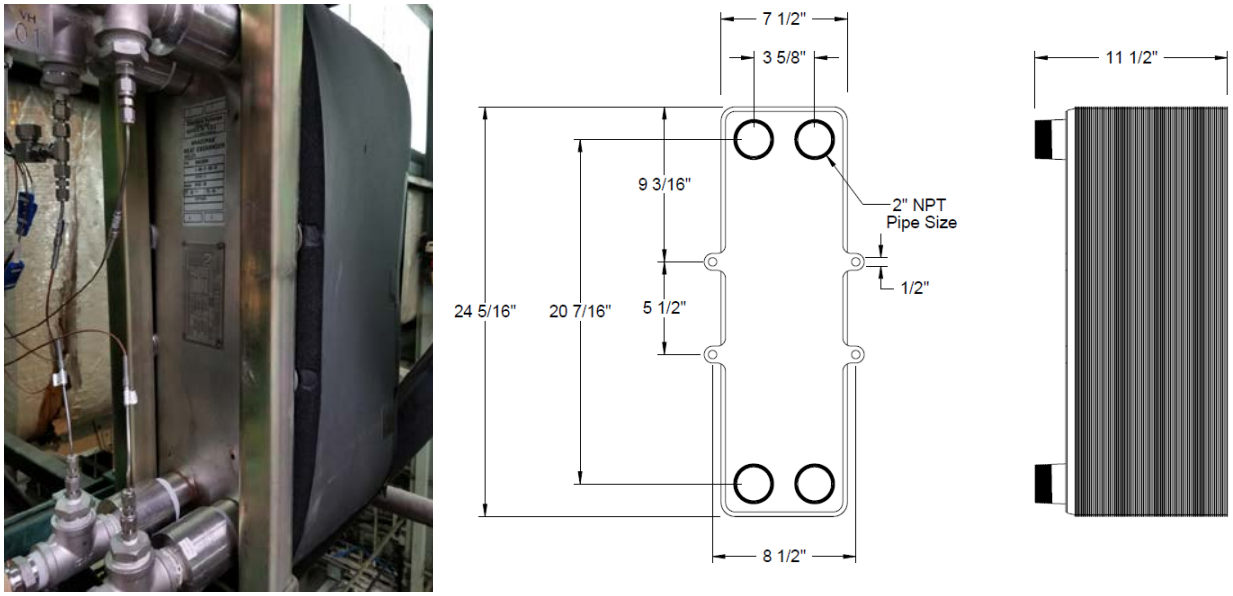

Figure 7: Standard Xchange Brazepak heat exchanger used for heat removal, shown with insulation partially removed for clarity (left), dimensions (right)

Figure 8: Sparger for liquid return, install inside tank near top

3. Testing Method

3.1. Testing objectives

Testing objectives have been established to ensure the experimental data generated will be relevant for assessing performance of a water-based RCCS for passive decay heat removal, along with ensuring that the experimental data is suitable for licensing and code validation purposes. To meet these objectives, a test plan has been identified where attention will first be given to characterization of key design features, form and heat losses, nominal behavior, and repeatability. Tests performed in the single-phase flow regime will evaluate steady-state behavior and heat removal performance. Of primary interest are areas of scaling verification, heat flux variation (integral levels and profiling), geometry, orificing, and investigations into the role of the inventory storage tank. Following the transition to saturation with inventory loss due to boil-off will provide insight into design basis accident conditions, complex two-phase flow behavior, and expected levels of heat removal performance during accident conditions.

As previously stated, the NSTF retains aspects common to a fundamental boiling water thermosiphon. Accordingly, it is likely to exhibit complex and uncertain thermal hydraulic behavior due to its inherent sensitivity. Collaborations with modeling and simulation efforts at Argonne have identified nominal system behavior and have predicted development of various instability modes such as flashing, density wave oscillations, and other two-phase induced flow mechanisms [16]. Similarly, the facilities response in single-phase will be a strong function of the piping geometry and local boundary conditions.

3.2. Programmatic method

The method for conducting data-quality matrix testing follows NQA-1 guidelines and is based on previously established processes during the air-based portion of the NSTF program [4]. Not including scoping or shakedown activities, testing performed for the purposes of Type-A data generation, otherwise known as data-quality or matrix tests, are classified according to the following metrics:

Accepted Data - Test was performed fully within scope and defined procedures. Submit for data qualification and Type-A evaluation
Trend Data - Some aspects of the test fell outside the intended scope and defined procedures, however still performed within NQA-1 guidelines. Data set may still be valuable for other use.
Failed Data - Test was not successful and fell well outside the intended scope and defined procedures. Likely the test was not realized through completion. Discard data.

The naming of each test was chosen based on the purpose and quality level required for the testing objective:

DataQuality0NN – programmatic matrix test for data collection per NQA-1 guidelines
Run0NN - alternate name for DataQuality0NN, common for figures and analysis
Characteriz0NN - formal test for the purposes of generated data for separate effects testing, geared directly towards supporting analysis development
Shakedown0NN - informal testing used to examine new configurations or procedures
BakeOut0NN - informal testing used to prepare materials and facility components

3.3. Experimental test procedure

A detailed test procedure in compliance with NQA-1 Type-A requirements has been developed and followed for data-quality test operations, with a sample from one completed single-phase test provided in the Appendix. For different cases the procedure will be slightly modified, but in general, it consists of a pre-test preparation, pre-test loop characterization, single- or two-phase test, post-test check, and data archiving.

For each test, the test objective must be clearly defined first, and prerequisites including training, access control, etc., must be met. After filling the NSTF to the desired inventory level, the pre-test preparation starts with documentation of the system setup and configuration, including the initial positions of the two pneumatic valves and eight manual valves, water storage tank inventory fill height, inlet static pressure, global summary of data acquisition channel and devices, engineering drawings of included instrumentation position, specifications of analogue flow and pressure devices, and differential pressure impulse plumbing. Following that, data acquisition related hardware, emergency dump system, pneumatic valve control system, and steam vent system will be verified to ensure functionality. In addition, the chiller needs to be powered on to allow compressor warm up at least 24 hours prior to the test.

For the pre-test loop characterization, the cold-start and zero-flow baseline is recorded. This step starts with bleeding all the differential pressure transducers and then establishing isothermal condition by circulating the water for approximately 20 minutes. The isothermal condition is confirmed through the piping thermocouple readings (within 0.1ºC) within LabVIEW. The zero-flow condition is then achieved by closing the inlet throttling valve. The cold-start and zero-flow values are subsequently monitored and recoded. Lastly, quality of the water inside the NSTF loop is surveyed.

On the test day, activities begin with the building & administrative tasks, including notifying the building occupants of the ongoing test, inspecting the test area (to make sure no combustibles were present), and setting up the proper warning signs. Data logging on LabVIEW is then initiated to record the test. With proper settings, heating is initiated and an automatic power ramp-up is performed to reach the desired power level. For single-phase tests completed so far, upon completion of power ramp, and after thermal power in test section exceeds 20 kW_t, the heat removal loop is enabled. The heat removal rate is constantly adjusted by adjusting the chiller set point and HXG loop flow rate to match the test section thermal power, eventually reaching a steady state. For the steady state, two acceptance criteria have been defined and must be met:

I. Acceptance Criteria #1 – Test facility thermal equilibrium
   i. Test section thermal power within ±20% of the desired power
   ii. Riser inlet liquid temperatures near 30°C, bounded between 20°C and 50°C

II. Acceptance Criteria #2 – Test facility and heat removal steady-state
   i. Riser inlet liquid temperatures of 30°C, maximum variation ±1°C
   ii. Test section thermal power within ±20% of the desired power
   iii. Flow rate variation within ±10%

Criteria #2 must be met and maintained over at least 2 hours while the steady state is being recorded. For two-phase tests to be performed, similar acceptance criteria for the two-phase quasi-steady state will be developed. Upon completion of the steady-state data acquisition, a power ramp down to 8 kW is initiated, following which, the power is killed and test is concluded. The test data is archived 4 hours after test conclusion.

The post-test check includes physical configuration verification, instrumentation operation limit check, and continuity and general instrument check. In addition, the cold zero-flow baseline is repeated and compared with the pre-test baseline to identify any abnormalities. Data archiving is then repeated to include the post-test survey data. Upon completion of the entire test, it is assessed and classified as one of the following:

A. Fully within scope and procedures (submit for Type A evaluation);
B. Areas outside scope or procedures (submit for trend evaluation);
C. Failed (data not suitable for evaluation or use).

3.4. Test matrix

To ensure data relevancy and overall impact for the future customers of the planned data sets, the program team has included key players in regular discussions and review meetings. This involvement has included federal sponsors, regulatory oversight, national labs, industry partners, and university collaborators. These interactions occur at major programmatic milestones (design phase, after shakedown testing, etc.), and are documented in the programs control records [17]. The resulting plan and projected schedule for matrix with the water-based NSTF is detailed in previous reports [7], and summarized in brief in Table 6.

Table 6: Full test matrix with planned schedule and testing objectives

	Year-0	Year-1	Year-2	Year-3	Year-4	Year-5
Facility Checkout Activities						
Electrical & sensor checkout						
Insulation & heater bake out						
Leak check and pressure test						
Facility Verification Testing						
Single-phase demonstration						
Two-phase demonstration						
Energy balance verification						
Facility Characterization						
Gross mass balance & flow meter verification						
Isothermal characterization						
Facility energy characterization						
K-factor characterization						
Baseline test case						
Single-phase baseline test						
Baseline modified at 15°C ΔT						
Two-phase baseline matrix test						
Parametric - Integral Power						
Reduced - 700 kW_t						
Normal - 1.4 MW_t						
Accident - 2.1 MW_t						
Elevated - 2.8 MW_t						
Parametric - Inventory Levels						
Inventory parametric - 100% fill						
Inventory parametric - 60% fill						
Inventory parametric - 40% fill						
Inventory accelerated loss						
Parametric - System Pressure						
1 bar elevated						
2 bar elevated						
Accident Scenario Testing						
Accident scenario with full power history						
Full tank depletion and dry-out						
Geometric Variations						
Riser throttle						
Riser blockage						
Lower tank inlet port						
Alternate chimney route						
Network short circuit						

4. Testing Results

4.1. Isothermal characterization

The behavior of natural circulation flow is strongly dependent on both local and system level conditions, resulting in accompanying phenomena that become highly sensitive to even minor changes within loop. Geometry and form losses are one of the most dominating influences, so accurate knowledge of their magnitude and response is critical to overall understanding of the loops performance. Thus, a number of characterization tests were performed on the test facility to establish reference values for governing thermal and hydraulic factors.

The first characterization test series was performed at isothermal and forced flow (pumped) conditions, which eliminated buoyancy and thermal driven influences on the system behavior. Loop operation was established by means of the tank outlet by-pass network, redirecting the flow path through a centrifugal pump and throttle valve, before returning back into the downcomer pipe.

Three characterization tests were performed across an 8-month duration, and followed similar procedures to simplify comparisons of measured values. Additionally, this allows early detection of anomalies that may arise in the loop behavior, such as foreign objects or changes in pipe surface conditions. Each test began with continuous circulation until the loop reached uniform temperature with maximum variation within ±0.1°C. Then, the pump was stopped, riser inlet valve shut to stabilize loop flow, and differential pressure transmitters bled and zeroed. This removed any lingering effects of hydrostatic head pressure in the impulse tubing and ensured that only friction and acceleration related pressures were measured by the sensors. The by-pass loop was then re-enabled and loop flow rate adjusted in 5 – 10 level increments, up to the maximum flow rate the pump is capable of generating, approximately 2.8 kg/s. An example of the time history for the loop flow rate in Characterization002 is given in Figure 9.

Measurements by the differential pressure transmitters were also examined as a function of flow rate, which provide insight into the relative magnitude of frictional losses across various segments of the flow loop. The test section dominates, which is expected given the small diameter and large count of riser tubes leading to with multiple changes in not only flow direction but flow area as the inventory travels across the riser assembly. Across the large 4.0” diameter chimney regions, the losses are significantly lower, averaging a mere 10% of values measured across the riser tubes, Figure 10.

Additional analysis can be made for the symmetry of flow distribution across the eight individual risers. The relationship of individual riser flow rates to loop flow rate is shown in Figure 11 and Figure 12. As the loop flow rate increases, readily apparent is a growing spread of flow across the eight tubes, favoring the eighth riser, or tube furthest from the inlet. This can be attributed to the flow path and velocities within the header sections, with little resistance being offered to change the direction of high momentum incoming fluid into the first or closest riser. At the opposite spectrum, the abrupt stop at the end of the inlet header pipe forces the fluid to decelerate, easing the change of direction into the eighth or last riser. With higher flow rates of incoming fluid, this behavior is magnified and spread enlarged.

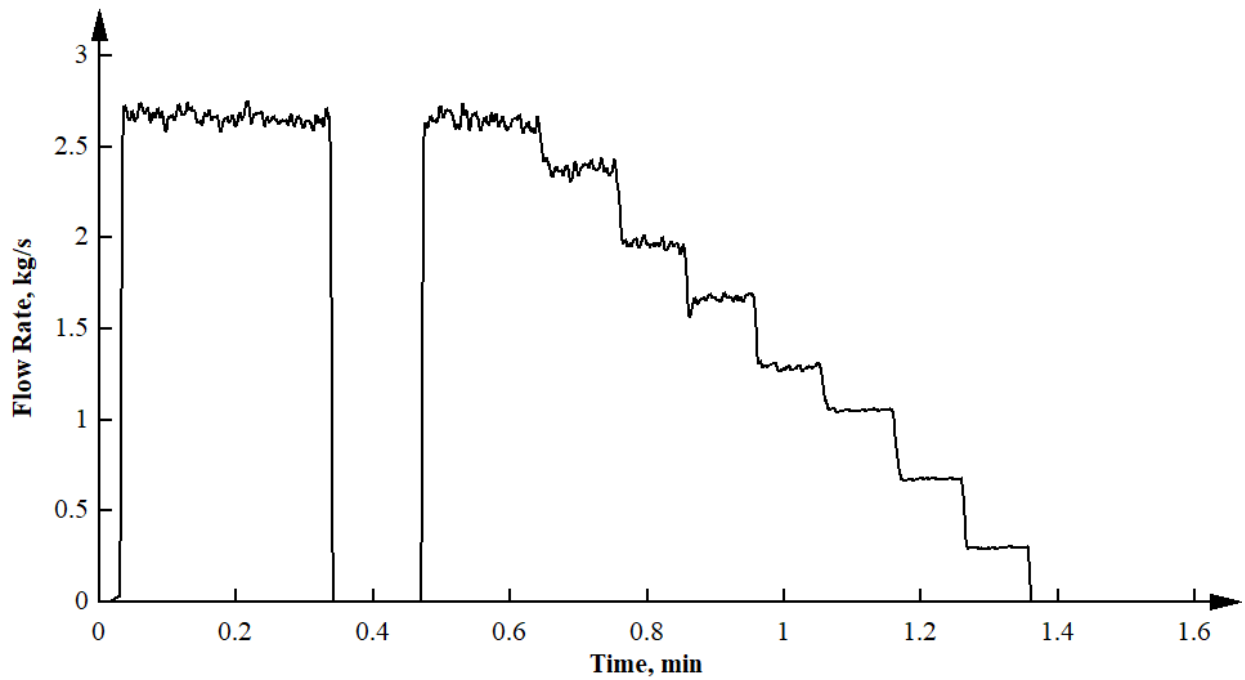

Figure 9: Time history of typical isothermal characterization test, primary flow rate vs time

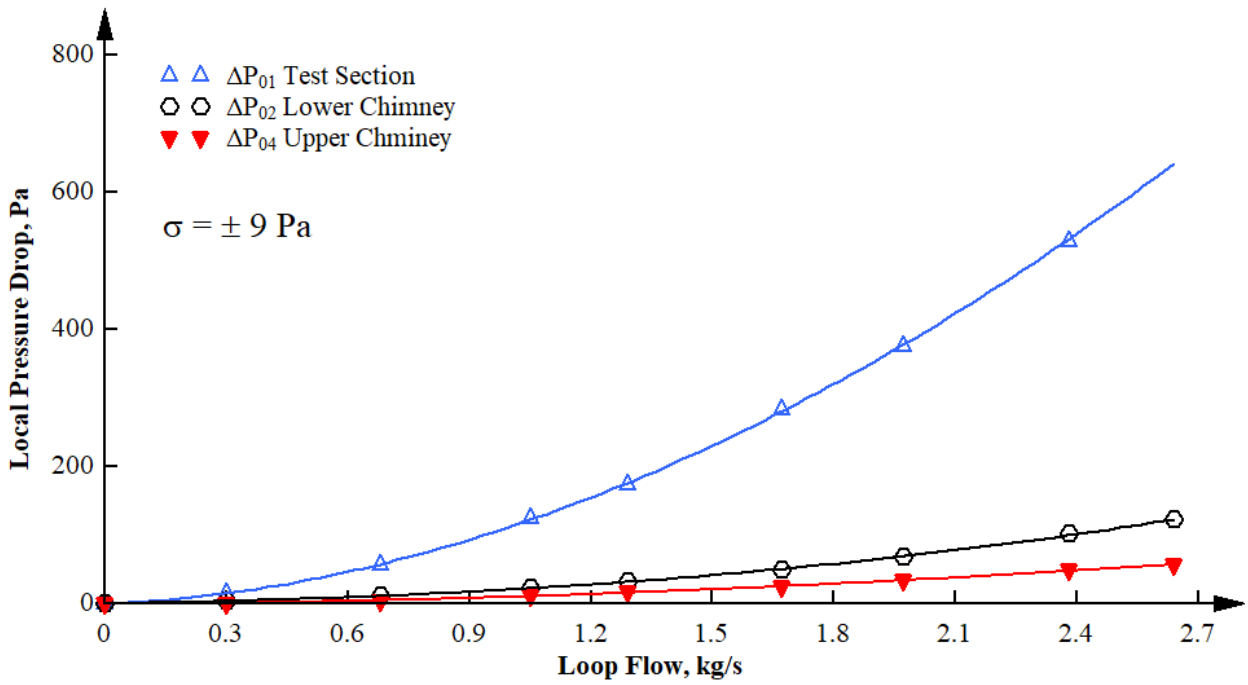

Figure 10: Measured frictional pressure drop across piping segments of test facility, isothermal flow

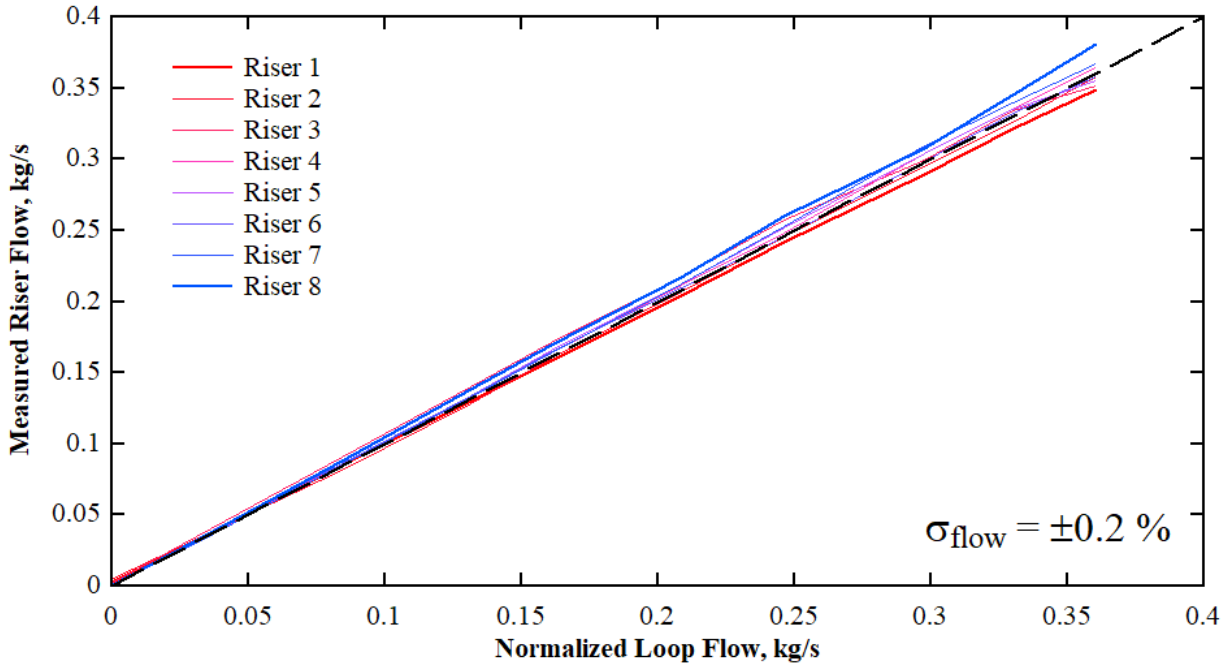

Figure 11: Individual riser flow rate, actual measured values compared to ideal uniform split

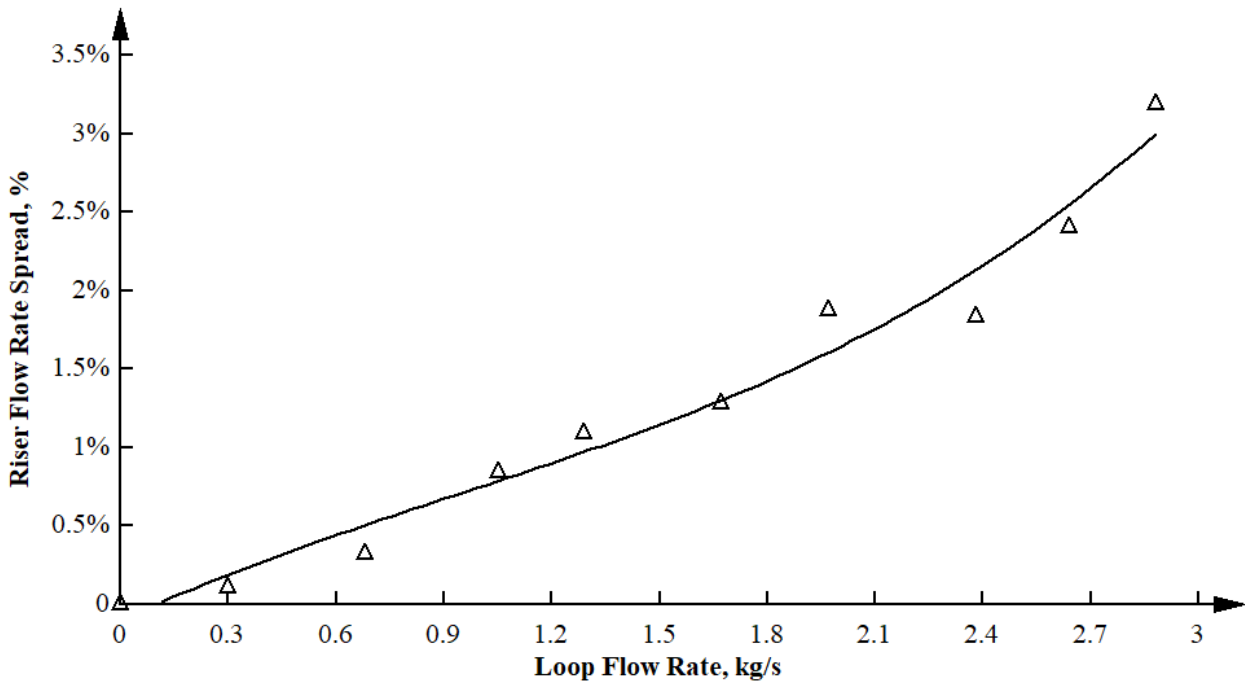

Figure 12: Variation across risers ducts with increasing loop flow rate

Repeat testing at isothermal conditions is able to provide a means to verify that loop geometry or surface conditions have not changed overtime, for example due to the formation of scale, rust, or other contaminates. The accumulation of these formations can affect surface roughness, influencing frictional losses, and ultimately performance during heated natural circulation testing. Thus, isothermal testing was repeated at 2-month intervals over the period of heated matrix testing. The pressure drop curves across three characterization tests are shown in Figure 13. While some variability exists across the three tests, the magnitudes are within the expected noise levels, and more importantly, no clear trend or pattern of deviation, indicating that across the testing period, the condition of loop flow surfaces did not significantly change. A summary of the measured frictional parameters, including calculated K-factors and geometric dimensions, are provided in Table 7.

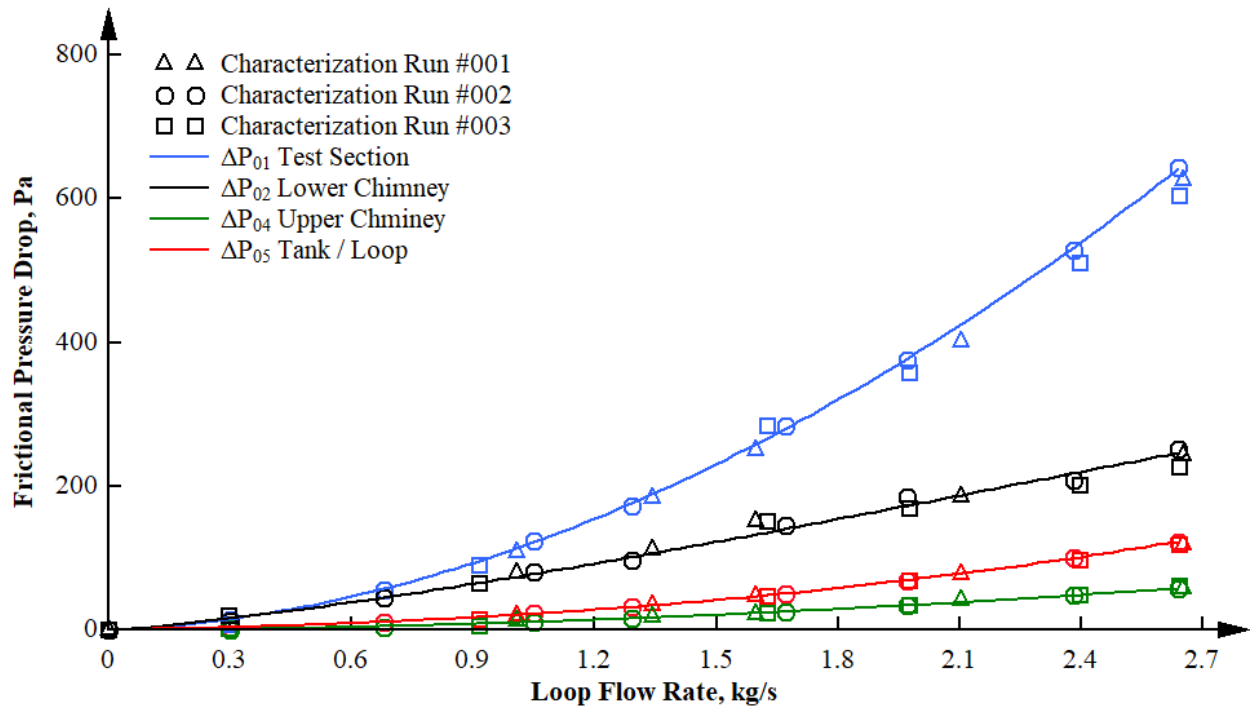

Figure 13: Repeated measurements of frictional pressure across three separate isothermal tests

Table 7: Loss coefficients and associated geometric values for primary loop segments

	Hydraulic Parameters			**Flow Path**	
	Velocity	ΔP	K-loss	Area	Length
	m/s	*Pa*	-	m^2	*m*
Test Section	0.093	124.1	15.8	0.01126	10.46
Upper Chimney	0.126	11.4	1.5	0.00838	5.11
Lower Chimney	0.126	22.8	2.9	0.00838	8.53
Downcomer	0.126	46.5	5.9	0.00838	24.89

Shut-off valves installed at the inlet of each riser tube were utilized to measure loop performance while operating in a single riser configuration. While maintaining constant bulk system flow rate, valves on seven of the eight risers were closed, forcing the full inventory to flow through a remaining tube. After allowing the flow pattern to stabilize, this process was repeated for each of the remaining seven tubes. The measured flow parameters, including flow rate and pressure drop, is shown in Figure 14 with steady-state averaged values detailed in Table 8.

The results indicate that flow rate and frictional losses are generally uniform across each of the individual eight risers, with a maximum deviation of 1.8% for the flow rate across riser #1, and 2.0% for the frictional pressure drop across riser #3. While deviations exceed the calibrated uncertainty of the instrumentation hardware, other sources of uncertainty are likely introduced from fluctuating bulk system flow and position of the shut-off valve handles. Thus, the measurement values do not point towards a any major geometric or design discrepancy and reaffirm the symmetry of the overall multiple-tube cooling panel test section.

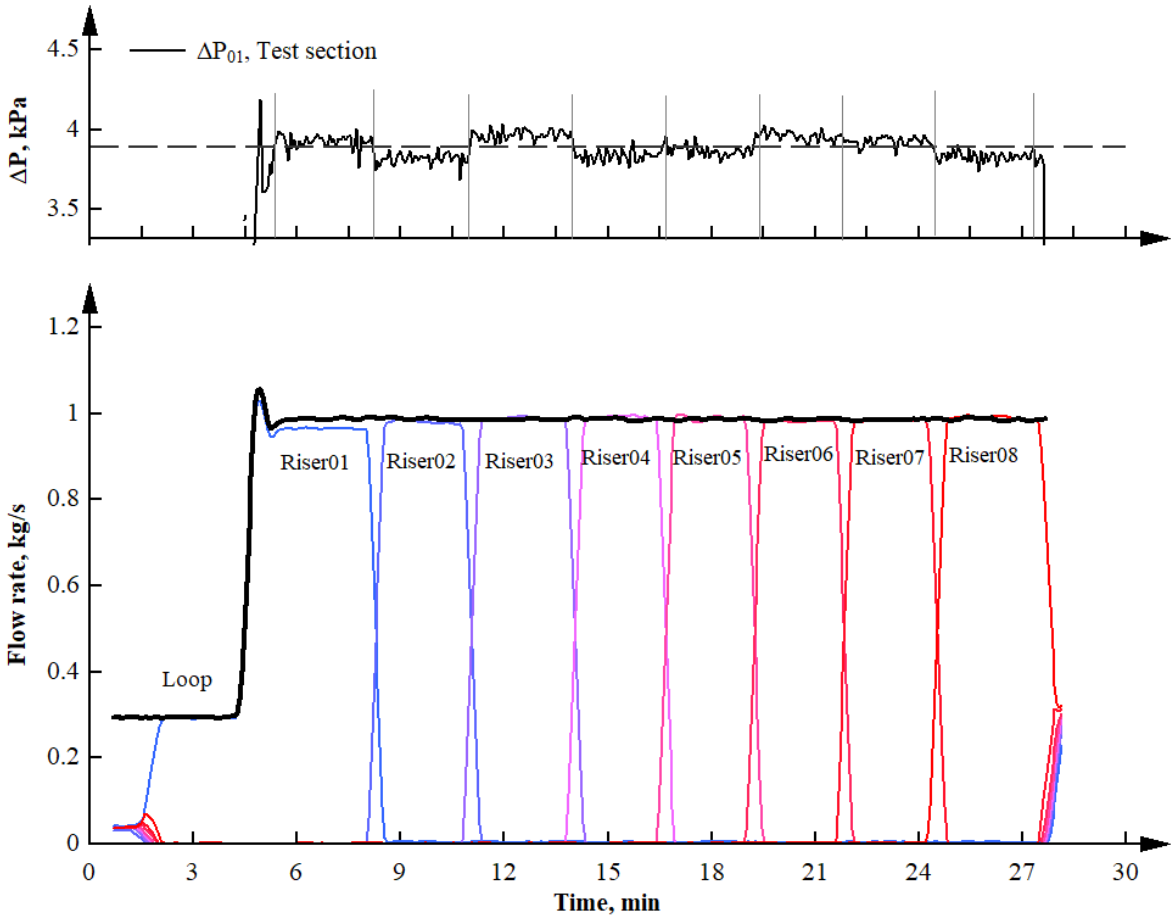

Figure 14: Time history of isothermal flow testing across single riser tubes

Table 8: Breakdown of hydraulic measurements for single-riser isothermal flow

	Measured Values				Deviation from mean	
	Loop Flow, kg/s	Riser Flow, kg/s	Test Section ΔP, Pa	Chimney ΔP, Pa	Riser Flow	Test Section ΔP
Riser #01	0.987	0.965	4,129	27.1	1.8%	1.0%
Riser #02	0.988	0.979	4,021	35.5	0.5%	1.7%
Riser #03	0.986	0.989	4,171	31.4	0.6%	2.0%
Riser #04	0.986	0.993	4,033	33.0	0.9%	1.4%
Riser #05	0.987	0.987	4,055	40.4	0.3%	0.9%
Riser #06	0.986	0.982	4,158	34.1	0.2%	1.7%
Riser #07	0.985	0.985	4,128	32.3	0.1%	0.9%
Riser #08	0.987	0.991	4,026	32.9	0.7%	1.6%
Min.	0.99	0.97	4,021	27.1	0.1%	0.9%
Max.	0.99	0.99	4,171	40.4	1.8%	2.0%
Mean	0.99	0.98	4,090	33.3	0.6%	1.4%

4.2. Transient heat behavior

One concern associated with the two-phase test is the structure vibration induced by flow instabilities at the initiation of flashing. Therefore, the test procedure requires the test to be attended when flashing initiates, which calls for accurate liquid inventory heat up rate prediction and test planning. To examine the liquid heat up rate under four different full scale power levels proposed in the test matrix, namely, 2.8, 2.1, 1.4, and 0.7 MW_t, a single-phase long characterization test (Run054) was conducted.

For this test, the facility was setup at baseline geometry configurations, as summarized in Table 9. The test consisted of four sub-tests, corresponding to nominal decay heat loads of 2.8, 2.1, 1.4, and 0.7 MW_t, respectively; or for the NSTF, 68.8, 51.6, 34.4, and 17.2 kW_t, respectively. For each sub-test, the heater power was applied across a 120-minute power ramp, facility allowed to heat up until the tank outlet liquid temperature reached 60 °C or the maximum liquid temperature at any location in the loop exceeded 65 °C, and then the heater power was ramped down to zero and the single-phase heat removal network was activated to cool the facility down to below 25 °C. Between the sub-tests, the facility was in an idle mode.

Table 9: Initial boundary and operating conditions for Run054

Facility geometry	
Heated – riser spacing	34.05 inch
Chimney-tank inlet position	Center tank
Heat load	
Power control	Burst firing
Distribution	Linear / uniform across 40 zones
Power level	96, 72, 48, and 24 kW_e
Valves	
Tank outlet:	Open
Loop inlet throttle:	Open
Riser(s) inlet:	All eight open
Differential pressure hookup	
ΔP-01	Test section, (DP_{20} – DP_{44})
ΔP-02	Lower chimney, (DP_{22} – DP_{20})
ΔP-03	n/a
ΔP-04	Upper chimney, (DP_{25} – DP_{22})
ΔP-05	Full loop/water tank (DP_{25} – DP_{40})
Liquid Inventory	
Inventory fill amount	80% tank level, ~1,004 gal
Inventory fill level	85.2” (sight glass), 106.17” (ΔP)
Liquid conductivity	4.56 μS/cm
pH	5.50 –
Total chlorine	~0 ppm
Total hardness	~0 ppm

The electric and thermal power profiles in this test are shown in Figure 15, along with the temperature points across the heated plate in Figure 16. Because cooling was not enabled during the heat up processes, thermal equilibrium was not achieved. The liquid heat up rates at four power levels are illustrated in Figure 17 to Figure 20. For a better presentation of the effect of heating power on liquid heat up rate, the riser outlet liquid temperatures under the four different power levels are normalized to the same origin (0 hr, 25 °C) and plotted together in Figure 21. The heat up rates are also summarized in Table 10. The entire heat up transient can be roughly divided into three stages, each of which is characterized by a near constant heat up rate. Among the three stages, stage 1 corresponds to the initial heat up when the structural materials absorb most of the heat, while stage 3 corresponds to the stable liquid heat up when the liquid absorbs most of the heat. As can be seen, the liquid heat up rate does not scale well with the power at lower temperatures (Stage 1 & 2), and much better at higher temperatures (Stage 3). This is understandable since the heat absorption by structures start to decrease at higher temperatures, and most of the electric power is used to heat up the liquid only. The heat up rates found will provide valuable guidance on test planning for future two-phase tests.

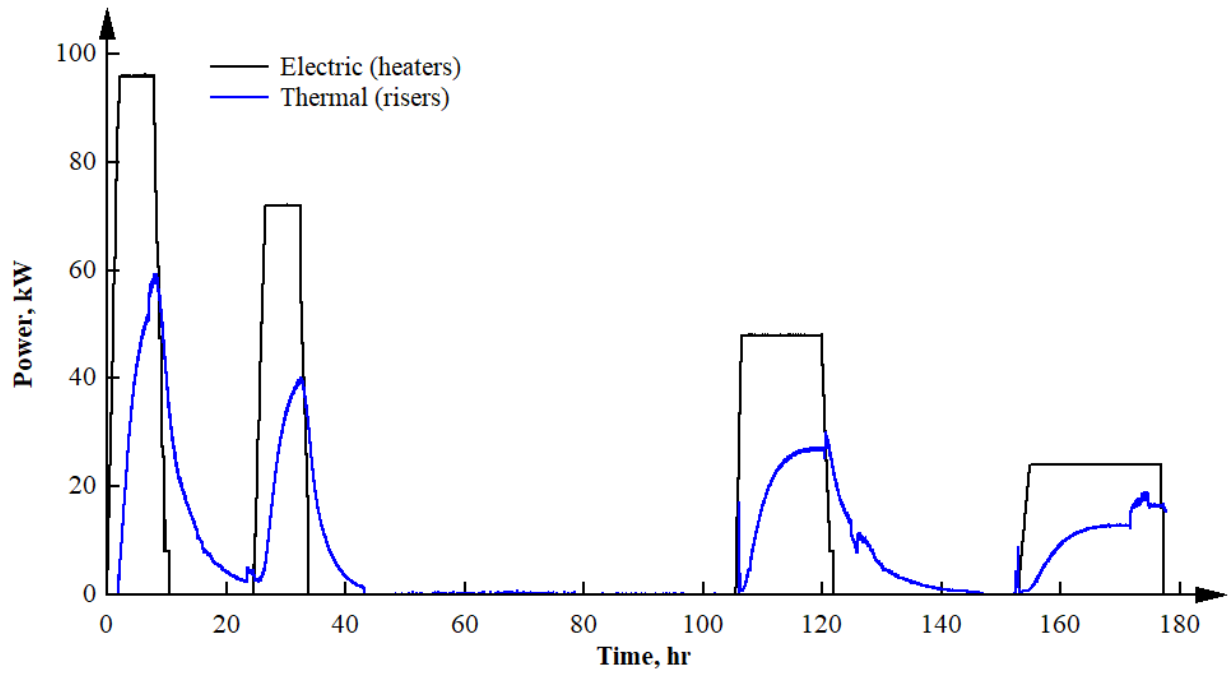

Figure 15: Full time history of electric and thermal powers profiles, Run054

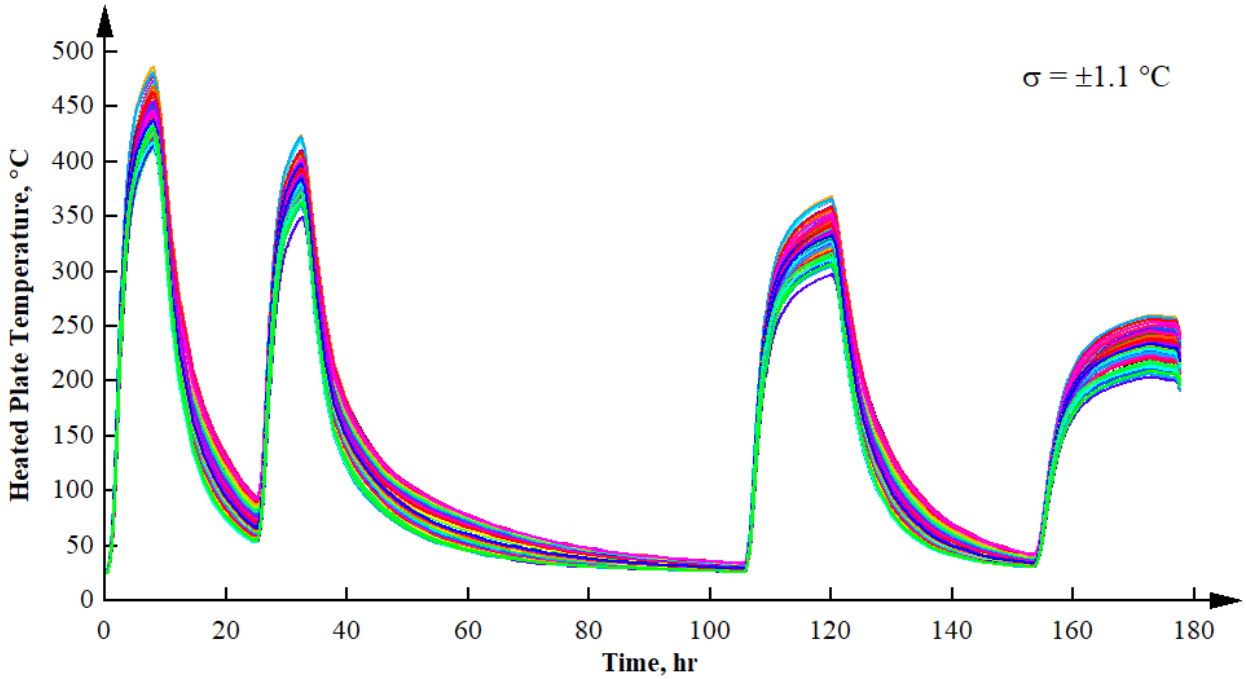

Figure 16: Full time history of heated plate temperature measurements, Run052

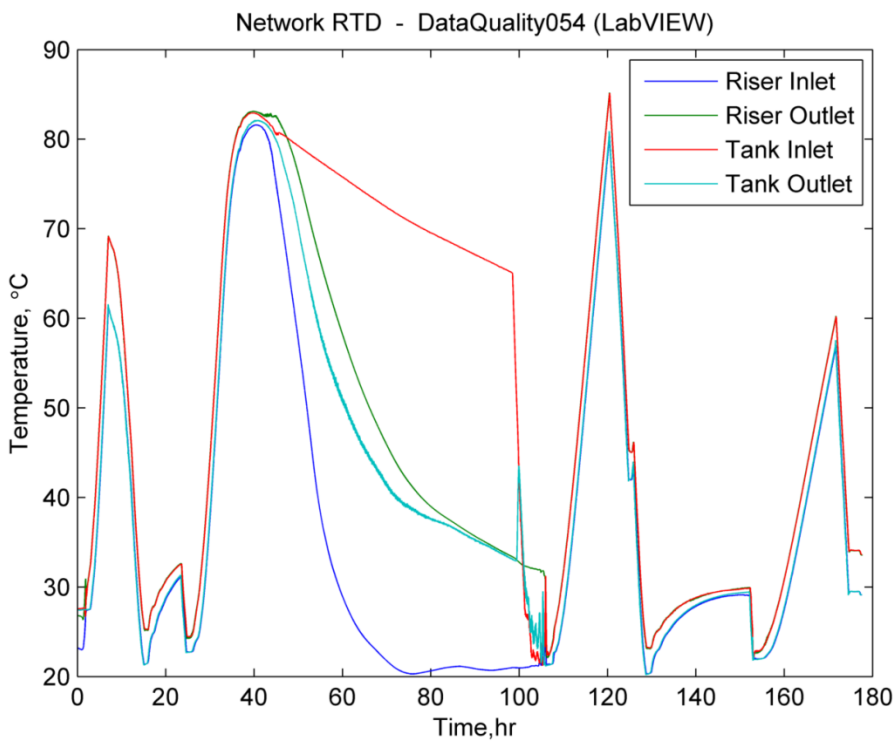

Figure 17: Liquid temperatures at riser and tank inlets and outlets

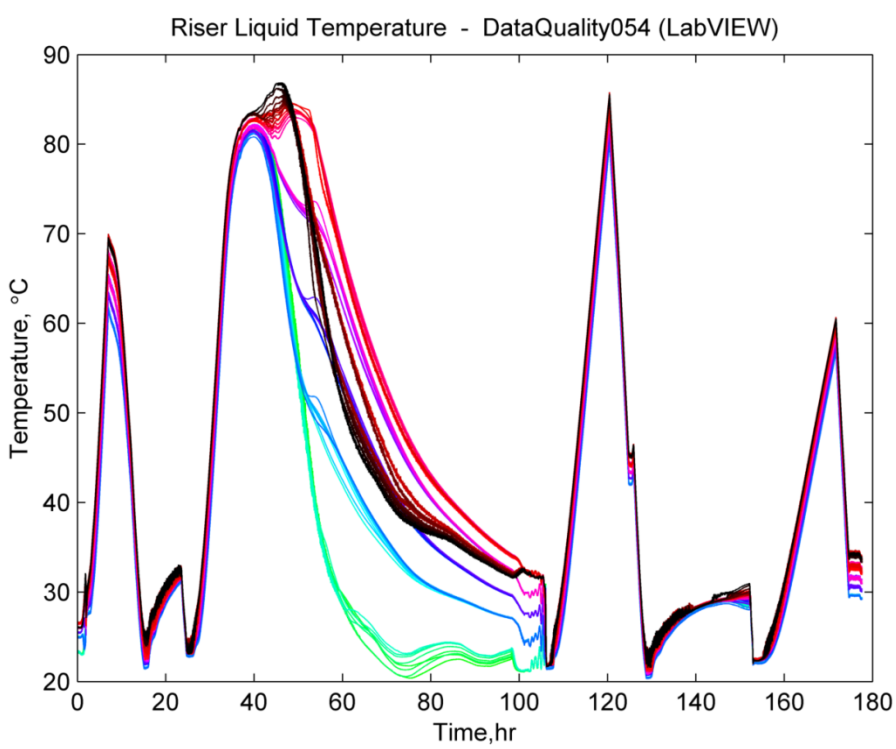

Figure 18: Liquid temperatures in the risers

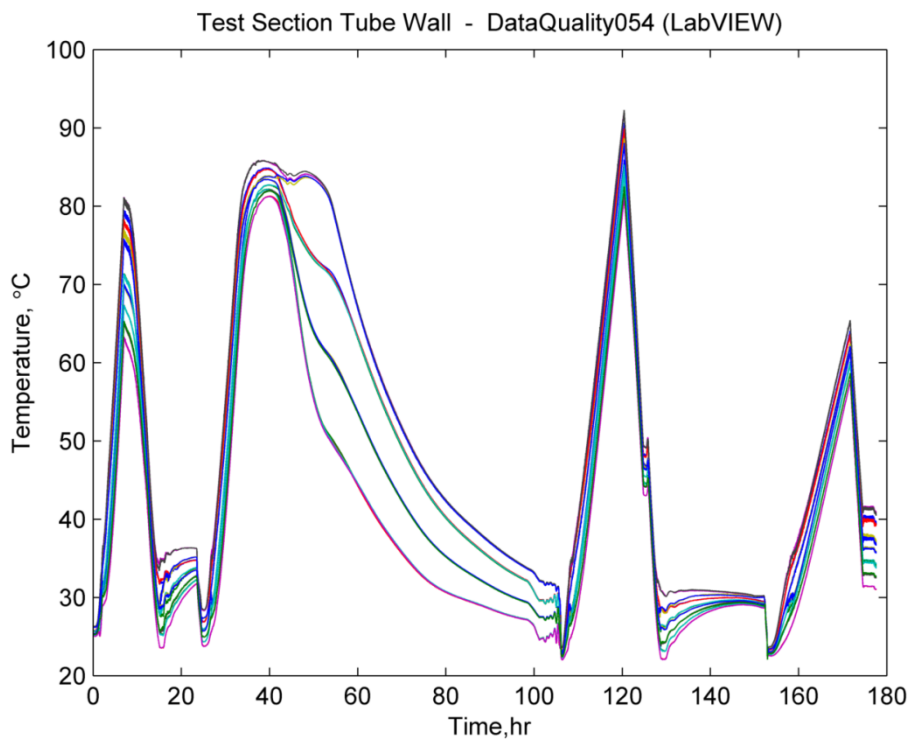

Figure 19: Test section riser tube wall temperature

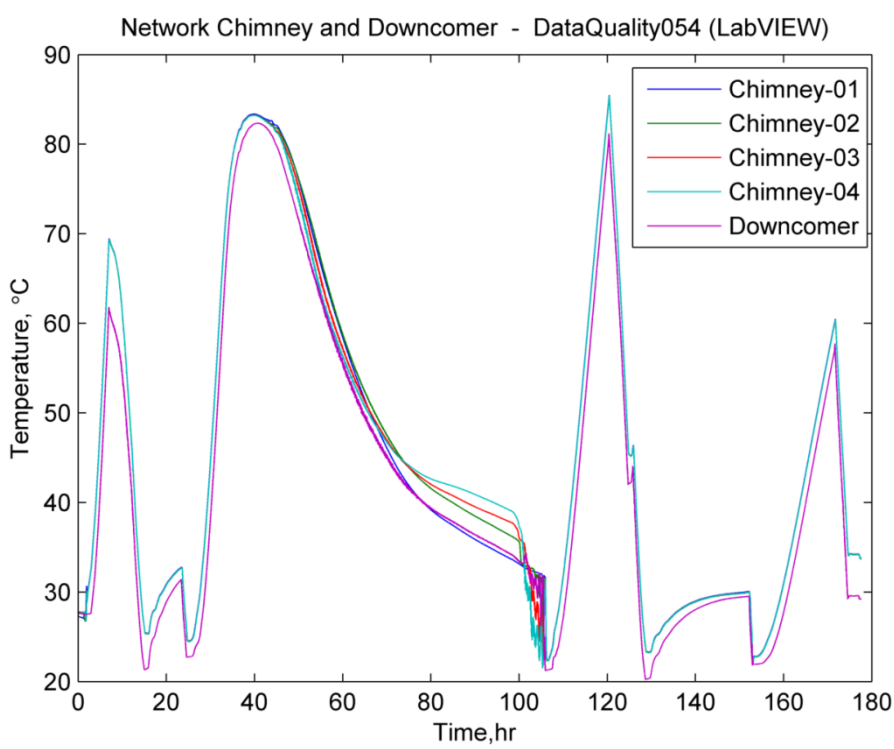

Figure 20: Liquid temperatures in the chimney and downcomer

Table 10: Calculated liquid heat up rates from Run054

	Subtest 1	Subtest 2	Subtest 3	Subtest 4
Electric Power	96 kW_e	72 kW_e	48 kW_e	24 kW_e
Stage 1, (amb. ~30 °C)	3.61 °C/hr	3.19 °C/hr	2.63 °C/hr	1.26 °C/hr
Stage 2, (~30°C ~ 40 °C)	6.79 °C/hr	5.32 °C/hr	4.21 °C/hr	2.03 °C/hr
Stage 3, (~40°C – max)	9.83 °C/hr	7.74 °C/hr	5.33 °C/hr	2.56 °C/hr

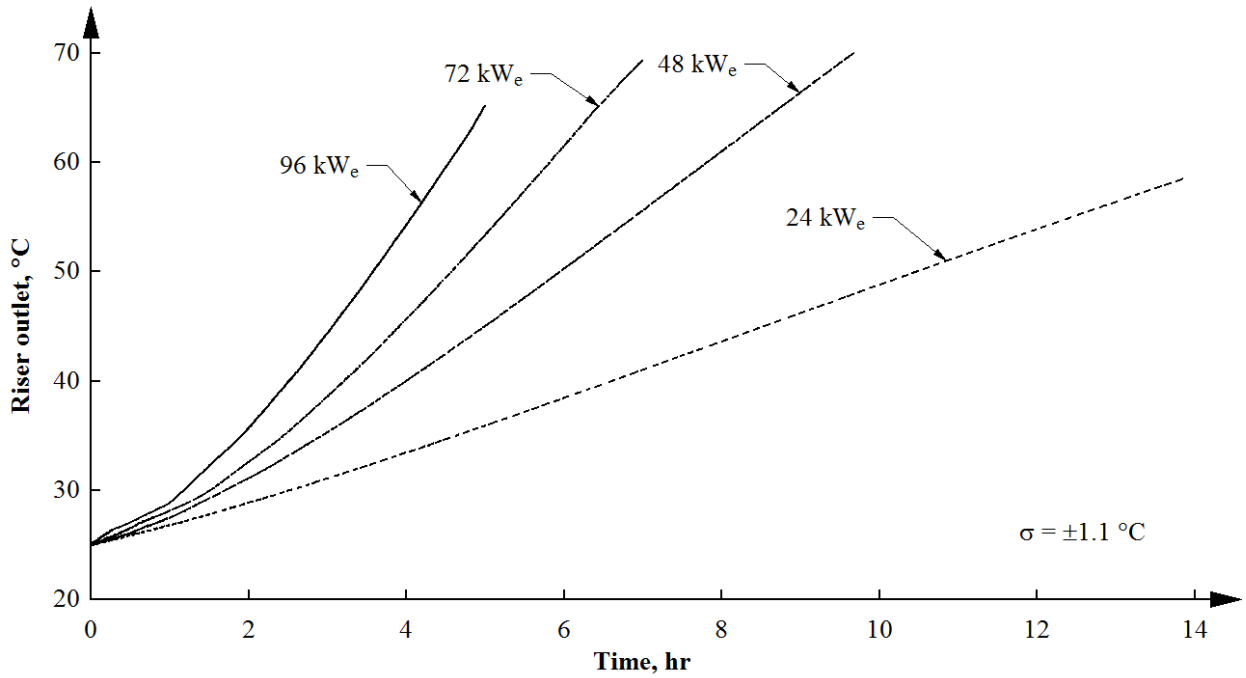

Figure 21: Liquid heat up rate comparison at four investigated electric powers

4.3. Facility heat loss

Due to significant structural members required to support the 4,500-lb heated plate, combined with high operational temperatures, parasitic heat losses are significant and must be considered when planning for test conditions. To reach a desired thermal power over the test section, a thermal efficiency is used to predict the required electrical power for test operations. A power parametric test series, discussed in detail is later sections, was used to quantify the test facilities thermal efficiency, Figure 22, and provide insight into the systems parasitic heat loss. The thermal power follows a linear relationship with the supplied electric, resulting in a near constant thermal efficiency of approximately 71% (i.e., 29% heat loss). This is a significant improvement compared to previous air-based testing, which averaged 60% efficiency. Improvements in the assembly of heated cavity insulation panels, along with a test section that spans the cavity width and isolated hot and cold regions, are likely contributors to this improvement.

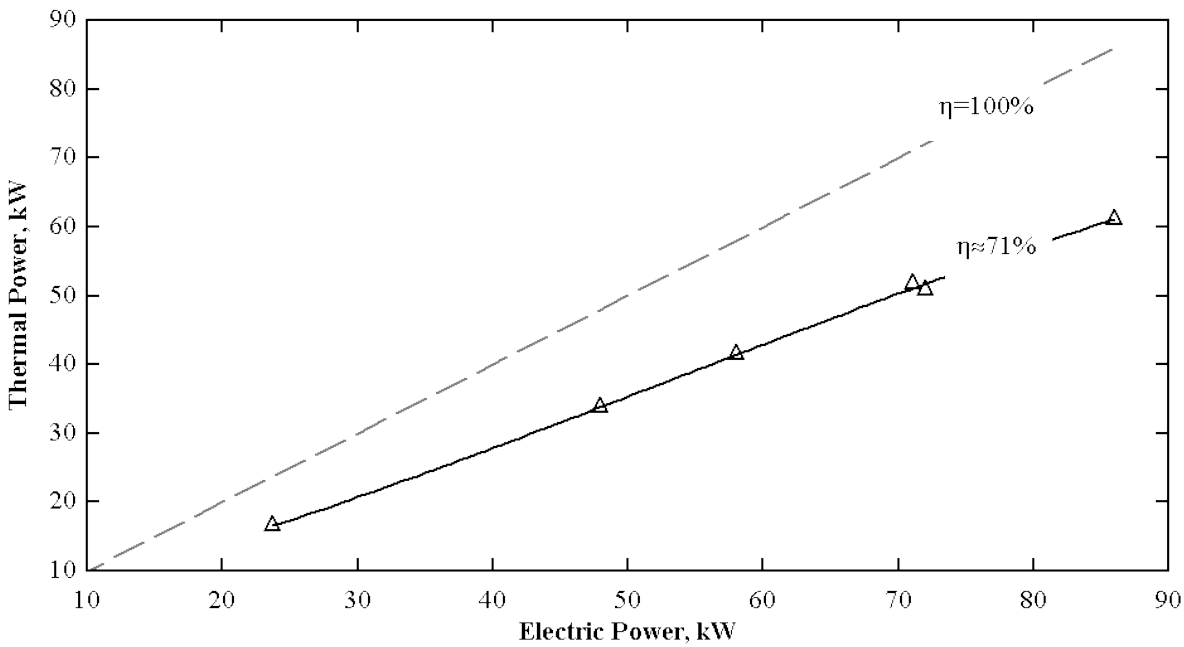

Figure 22: Thermal power vs electric power from during steady-state, single-phase testing

The total heat loss in the water NSTF can be attributed to losses off the heated cavity, along with network piping and storage tank. Heat losses in the chimney and downcomer piping sections are shown in Figure 23 for the two-phase demonstration test, which saw maximum electric power levels of 72 kW_e and liquid temperatures ranging from ambient to saturation. Heat losses along the piping were calculated based on the thermal energy differences from the inlet to outlet of the section:

$$Q_{loss} = c_p \dot{m} \Delta T$$

where C_p is the average fluid specific heat, $\dot{m}$ is the mass flow rate, and ΔT is the temperature difference between the piping inlet and outlet. At temperatures near ambient, these heat losses are insignificant and less than 2% of the electric power. However, as liquid temperatures increase and approach saturation, losses increase and account for nearly 8% of supplied electric power.

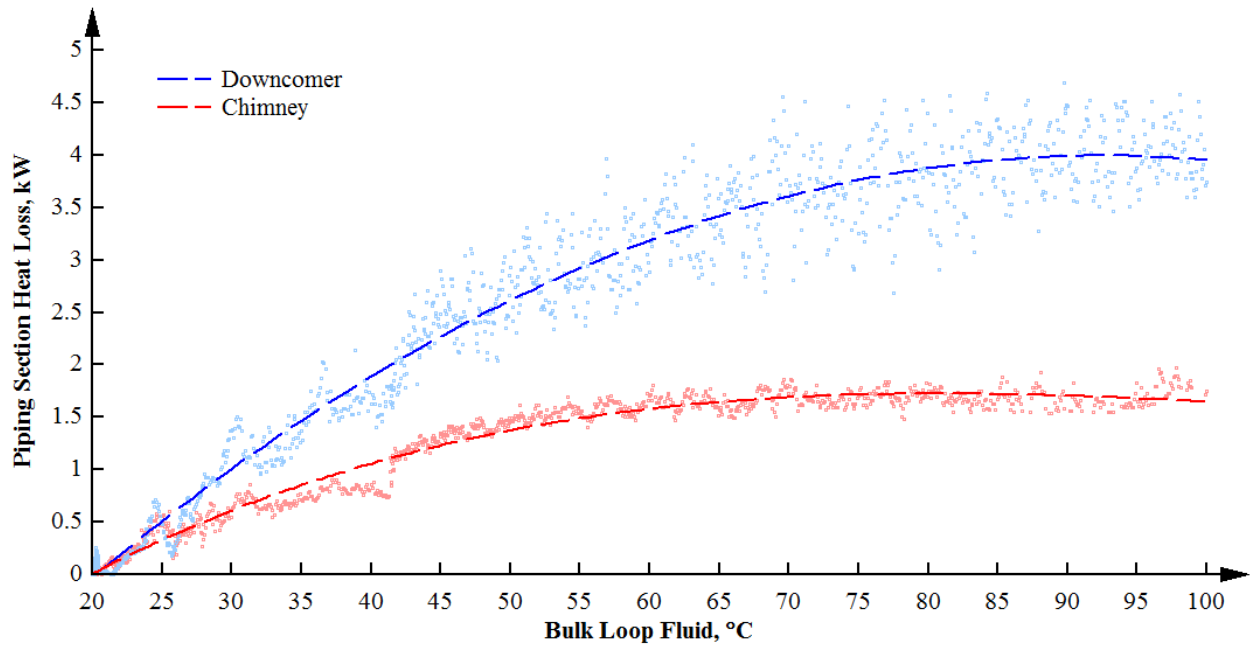

Figure 23: Thermal losses across loop piping vs fluid temperature, data from two-phase demonstration

Heat loss in the air cavity was estimated based on a simplified conduction method using the measured inside and outer surface temperatures of the cavity walls, Figure 24. These measurements can be used to determine losses by conduction through the insulation and convection off the outside surfaces; however other sources such as small areas of air exchange and local hot spots are more difficult to calculate. Considering bulk conduction losses through the panel, the heat loss can be calculated as:

$$q_{cond} = k\frac{\Delta T}{t}A$$

where k is the thermal conductivity of the insulation, ΔT is the temperature difference across the insulation, t is the insulation thickness, and A is the outer surface area. The cavity heat loss estimated using the above method was only a few kW, inconsistent with the previously found thermal efficiency. The main reason is the limitation in measured temperature locations, which are positioned near the centers of the insulation slabs and measure bulk outer surface temperatures. However, heat loss is more significant at the edges of the cavity where insulation slabs meet and may form small gaps. Given that the surface area of the heated cavity exceeds 40 m^2, it will be difficult to obtain high resolution in quantifying local heat loss distributions. While the program explores a more rigorous approach, the calculated thermal power within the test section have been used to guide test operations and assess thermal conditions.

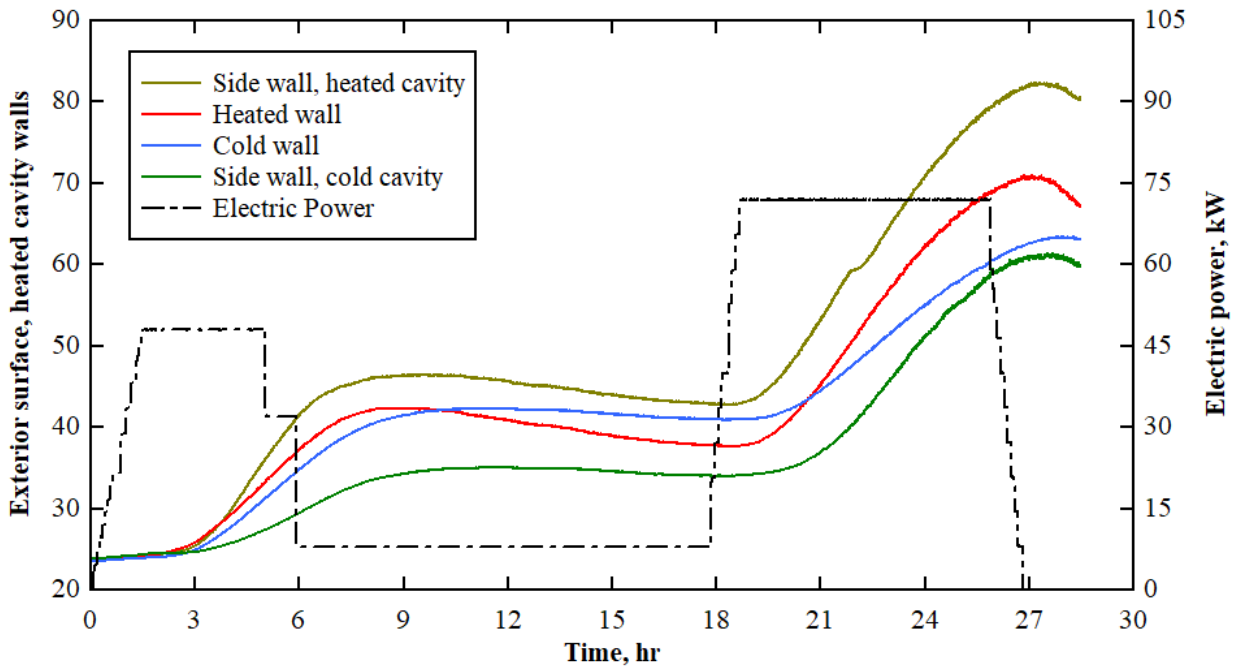

Figure 24: Outside surface temperatures of heated enclosure, data from two-phase scoping

4.4. Single-phase baseline

The single-phase baseline that defined a nominal decay heat load of 1.4 MW_t, or 34.4 kW_t for the NSTF scale was conducted during Run051. The facility configuration was similar to that in Run054, Table 9, with an electric power of 48 kW_e applied. The heater power was applied across a 90-minute power ramp, facility allowed to reach thermal equilibrium, and then the single-phase heat removal network was cycled until the test loop reached steady-state thermal and hydraulic flow conditions. Results of this test are presented in this section.

The total heater power is shown in Figure 25. As can be seen, the heater power was controlled stably at 48 kW_e after the initial ramp. Temperatures of the heaters, heated plate, test section tube wall, test section fin wall, test fluid, and side walls are shown in Figure 26 - Figure 31. The heater temperatures, the highest in the entire NSTF system, stayed below the preset safety trip point of 650ºC during this test. The heater and heated plate temperatures seem more sensitive to the source power, while the riser tube wall temperatures more sensitive to the fluid (heat sink) temperatures. After the heat removal rate was adjusted to surpass the test section thermal power at ~17 hr (discussed later), the fluid temperatures started to decrease, causing a decrease in the riser tube wall temperatures. However, mainly due to the high thermal resistance of the thermal radiation process, this effect did not propagate to the heaters and heated plate, which still experienced increasing temperatures. The riser fin walls, which were controlled by both the thermal radiation from the heat source and thermal conduction to the heat sink, experienced an average effect in terms of temperature development. Lastly, the side walls exhibit good symmetry in the temperatures.

The temperature distribution in the heated plate that simulates reactor pressure vessel is also illustrated in Figure 32. In the horizontal direction, the temperature is fairly uniform, except for the strong gradients near the edges of the plate, which suggests a modification of the power distribution in the heaters. In the axial direction, overall the temperature increases, consistent with the liquid temperature distribution. This may indicate the dominant effect of natural convection inside the cavity. In addition, a dip in the axial temperature distribution is seen near the center of the heated plate. This is main the result of how the heated plate is installed, which comprises two separate pieces that butt together at the center of the heated cavity.

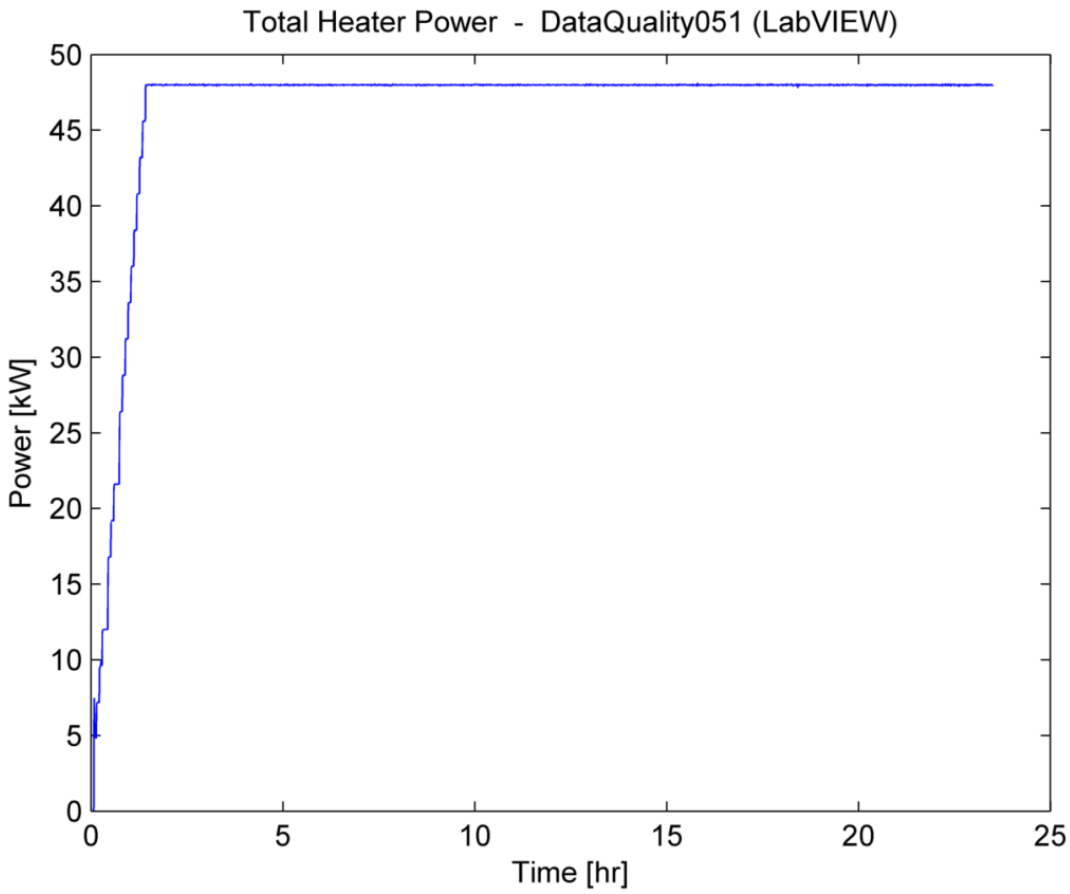

Figure 25: Total heater power, baseline case run #051

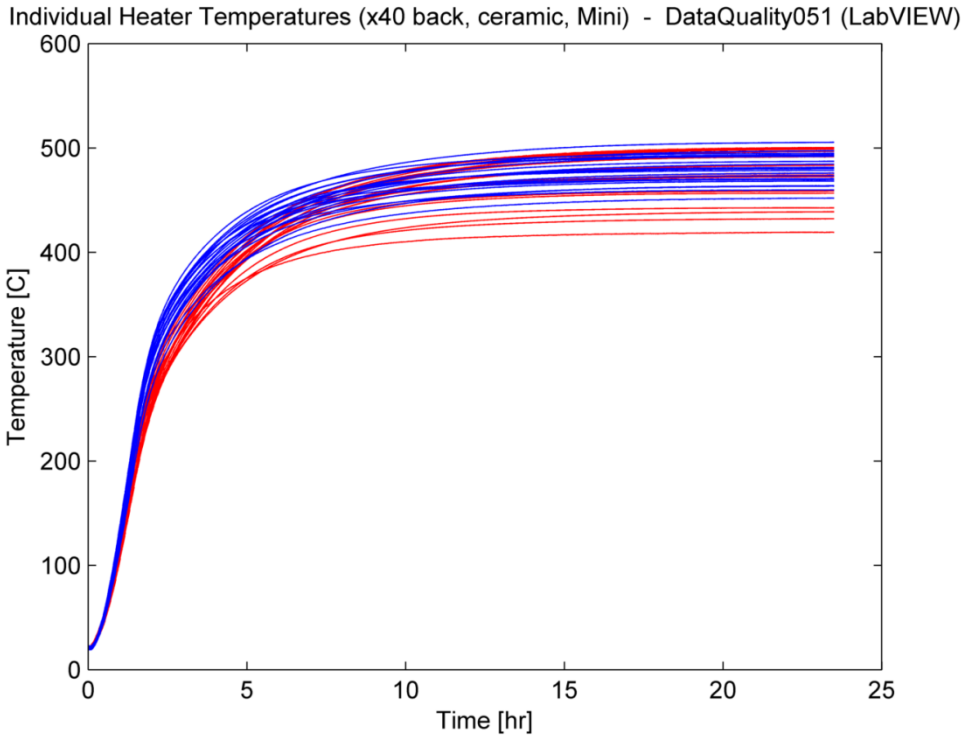

Figure 26: Heater temperature, baseline case run #051

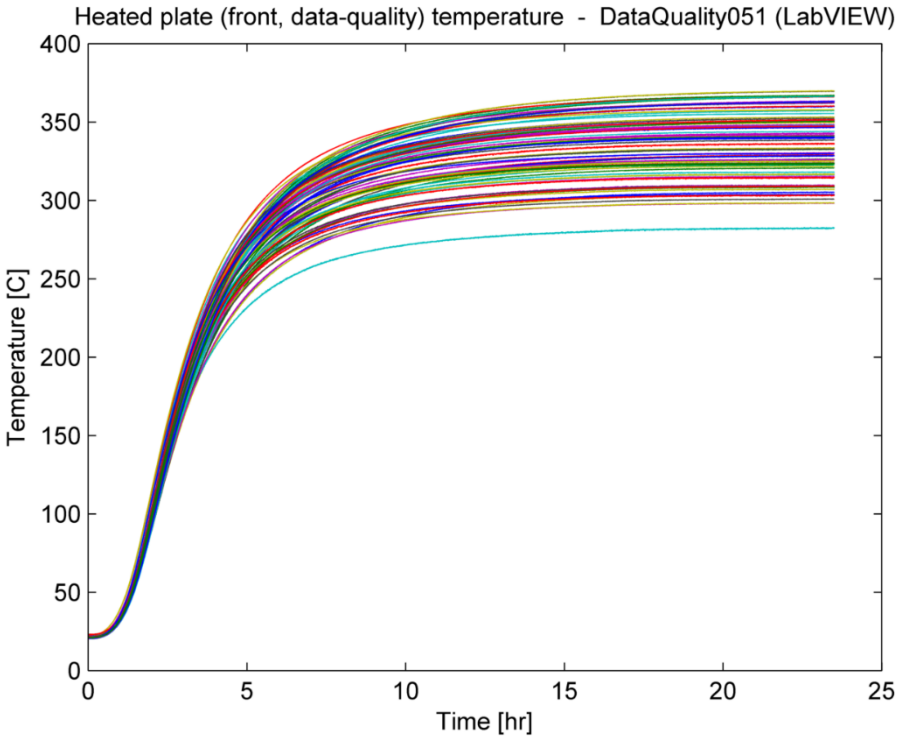

Figure 27: Heated plate temperature, baseline case run #051

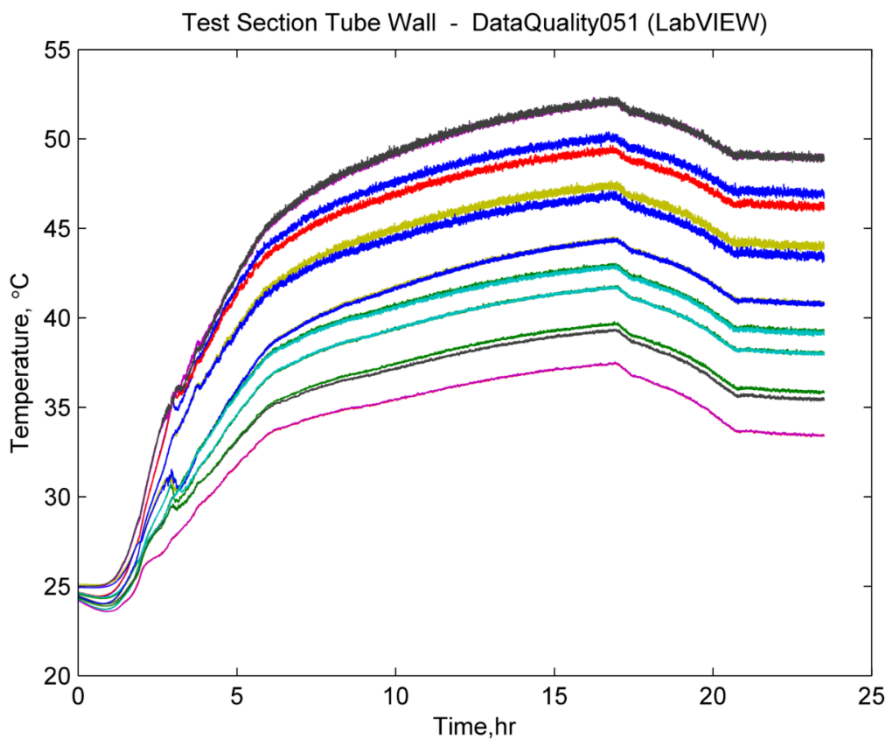

Figure 28: Test section tube wall temperature, baseline case run #051

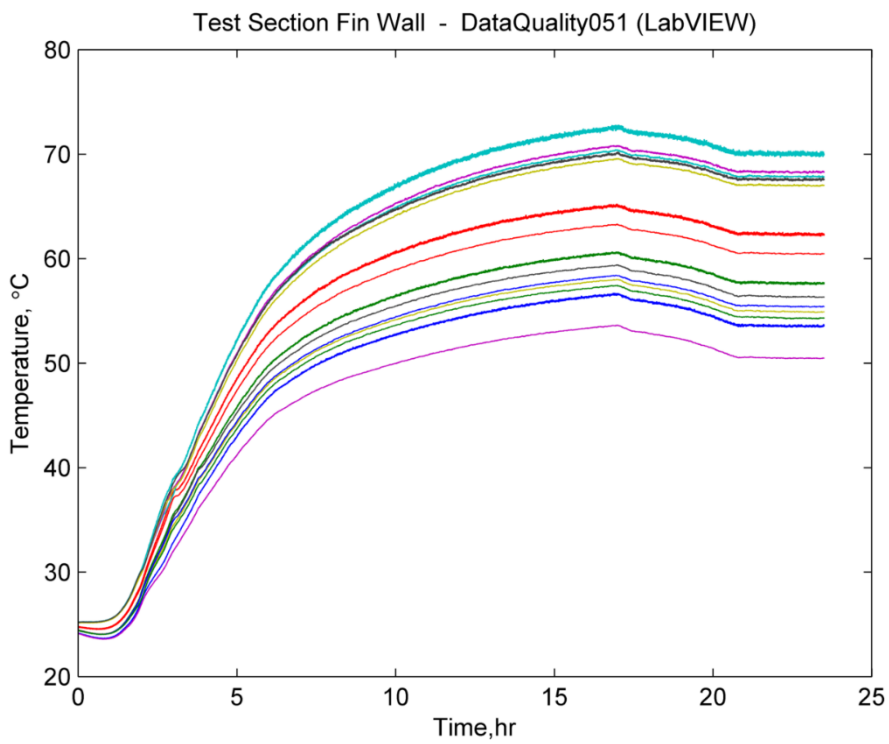

Figure 29: Test section fin wall temperature, baseline case run #051

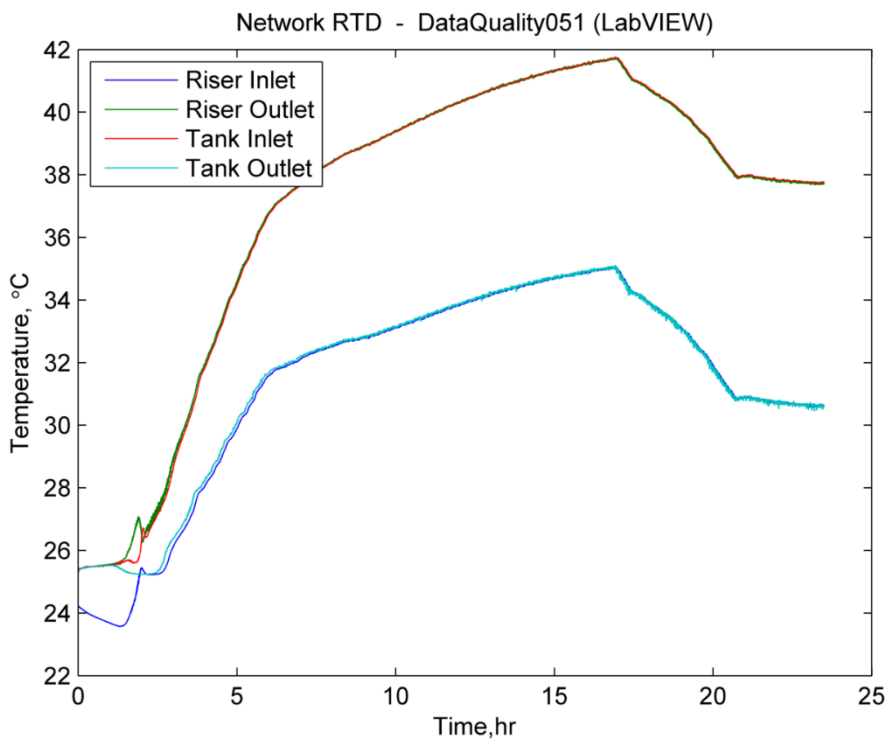

Figure 30: Fluid temperature, baseline case run #051

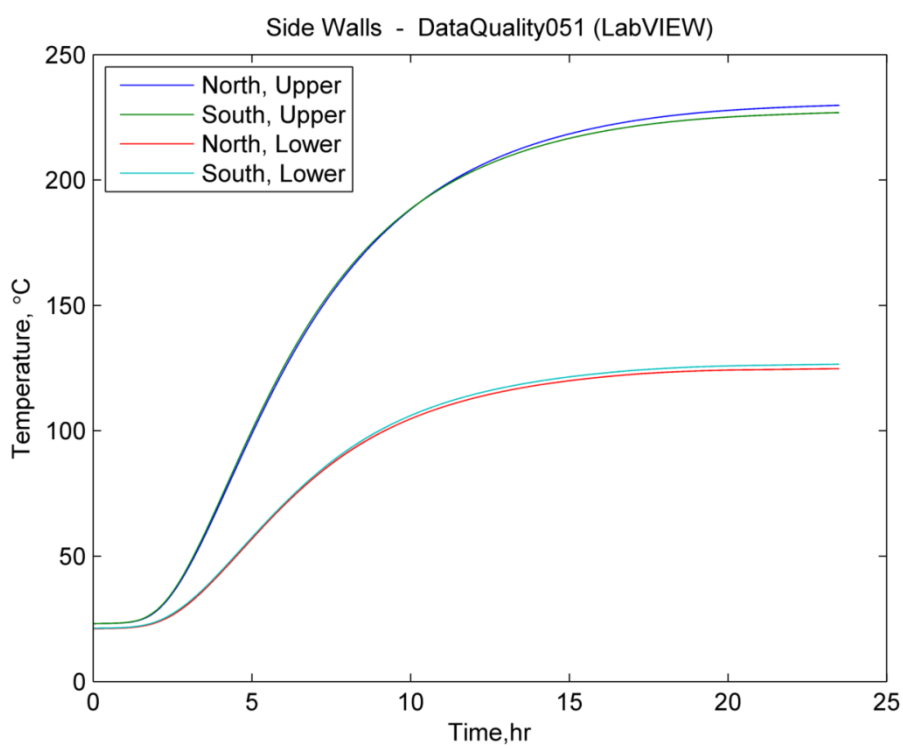

Figure 31: Side wall temperature, baseline case run #051

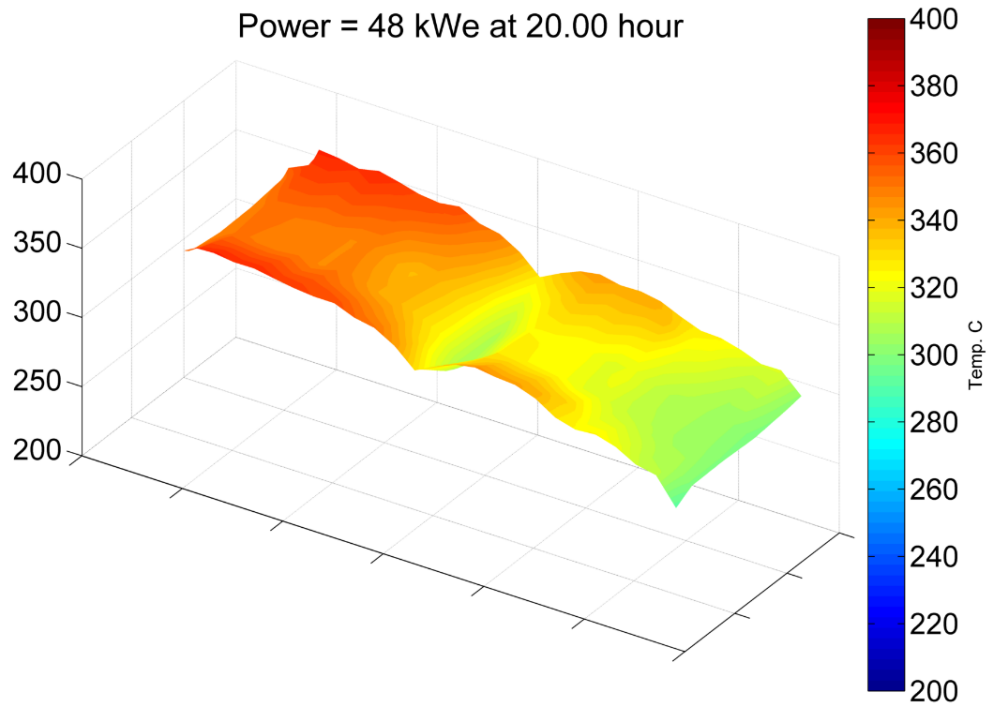

Figure 32: Heated plate temperature contour, baseline case run #051

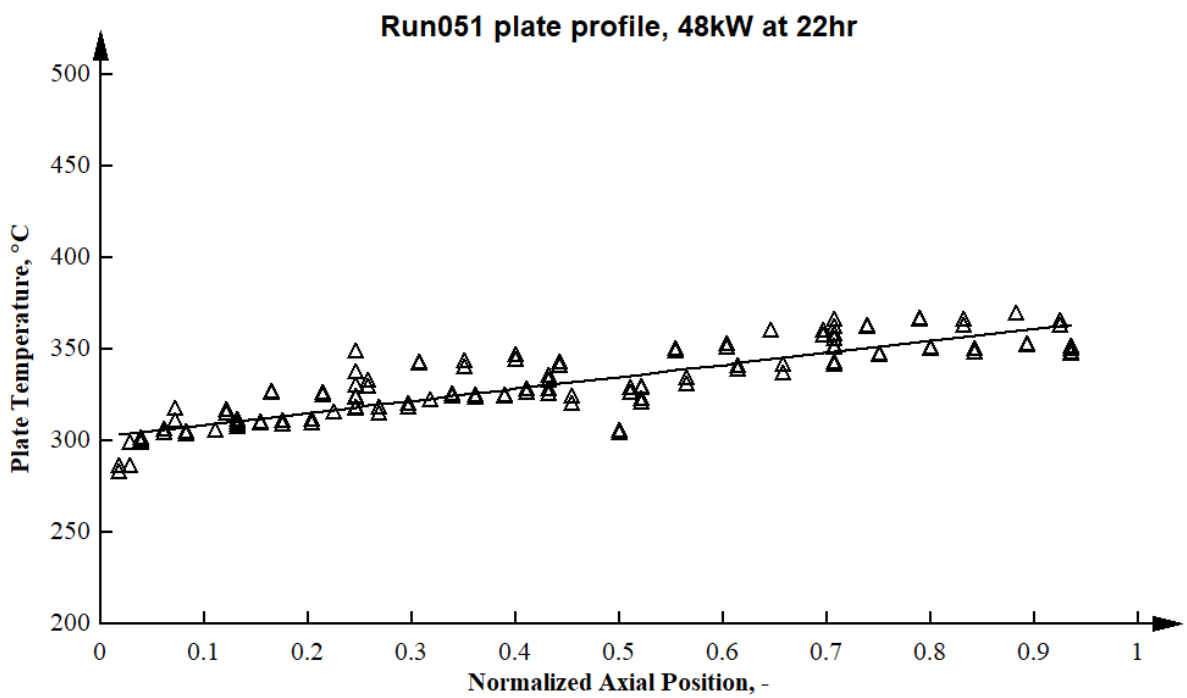

Figure 33: Heated plate temperature line plot, baseline case run#051

The total system flow and the individual riser tube flows are shown in Figure 34 and Figure 35, respectively. There was an abrupt jump in the flow when natural circulation initiated, following which the flow increased gradually and eventually reached steady-state. A second disturbance on the flow is caused by initiating the heat removal loop, which sent a cold slug of fluid into the downcomer leg thus increasing the driving head of the overall system, Figure 34. The flow distribution in the riser tubes exhibits minor asymmetry, with maximum riser-to-ideal split variations measured at 5.6%, and maximum riser-to-riser difference measured at 8.6%. This asymmetry is likely attributed to the momentum-driven phenomena discussed in the previous isothermal characterization. Separate effects testing in single-riser conditions have verified symmetry in bolted flange conditions and physical geometry, however there could still exists variations in the radial profile of the heat load and will be verified in future testing.

An energy balance analysis was performed, as shown in Figure 36. Over the course of the test, the thermal power into the test section was slowly increasing and then reached steady-state. Due to the size of the chiller, it had difficulty operating at very low heat loads and only stabilized when the test section thermal power reached ~ 20 kW. In this test, the heat removal rate has been constantly adjusted to match the test section thermal power. However, there was still a mismatch that caused the riser inlet temperature to overshoot above 30°C by ~ 17 hr, Figure 30. Because of that, the heat removal rate was increased to surpass the test section power to bring down the liquid temperature. When the riser inlet temperature was approaching 30°C, the heat removal rate was re-adjusted to match the test section thermal power, shortly after which the steady state was reached and maintained over 2+ hours (21 – 23 hr).

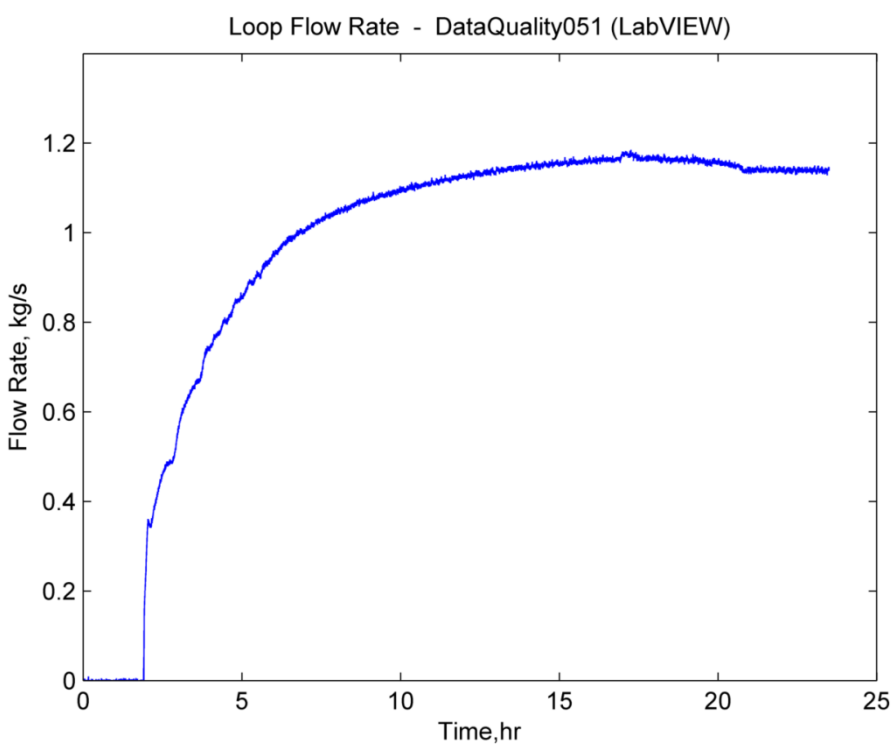

Figure 34: Total system flow, baseline case run #051

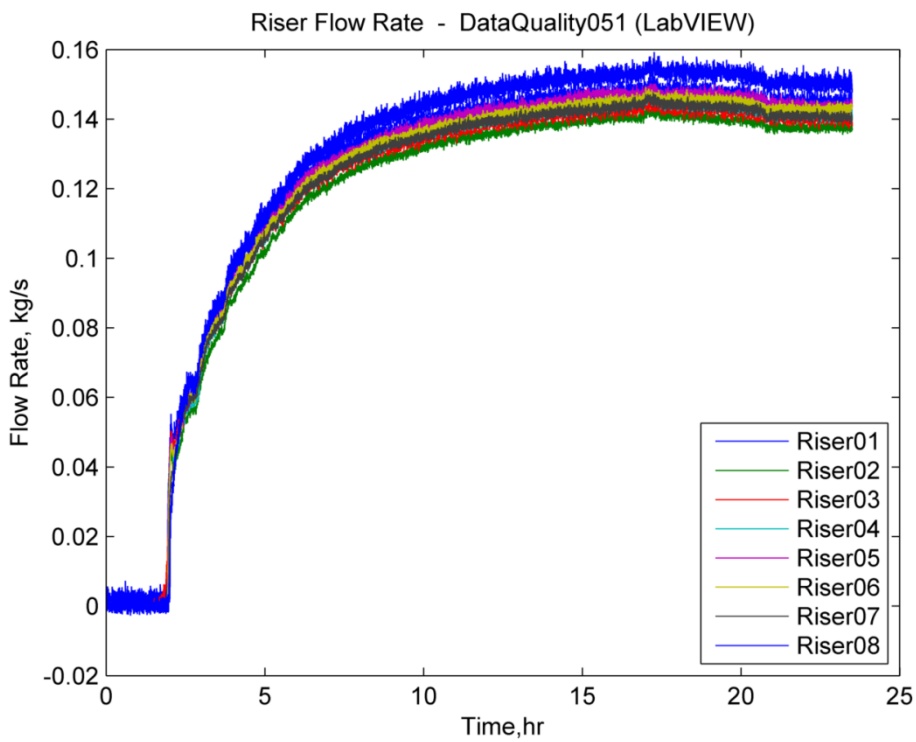

Figure 35: Individual riser tube flows, baseline case run #051

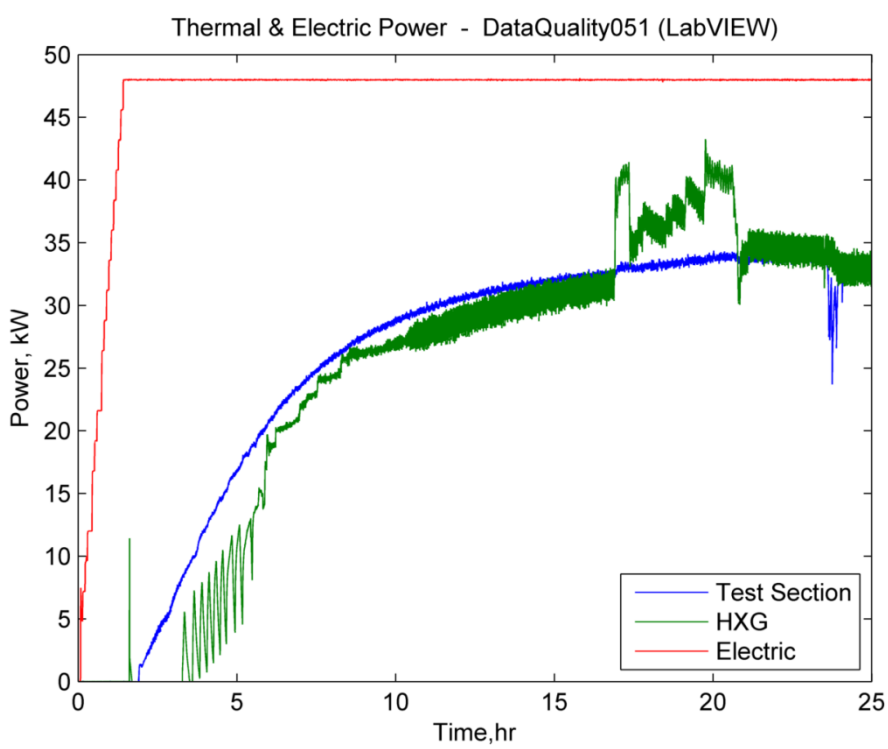

Figure 36: Energy balance, baseline case run #051

4.5. Power parametric series

The power parametric series, as described in the planned test matrix, define four different full scale power levels: a) Reduced – 700 kW_t (17.2 kW_t in NSTF), b) Normal – 1.4 MW_t (34.4 kW_t in NSTF), c) Accident – 2.1 MW_t (51.6 kW_t in NSTF), and d) Elevated – 2.8 MW_t (68.8 kW_t in NSTF). Four tests were conducted (Run051, Run052, Run054, and Run055) to investigate the power parametric series, with similar facility configuration as summarized in Table 9 except for the electric power. In test Run055 that simulates the case of 'elevated' power, a second steady state with an electric power of 58 kW_e was achieved, corresponding to a case in between the 'normal operation' baseline and 'accident scenario' baseline.

The steady-state results for the five different power levels are summarized in Table 11, trends depicted graphically in Figure 37 - Figure 40, and full system parameters averaged at steady-state conditions detailed in Table 12. For all the tests, the riser inlet temperature was maintained within 30±1°C, and the structure temperatures within the corresponding operation limits. As expected, all the heater and structure temperatures, liquid ΔT over the riser, and system flow rate increase with the electrical power. However, the relationship is not linear. The thermal power is in a good linear relationship with the electric power, resulting in a near constant thermal efficiency of approximately 71%, which has been improved compared to the previous air tests.

Table 11: High level summary of steady-state results at four examined power levels

	Run051	**Run052**	**Run054**	**Run055**	
Electric Power, kW_e	47.98	71.06	23.99	85.97	57.98
Heated Plate, °C	336.20	403.73	232.17	437.17	364.85
Riser Inlet, °C	30.74	30.37	29.47	30.67	29.47
Flow Rate, kg/s	1.14	1.34	0.86	1.43	1.22
Heated ΔT, °C	7.08	9.27	4.59	10.23	8.15
Thermal Power, kW_t	33.73	51.81	16.51	61.14	41.48

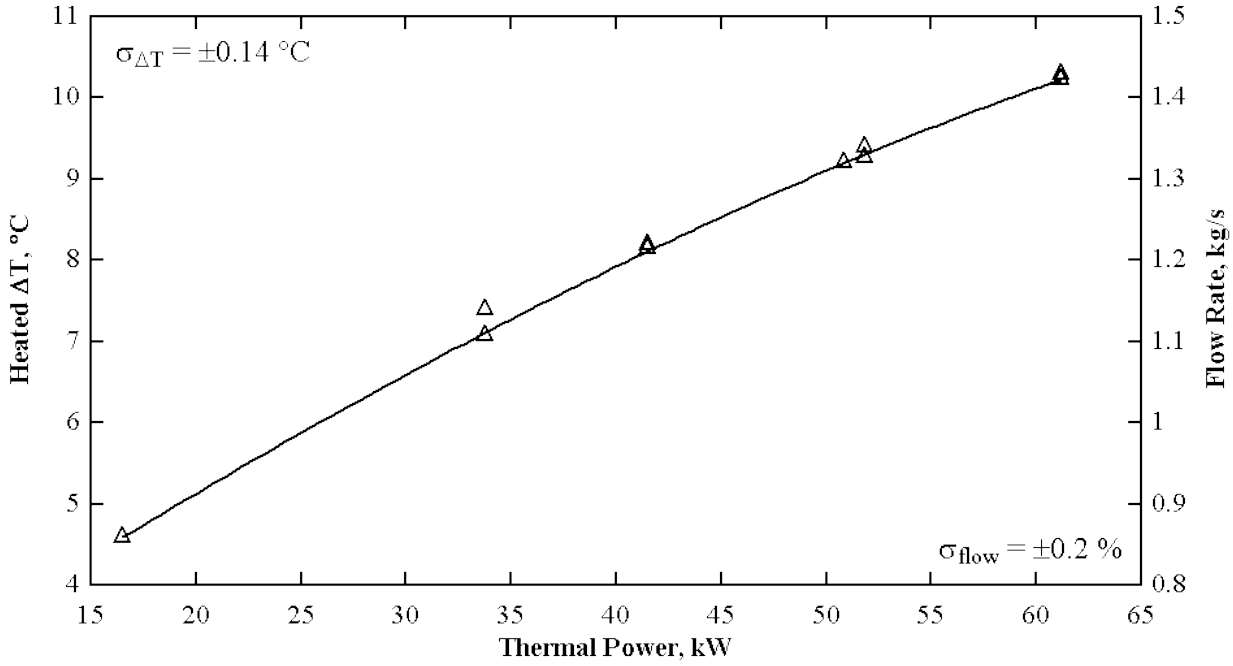

Figure 37: Heated ΔT and flow rate vs thermal power

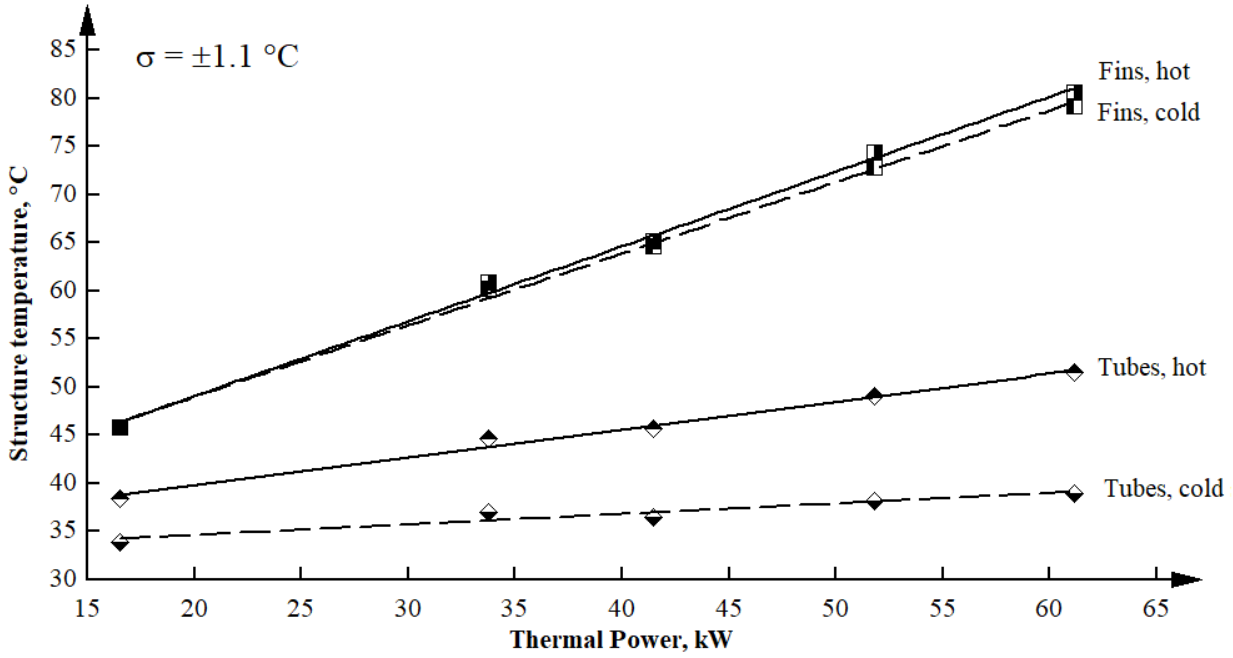

Figure 38: Structural temperatures of test section exterior surfaces vs thermal power

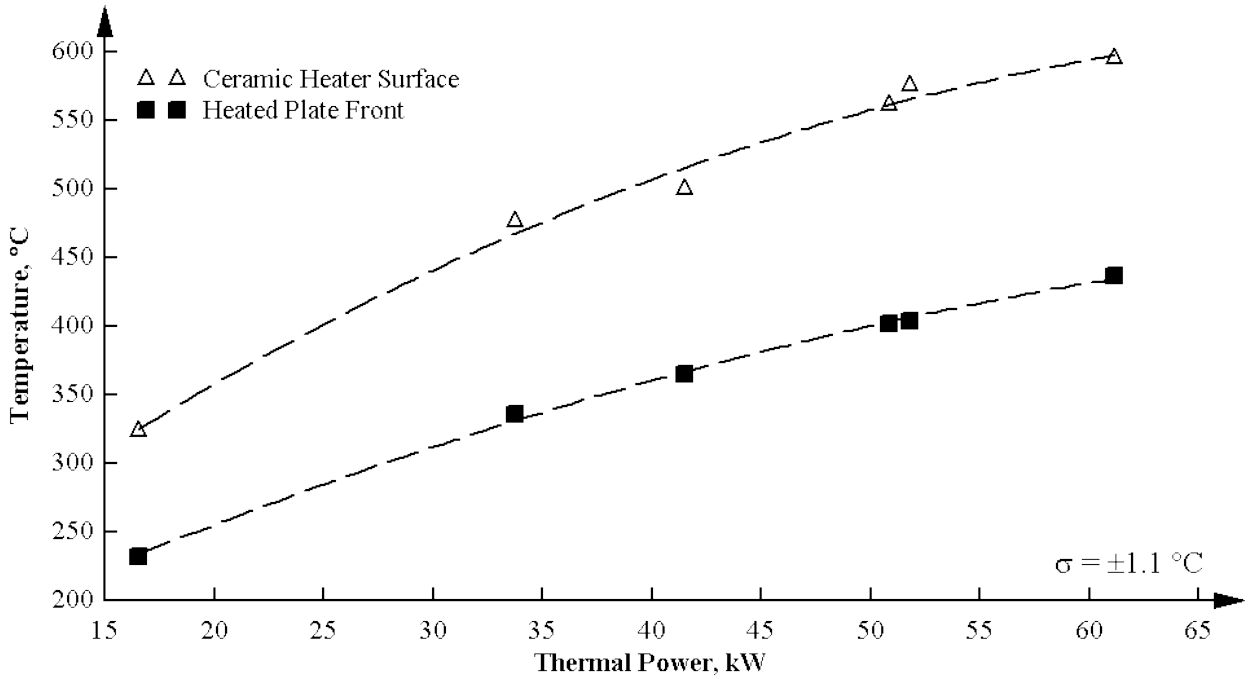

Figure 39: Heater and heated plate temperatures vs thermal power

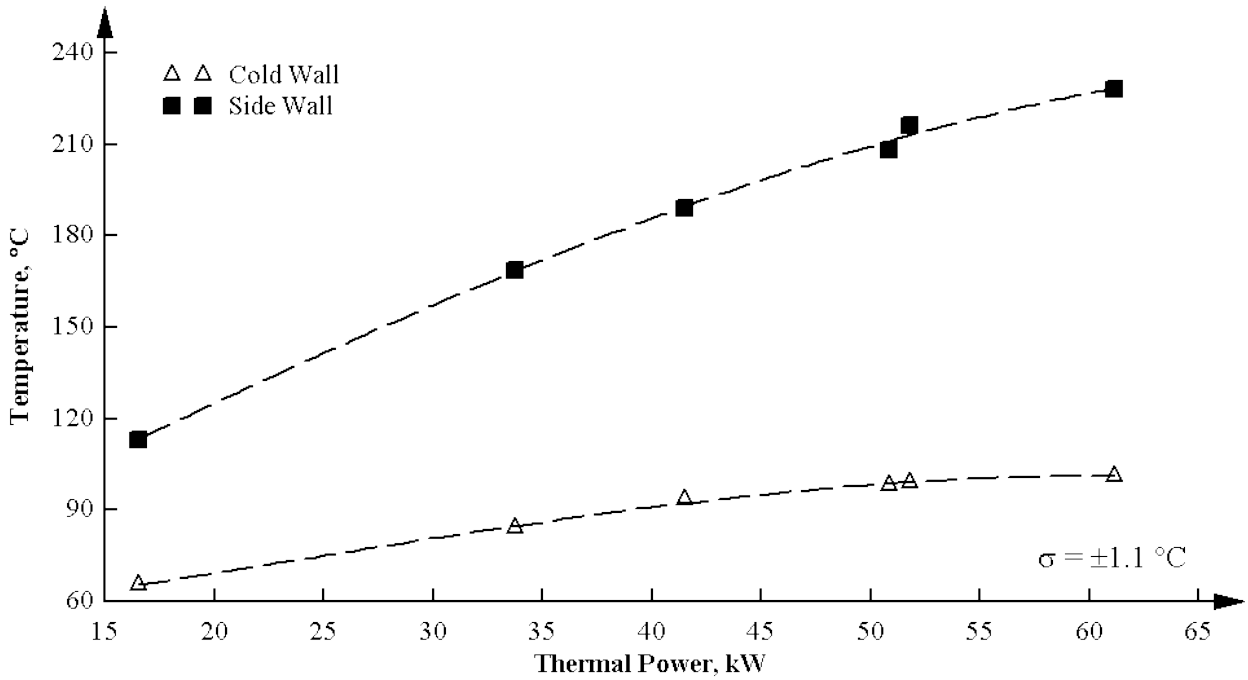

Figure 40: Cavity wall temperatures vs thermal power

Table 12: Summary of primary measurements across completed single-phase test cases

		Run051		Run052	Run054	Run055		
	Test date	11/2018		01/2019	05/2019	06/2019		
	Full power reference	1.4MW$_t$	1.4MW$_t$	2.1MW$_t$	0.7MW$_t$	2.8MW$_t$	1.7MW$_t$	
	Modification	-	15°ΔT	-	-	-	-	
Static pressure	Inlet header	37.61	37.62	37.73	37.79	37.72	37.74	*psia*
	Tank basin	14.24	14.24	14.35	14.35	14.34	14.36	*psig*
	Tank water level	99.42	99.45	104.57	105.91	105.20	105.21	*inWC*
Differential pressure	Δ01, Test Section	0.08	-0.68	0.13	0.65	0.14	0.08	*inWC*
	Δ02, Low chimney	-0.32	-0.58	-0.38	-0.24	-0.26	-0.27	*inWC*
	Δ04, Up chimney	0.01	-0.15	-0.15	0.10	0.25	0.02	*inWC*
	Δ05, Tank	-0.05	0.09	-0.43	-0.41	-0.44	-0.53	*inWC*
RTD Energy Balance Temp.	Tank inlet	37.85	45.35	39.67	34.09	40.94	37.66	*°C*
	Tank outlet	30.74	30.00	30.38	29.49	30.68	29.48	*°C*
	Header inlet	30.74	29.98	30.37	29.48	30.67	29.47	*°C*
	Header outlet	37.82	45.39	39.64	34.06	40.90	37.62	*°C*
HXG Loop	Hot supply	30.98	30.23	30.61	29.88	30.81	29.65	*°C*
	Hot return	17.17	17.04	11.48	12.43	17.08	13.18	*°C*
	Cold supply	15.39	15.32	8.07	10.96	8.09	9.07	*°C*
	Cold return	23.12	22.71	19.86	22.12	26.43	21.54	*°C*
	HXG flow rate	9.50	9.50	10.30	3.68	16.80	9.62	*GPM*
Piping Flow Rates	Primary loop	1.140	0.516	1.338	0.861	1.431	1.218	*kg/s*
	Riser 01	0.145	0.071	0.169	0.111	0.182	0.155	*kg/s*
	Riser 02	0.138	0.058	0.161	0.103	0.174	0.147	*kg/s*
	Riser 03	0.140	0.063	0.164	0.108	0.185	0.158	*kg/s*
	Riser 04	0.142	0.062	0.166	0.107	0.180	0.153	*kg/s*
	Riser 05	0.144	0.066	0.170	0.110	0.189	0.160	*kg/s*
	Riser 06	0.143	0.066	0.168	0.108	0.180	0.154	*kg/s*
	Riser 07	0.141	0.061	0.165	0.107	0.176	0.151	*kg/s*
	Riser 08	0.150	0.068	0.177	0.114	0.190	0.162	*kg/s*
Test Section Surface	Tubes, hot side	44.69	53.58	49.12	38.40	51.52	45.67	*°C*
	Tubes, cold side	37.06	45.07	38.22	33.85	38.92	36.55	*°C*
	Fins, hot side	60.89	69.77	74.31	45.82	80.54	65.13	*°C*
	Fins, cold side	60.28	69.61	72.84	45.83	79.19	64.63	*°C*
Heated Cavity Surface	Cavity cold walls	84.07	86.72	99.01	65.38	101.29	93.39	*°C*
	Cavity north wall	168.09	169.91	215.30	112.36	227.07	187.96	*°C*
	Cavity south wall	169.28	171.04	217.20	113.94	229.28	190.43	*°C*
Heaters	Heater plate, front	336.20	337.51	403.73	232.11	437.17	364.85	*°C*
	Ceramic heaters	476.37	477.00	575.40	323.67	595.13	500.17	*°C*
Power	Electric supplied	47.98	47.98	71.06	23.71	85.97	57.98	*kW$_e$*
	Riser panel thermal	33.73	33.24	51.81	16.51	61.14	41.48	*kW$_t$*
	HXG thermal	34.50	32.96	51.92	16.93	60.72	41.76	*kW$_t$*
	Thermal efficiency	70%	69%	73%	70%	71%	72%	*%*

4.6. Two-phase scoping

In parallel with conducting the single-phase test campaign, efforts were underway to prepare the facility for operation and eventual matrix testing at two-phase flow conditions. Under these conditions, the heat removal network will act as a means for steam condensation, and not active heat removal for the system's liquid inventory. Without active cooling, the system inventory will increase in temperature until it reaches saturation, at which point boil-off will begin with gradual loss of system inventory. Provisions for operating in this mode had been included since the facility inception, however they had not yet been verified or tested. Thus, a scoping test was performed to demonstrate the facility's ability to operate at a boiling and two-phase flow regimes.

Due to the installation of multiple valves, changes to the facility were minor and could be performed by a single operator during the test. The steps required to convert the facility from single-phase to two-phase operation are summarized below:

A. Storage tank valve adjustments:
    a. Shut-off all liquid discharge and return valves off the storage tank
    b. Shut-off HEPA filter breather vent on the top dome of the tank
    c. Open steam discharge valve off the upper dome of the tank
B. HXG valve adjustments:
    a. Actuate three-way valve on the hot supply side of the HXG, shutting off liquid supply from the lower basin of the storage tank, and opening a steam line from the upper dome
    b. Actuate three-way valve on the hot discharge side of the HXG, shutting off liquid return to the sparger to the tank, and opening condensation discharge to a reservoir
C. Condensation preparations
    a. Open valve at hot side discharge from HXG to condensation reservoir

Since the facility had never been operated at boiling conditions, a modified test procedure was used to ensure that the timing of boiling incipience occurred during working hours when all program staff were present. Furthermore, the boiling duration was limited to a 3-hour window to ensure adequate cool-down time. Given the enormous inventory and heat capacity of the various structures, it was anticipated that boiling would continue for several hours after the electric heaters were powered down.

Initial heating on Day 1 at baseline power levels for a 6-hour duration brought the loops inventory temperature to approximately 40°C. The heater power was reduced to a mere 10 kW_e, and by the following day, the liquid temperatures rose another 20°C. At the start of Day 2, 18 hours into the test, the heater power was increased to 72 kW_e and held constant for the remaining duration. The first indication of boiling was observed shortly before the 25-hour mark, where a stark rise in temperatures and flow rates were observed, Figure 41. Within a brief 18-minute period, voiding was detected in the upper chimney and the system began experiencing large magnitude oscillations. These oscillations continued for approximately 48 minutes, before stabilizing into a stable mode of boiling loop flow operation, Figure 42.

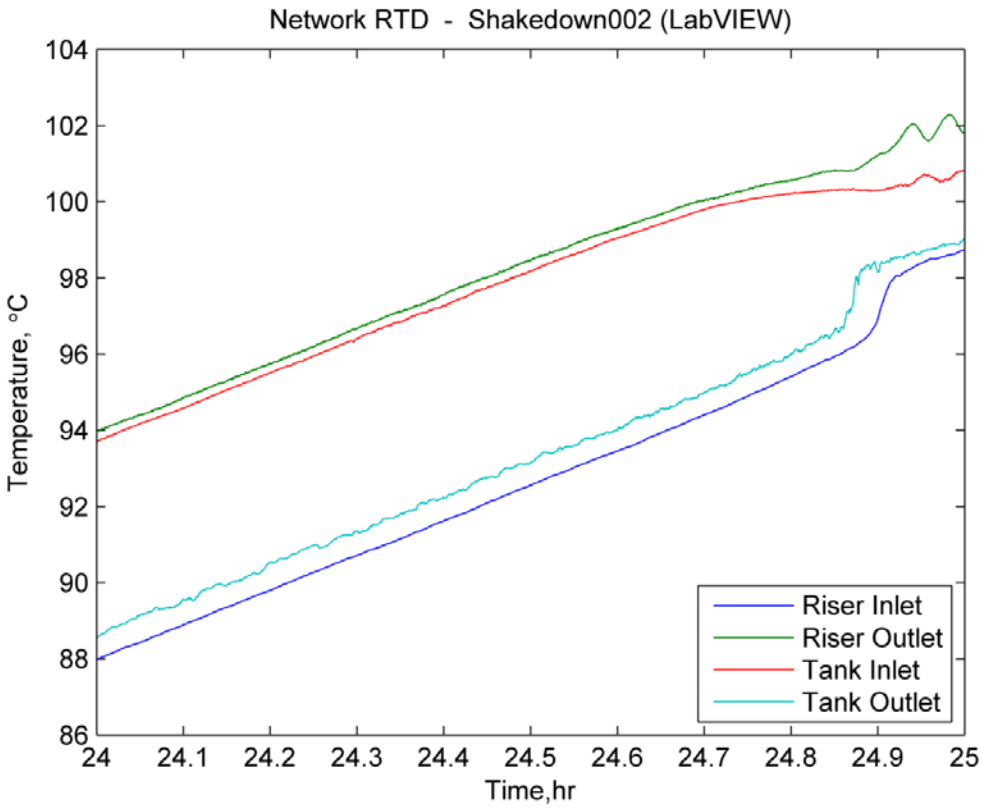

Figure 41: First indications of boiling incipience

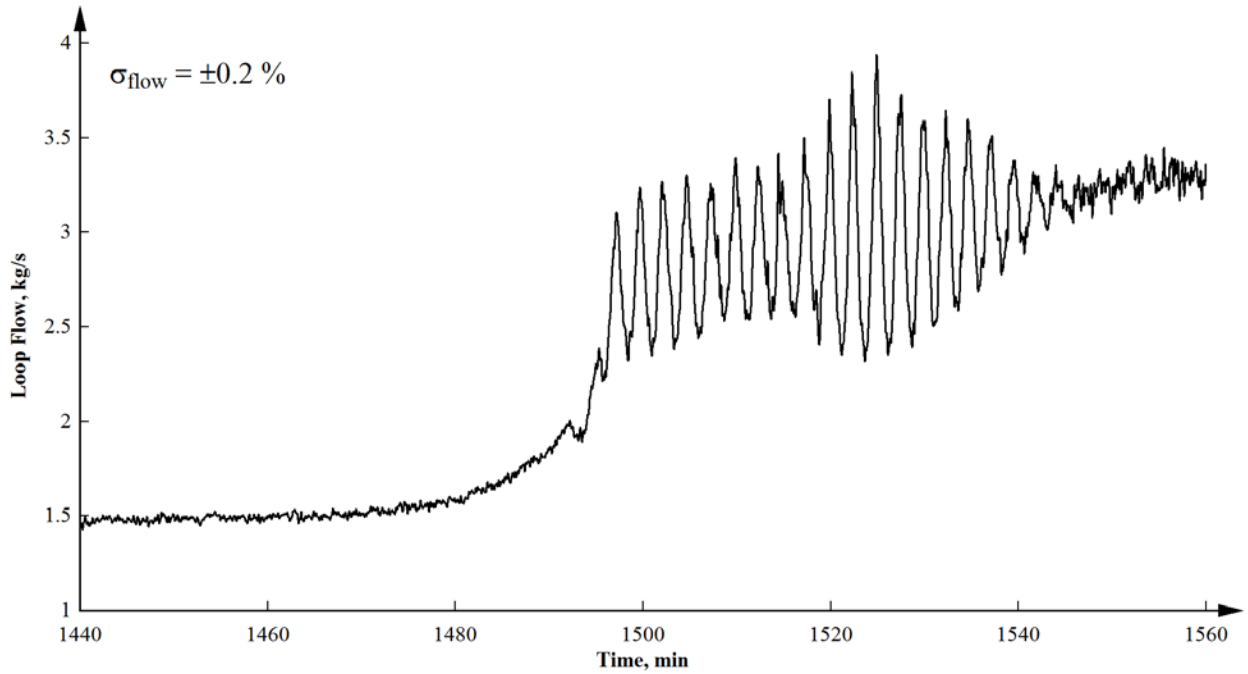

Figure 42: Large magnitude system wide oscillations as measured by the loop flow rate

At approximately the 26-hour mark, a power down was initiated to the electric heaters. As expected, two-phase flow was observed well past electric power shutdown, with measured void fractions continuing to rise until peaking at approximately 11% at the 26h20minute mark. Boiling continued through hour 28, at which point the HXG network was configured back to a liquid cooling configuration. Operators began active cooling of the system inventory, reducing the liquid temperatures below the saturation point and as indicated by the measured void fraction, Figure 43, ceasing steam generation and two-phase flow.

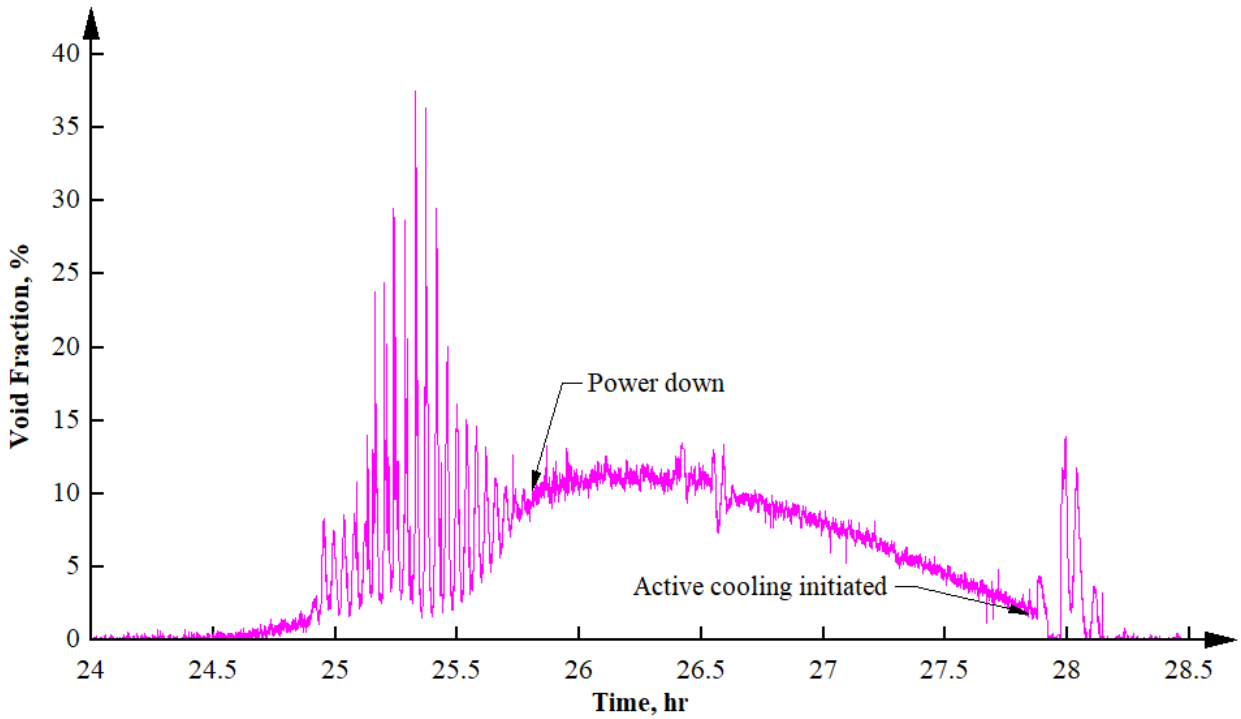

Figure 43: Detailed response of void fraction in upper chimney during two-phase scoping test

Measurements from the differential pressure sensors along the chimney indicate opposing phases of the pressure oscillations, suggesting that the boiling boundary occurred at some point along the upper portion of the chimney, Figure 44. These oscillations occurred with a period averaging 2.5 minutes, Figure 45, which is nearly equal to the transit time of the loop, calculated at 2.2 minutes at the average system flow rate of 2.97 kg/s. This suggests the instability mechanism may be characteristic of density wave oscillations, [18]. However, these values were determined during a start-up transient where the facility had not reached a quasi-steady mode of two-phase flow. Thus, determination of instability modes will require operating at longer durations of two-phase operation.

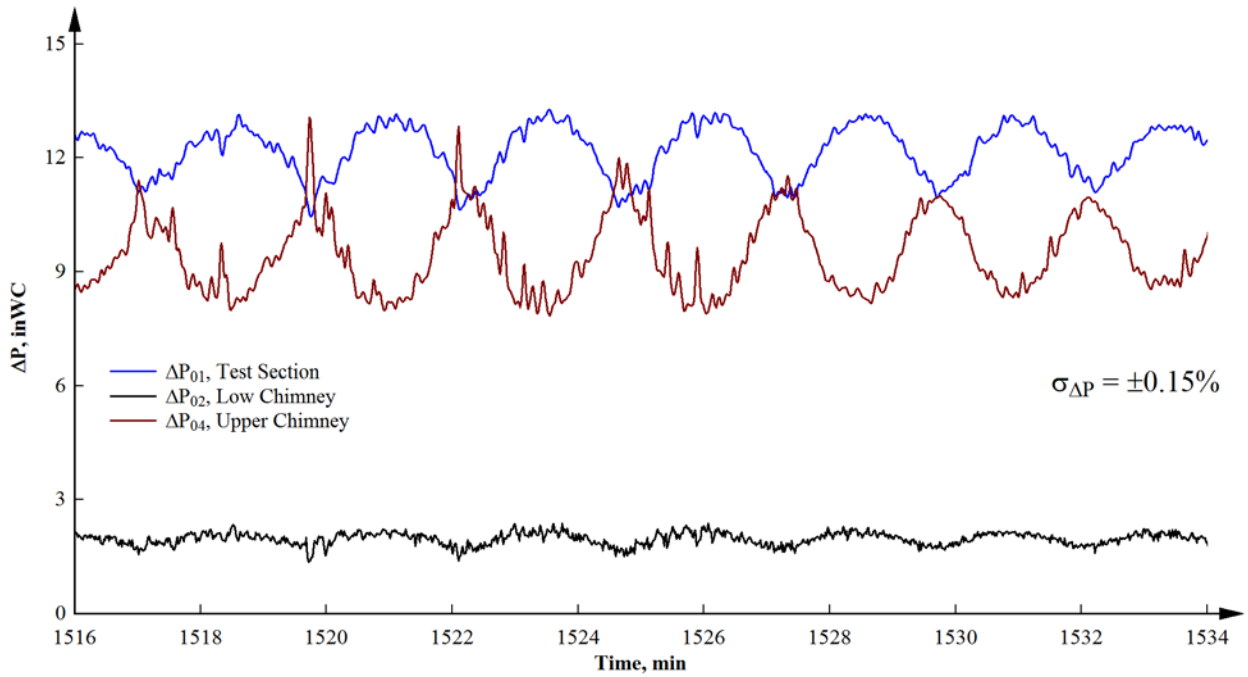

Figure 44: Phase shifted differential pressure curves during peak of two-phase oscillations

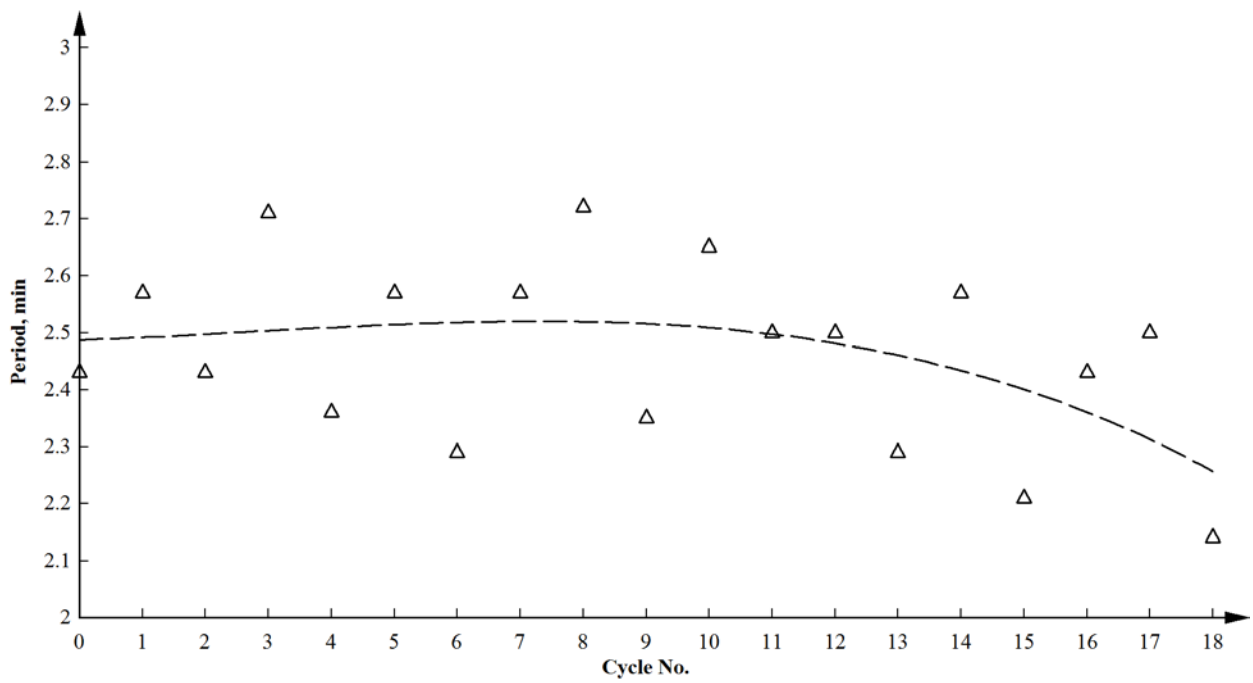

Figure 45: Flow rate oscillation period as a function of cycle number

5. Discussion and Path Forward

After the first year of matrix testing with the water-based NSTF, the program has completed four bake-out and shakedown test procedures, six single-phase heated test cases, three isothermal characterization tests, and one two-phase demonstration. In total, 370 hours of active test operations were logged across 12 separate test operations. Of these, four have been classified as successful matrix tests, appended with preliminary test acceptance reports (PTAR), and entered in the program archives. A summary of all the test operations conducted on constructed water-based test facility is provided in Table 13, and sample PTAR provided in the Appendix.

Table 13: Summary of test operations conducted through first year of facility operation

Test Name	Date	Duration	Purpose	Classification
BakeOut003	06/01/2018	010h06m	Heater & insulation bake out	⊖ Non-matrix
BakeOut004	06/07/2018	007h26m	Heater & insulation bake out	⊖ Non-matrix
Shakedown001	07/05 – 06/2018	024h22m	Single-phase demonstration,	⊖ Non-matrix
DataQuality050	08/03/2019	008h57m	Single-phase, 1.4 MW_t baseline,	☒**Failed**
DataQuality051	11/28 - 29/2018	026h53m	Single-phase, 1.4 MW_t baseline,15°ΔT over riser	☑**Accepted**
Characteriz001	01/15/2019	001h26m	Isothermal characterization test	⊖ Non-matrix
DataQuality052	01/16 - 17/2019	029h4m	Single-phase, 2.1 MW_t	☑**Accepted**
Shakedown002	02/19 – 20/2019	028h29m	Two-phase demonstration	⊖ Non-matrix
DataQuality053	03/26 – 27/2019	026h52m	Single-phase,2.1 MW_t, throttle	⊟ **Trending**
DataQuality054	04/25 – 05/01	177h37m	Transient heat-up; Single-phase 0.7 MW_t baseline	☑**Accepted**
Characteriz002	06/03/2019	003h00m	Isothermal characterization test	⊖ Non-matrix
DataQuality055	6/13 – 14/2019	026h01m	Single-phase, 2.8 MW_t	☑**Accepted**
Characteriz003	07/22/2019	001h28m	Isothermal characterization test	⊖ Non-matrix

5.1. Observations

Early shakedown testing saw the first development of natural circulation flow, with follow-on testing suggesting adequate levels of heat removal performance and flow stability, providing early insight into the viability of the passive safety RCCS concept for application to HTGRs. The isothermal characterization tests identified pressure loss coefficients and nominal flow throughout the NSTF loop, which provide critical parameters to support analytical and computational support efforts, such as RELAP5, Star-CCM+, and other CFD and system level code validations.

A transient heating characterization test was performed to examine the liquid heat up rate with different power levels. It was found that the liquid heat up rate scales well with the power at higher temperatures when most of the electric power is absorbed by the liquid inventory. The heat up rates found will provide valuable guidance on test planning for future two-phase tests. The power parametric series then covered five different power levels, including the single-phase baseline, scheduled two-phase baseline, along with very low and very high discovery power levels. The calculated thermal power is in a linear relationship with the electric heat load, resulting in a near constant thermal efficiency of approximately 71%.

The demonstration test conducted at boiling conditions established the facilities readiness to initiated two-phase matrix testing. The facility responded as designed, and was able to reliably maintain saturations conditions while safely condensing boil-off into controlled storage reservoirs. Due to the enormous inventory and thermal mass, the operators observed continued steam generation for several hours past the heater power off. Thus, provisions have been put in place to provide immediate cooling of the system inventory down below saturation, along with an option of redirecting steam discharge directly into the outdoor environment.

From an operational perspective, testing in year one indicated that the facility is reliable in its behavior and predictable in response to operator interactions. Some issues were encountered through the testing period, however were relatively minor and were perhaps expected given the scale and complexity of the overall facility. A number of improvements were also made throughout the testing year which has allowed a greater range of remote operator control over the multitude of flow valves and water pumps. Additionally, new systems have been put in place to automate actions during overnight hours, as well as automatic facility response during unplanned events.

5.2. Analytical and computational support

In parallel to the experimental effort for the NSTF project, there has been great support from the analytical and computation team. Both system-level and high fidelity Computational Fluid Dynamics (CFD) analyses have been performed to better understand the complex flow and heat transfer phenomena in natural convection systems. As one of the objectives for the NSTF analyses, system-level and CFD codes that may be used in licensing are assessed and validated. In addition, the NSTF analyses provided significant aid in the facility design improvement and experimental activities in the previous air campaign. Because of this successful experience with the air NSTF, the analytical and computational effort was continued with the water NSTF.

For the integral system performance analysis of the NSTF, RELAP5 has been selected as the primary tool. So far, a reference model has been developed for the water NSTF. With the reference model, parameter studies were performed, including the power parametric series. The simulation results provided useful guidance on the experimental investigation of the power parametric series. With the power parametric series testing completed, single-phase test data is available for the benchmark of the RELAP5 code, which is the focus of the current system level modeling work. To supplement the system analysis of the NSTF through RELAP5, CFD analysis of important component-level phenomena has also been undertaken. Previously, CFD analysis of the three-dimensional phenomenon inside the water tank was performed, which helped with the development of the tank model in the reference RELAP5 model. Current CFD work is focused on the modeling of the air cavity to provide guidance on the cavity model development in the RELAP5 model.

As the testing progress into two-phase operation, these models will be valuable tools in understanding of boiling phenomena and resulting instability modes.

5.3. Path forward

As the program enters a second year of testing, activities will begin with the installation of new shut-off valves at the outlet of each riser tube. This planned upgrade will facilitate testing at conditions where the inventory in one or more riser tubes is drained and the test section functions partially dry. The new valves will change the dimensions of loop piping, lengthening the risers, and consequently shortening the chimney, by 2.5-inch. This will be a relatively minor change in the loop geometry, however may alter the distribution of loop frictional losses. Thus, the facilities state and condition will be benchmarked by repeating isothermal characterization and a baseline test case. While the impact is expected to be minor if not negligible, comparisons will be made to previous measurements to evaluate any impact and verify similarity to data collected during the single-phase campaign.

Following successful verification of the new loop configuration, the program will commence two-phase matrix testing and conduct a single, full length, baseline test case at boiling flow conditions. Flashing phenomena and large amplitude system-wide flow oscillations are a few of the instabilities that are likely to be observed during these extended duration two-phase tests. An evaluation will be made if any changes to the facilities control or support systems are required, after which a second baseline test will be performed and evaluated for repeatability.

For the remainder of the testing year, parametric studies will be initiated with examination of the influence of system inventory. Multiple quasi-steady state tests will be conducted at varying tank inventory levels, e.g. 80%, 60%, 40%. Then, an accelerated tank depletion condition will be implemented, and continued until full tank depletion and stagnation of loop flow. Testing results will be compared against computational models in RELAP5 and Star-CCM+, and models tuned as required. They will then be used to guide future test operations, along with predicting off-normal scenarios otherwise difficult or dangerous to perform experimentally.

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Lastly, the program wishes to remember Tony Tafoya, a core member of the laboratory support team who made significant contributions in construction and maintenance of the experimental test facility. He will be remembered for his dedication to research and kindness to all.

Appendix A – Baseline Test Procedure, sample

Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

Nuclear Science & Engineering Division

Water NSTF Baseline Test Procedure for Data Collection (NQA-1, Type A)

ANL-NSTF-000000-TEST-021-R2

January 14th 2019

Prepared by: _____ 01/29/2019
Q. Lv, Lead Experimenter — Date

Reviewed by: _____ 29 JAN 2019
N. Bremer, Test Engineer — Date

Approved by: _____ 01/29/2019
D. Lisowski, NSTF Facility Manager — Date

Notice: Printed and electronic copies of this document are not controlled. The current approved release of this document is maintained by the Configuration Manager.

REVISION HISTORY

Rev	Date	Purpose	Authorization
0	08/01/2018	ANL-NSTF-000000-TEST-021 Initial release	D. D. Lisowski
1	11/26/2018	Administrative revisions for updated control software; pre-test checks for emergency dump; addition of lower power heat removal sequence	D. D. Lisowski
2	01/14/2019	Administrative revisions for documentation	D. D. Lisowski

WATER NSTF BASELINE TEST PROCEDURE FOR DATA COLLECTION (NQA-1, TYPE A)	Identifier: ANL-NSTF-000000-TEST-021 Revision: 02 Effective Date: January 14th 2019	Page 3 of 24

Test Series & No: Data Quality 052 Test Start Date: 01/15/2019

Test Objective: Matrix Test of Single-phase Steady State

Involved Personnel (IP): Qiuping Lu & Darius Lisowski

0.0 **Scope** – This procedure governs activities related to conduct of an NSTF test for data collection for purposes of qualification at Type A data metrics under NQA-1 standards. The following steps are to be directed by the Lead Experimenter, with approval from the Project Manager. Only Involved Personnel identified above may participate in test operations. Outlined tasks are to be conducted in the prescribed, sequential order, according to the written procedure.

1.0 **Prerequisites**

1.1 Training - All Involved Personnel must: i) undergo NSTF indoctrination training, and ii) undergo training for this test procedure (training documented in Appendix A), and be up-to-date on the active WPC training through their TMS profile.

1.2 Access control – Non-involved personnel shall not modify or otherwise access critical data acquisition or loop piping including cDAQ units or any valves (manual or automated) for a period beginning 2 days prior to test commencement until a period of 4 days post-test conclusion. These control areas are to be marked and posted with visible signage. Any of these activities performed by Involved Personnel must be carried out under the lead experimenter's guidance and control. Related computer systems shall be limited to test specific activities only.

1.3 Delegation of roles and monitoring shifts - Given the possible multiday duration of the test, the lead experimenter will designate responsibilities and operating shifts for the full duration of heater-on power testing. Active monitoring is not required during overnight periods (only if initiation of flashing or system dry out is not anticipated during this period), but efforts should be made to: minimize unattended operation to periods no greater than 8 hours and only after at least 10 hours of initial heating, or at the lead experimenters' discretion.

1.4 The following attachments must be printed and included in the final test report folder

1.4.1 A complete set of instrumentation-related engineering drawings printed in full (8.5"x11") that provide details of sensor types, locations, and names

1.4.2 A tabulated data acquisition list detailing connected devices, cDAQ channels, that cross-reference instrumentation-related engineering drawings

1.4.3 Tabulated list of calibration dates for applicable instruments

Date: 01/15/19 Initial: QL

2.0 Documentation of System Setup and Configuration

2.1 Document intended position of x2 pneumatic valves (one prior to inlet header and the other beneath water tank) and x8 manual valves (one per riser tube). The position of the pneumatic valves can be checked through either the LabVIEW DAS or the position indicator on top of the valves (*per ANL-NSTF-WPIPE01-DWG-034*)

Header	Open	Riser4	Open
Tank	Open	Riser5	Open
Riser1	Open	Riser6	Open
Riser2	Open	Riser7	Open
Riser3	Open	Riser8	Open

2.1.1 Water storage tank inventory fill height (*per ANL-NSTF-WTANK01-DWG-005-R0*)

Sight glass (inch) 84.25 "

ΔP-LEVEL-01 (inWC) 105.88 "

P-STATIC-INLET (psia) 37.85 psia

Date: 01/15/19 Initial: QL

2.2 Global summary of data acquisition channel and devices:

2.2.1 Obtain a hard copy of thermocouple and instrumentation summary. Initial, date, and note test name. The print out will include: instrument identification name, signal output, range, accuracy, manufacturer, calibration (if applicable, and if so ensure calibration date is valid for test duration), DAQ channel, and engineering drawing reference numbers.

Date: 01/15/19 Initial: QL.

2.3 Engineering drawings of included instrumentation position

2.3.1 Obtain hard copies of engineering drawings, which detail above devices and correspond to the above reference numbers. Initial, date, and note test name.

Date: 01/15/19 Initial: QL

2.4 Specifications of analogue flow and pressure devices. Include original output signal, resistor value (if applicable for I->V), full scale range, and any user-configurable settings

	Model	Full Scale	Output	Other
FLOW-RISE02 FLOW-RISE03 FLOW-RISE04 FLOW-RISE05 FLOW-RISE06 FLOW-RISE07	Khrone 4000	0 - 2 kg/s	4-20 mA	NA
FLOW-RISE01 FLOW-RISE08	Khrone 4000	± 5 kg/s	4-20 mA	
FLOW-LOOP01	Khrone 4000	± 10 kg/s	4-20 mA	
FLOW-HXG01	Khrone 4000	0 - 25 GPM	4-20 mA	
P-STATIC-INLET	Rosemount 3051S	150 psia	4-20 mA	
P-STATIC-TANK	Rosemount 3051S	150 psia	4-20 mA	
ΔP-DIFF-01 ΔP-DIFF-03 ΔP-DIFF-05	Rosemount 3051S	250" WC	4-20mA	
ΔP-DIFF-02 ΔP-DIFF-04	Rosemount 3051S	± 25" WC 25" WC	4-20 mA	
ΔP-LEVEL-01	Rosemount 3051S	250" WC	4-20 mA	
Chimney α	ThermoFisher DensityPRO	0 - 1	4-20 mA	

Date: 01/15/19 Initial: RL

2.5 Differential pressure impulse plumbing (*per ANL-NSTF-WPIPE01-DWG-033-R0*)

Device	Range	Tap	Impulse Connection	Description
DP-DIFF-01	250" WC	Low	DP20	Test Section
		High	DP44	
DP-DIFF-02	± 25" WC	Low	DP22	Lower Chimney
		High	DP20	
DP-DIFF-03	NA	Low		NA
		High		
DP-DIFF-04	25" WC	Low	DP25	Upper Chimney
		High	DP22	
DP-DIFF-05	250" WC	Low	DP25	Full Loop
		High	DP40	

Date: 01/15/19 Initial: RL

2.6 Document any abnormalities, deviations, findings discovered, or comments on tasks performed in task 2.0 Documentation of System Setup and Configuration

All OK

Date: 01/15/19 Initial: QL

WATER NSTF BASELINE TEST PROCEDURE FOR DATA COLLECTION (NQA-1, TYPE A)	Identifier: ANL-NSTF-000000-TEST-021 Revision: 02 Effective Date: January 14th 2019	Page 7 of 24

3.0 Pre-test setup and hardware verifications

3.1 Data acquisition computer preparation

3.1.1 Reboot primary control computer

3.1.1.1 Verify system clock to 'time.nist.org'

3.1.1.2 Create test folder, '*%DATE%*_DataQuality0NN'

3.1.2 Verify communication lines with Eurotherm & Mini controllers

3.1.3 Open communication lines with NI cDAQ chassis

3.1.3.1 If necessary, reset chassis (listed in §3.3) via DaqMX

3.1.3.2 Export NI-MAX configuration 'NSTF_*%DATE%*.nce in DAQMX

3.1.4 Launch LabVIEW 2014 'NSTFProjMain_2017.proj'

3.1.4.1 Backup full VI library within test folder 'viDataQuality_*%DATE%*'

3.1.4.2 Export channel listings to .csv file, 'DataQuality0NN_*%DATE%*'

3.1.5 Attached latest release of ANL-NSTF-000000-SC (software config.)

3.1.6 Attached latest release of ANL-NSTF-000000-SB (calibration records)

3.1.7 Record specific LabVIEW vi filename and revision number

3.1.7.1 .vi name, revision NSTF Proj_2017.vi 1373

Date: 01/15/19 Initial: QL

3.2 Confirm working communication with iTools

Main1_2	✓	Guard1_2	✓
Main3_4	✓	Guard3_4	✓
Main5_6	✓	Guard5_6	✓
Main7_8	✓	Guard7_8	✓
Main9_10	✓	Guard9_10	✓
Mini1	✓	Mini2	✓
Mini3	✓		

Date: 01/15/19 Initial: QL

3.3 Confirm working communication with cDAQ

LowerNorth	✓	LowerSouth	✓	Mezzanine	✓
UpperNorth	✓	UpperSouth	✓	TowerMid	✓

Date: 01/15/19 Initial: QL

3.4 Confirm working UPS operation and communication with computer

Date: 01/15/19 Initial: QL

3.5 Confirm working remote desktop operation via TeamViewer

Date: 01/15/19 Initial: QL

3.6 Enable remote watchdog in LabVIEW. Verify operation and triggered communication

Date: 01/15/19 Initial: QL

3.7 Initialize and verify operation of emergency dump valve

3.7.1 Route 2.0" lay-flat fire hose along pit floor

3.7.2 Connect one end of hose to pneumatic 2.0" valve VP-04

3.7.3 Connect other end to holding tank VF-02

3.7.4 Verify no kinks are present in fire hose and that Cam-Lock fittings are secure

3.7.5 Verify that compressed gas cylinder supply pressure is at or above 1,000 psig

3.7.6 Adjust regulator for delivery-side pressure to 60 psig

3.7.7 Close manual 2.0" ball valve VL-02

3.7.8 Toggle emergency dump switch and visually verify that VP-04 opens and closes

3.7.9 Repeat toggle and visual verification for secondary switch in control room

3.7.10 Verify that final toggle state closes VP-04

3.7.11 Manually open VL-02

Date: 01/15/19 Initial: QL

3.8 If required for test, verify movement of the pneumatic valve prior to inlet header and the pneumatic valve at water tank outlet. Cycle full open and full closed in LabVIEW, and visually verify that the valves move as intended.

Date: 01/15/19 Initial: QL

3.9 At least 24 hours prior to test operations, turn on 480VAC power to chiller unit to allow compressor warm up. Do not 'Start' system.

Date: 01/15/19 Initial: QL

3.10 Document any abnormalities, deviations, other findings discovered, or comments on tasks performed in task 3.0 Pre-test setup and hardware verifications

Date: _____ Initial: _____

No insulation on the inlet header

Open TC's: SW6556-TC224
NW-5616-TC204

Date: 01/15/19 Initial: QL

4.0 Test Day: cold-start circulation and zero-flow baseline

4.1 On day test day, but before commencing test operations, perform loop circulation in preparation for cold-start, zero-flow verifications.

4.1.1 Close the pneumatic valve at tank outlet and ensure all other valves are open

4.1.2 Turn on the circulation pump to establish isothermal condition. Allow loop to circulate for 20 minutes, or until piping thermocouples are within 2°C.

4.1.3 Monitor thermocouples within LabVIEW. Verify that all read values stable and nominally near ambient (variations should be minimal with isothermal condition reached). Document any abnormalities, and if open TC detected, document the location and channel

4.1.4 After confirming isothermal condition, turn off the circulation pump

4.1.5 Re-open the pneumatic valve at water tank outlet

Date: 01/15/19 Initial: QL

4.1 Establish zero-flow conditions and record sensor values

4.1.1 Close inlet throttle valve to establish zero-flow while maintaining free-surface

Date: 01/15/19 Initial: QL

4.2 Zero differential pressure transmitters

4.2.1.1 Close the equalizer valve

4.2.1.2 Open the H isolation valve

4.2.1.3 Open the H vent valve, observe the bleeding flow in the clear tube and wait until there are no air bubbles, close vent valve

4.2.1.4 Repeat steps 4.2.1.2 and 4.2.1.3 for L side

4.2.1.5 Close the L isolation valve

4.2.1.6 Open the equalizer valve

4.2.1.7 Open the L vent valve, observe the bleeding flow in the clear tube and wait until there are no air bubbles, close vent valve

4.2.1.8 Check transmitter reading, if zero, close the equalizer valve and open the L isolation valve, and skip the remaining steps; if non-zero, close the H isolation valve and open the L isolation valve

4.2.1.9 Open the H vent valve, observe the bleeding flow in the clear tube and wait until there are no air bubbles, close vent valve

4.2.1.10 Check transmitter reading, if zero, close the equalizer valve and open the H isolation valve, and skip the remaining steps; if non-zero, proceed

4.2.1.11 Repeat steps 4.2.1.1 – 4.2.1.10. If transmitter still does not read zero, consult the lead experimenter

Date: 01/15/19 Initial: QL

4.3 Record cold-start, zero-flow values for 5 – 10 minutes in LabVIEW

Data file name: DataQuality052 - forceCirculation

4.3.1 Monitor flow meter and differential pressure. Verify that readings are within nominal ranges, and then record actual value.

Header inlet (< 0.1 kg/s)	~ 0.00	HXG loop (< 0.01 kg/s)	~ 0
Riser 01 (< 0.01 kg/s)	~ 0	Riser 05 (< 0.01 kg/s)	~ 0
Riser 02 (< 0.01 kg/s)	~ 0	Riser 06 (< 0.01 kg/s)	~ 0
Riser 03 (< 0.01 kg/s)	~ 0	Riser 07 (< 0.01 kg/s)	~ 0
Riser 04 (< 0.01 kg/s)	~ 0	Riser 08 (< 0.01 kg/s)	~ 0
ΔP01 (< 0.25 inWC)	~ 0.35	ΔP04 (< 0.025 inWC)	~ 0.06
ΔP02 (< 0.025 inWC)	~ -0.22	ΔP05 (< 0.25 inWC)	~ -0.38
ΔP03 (< 0.25 inWC)	NA	Gamma void (< 1%)	~ 0

Date: 01/15/19 Initial: QL

4.4 Using sample port on header inlet, draw 500 mL of inventory, discard. Draw an additional 200 m L of inventory and measure water quality parameters

Conductivity	13.42 µS/cm	Total chlorine	0 ppm
pH	7.72 -	Total hardness	~ 50 ppm

Date: 01/15/19 Initial: QL

Conductivity : OAKTON CON 150 , Serial#: 2730916

PH : OAKTON PH 30 ,

Test Strips { Total chlorine : AquaChek by HACH , 2021/07
Total hardness: SofChek by HACH , 2021/08

4.5 Document any abnormalities, deviations, other findings discovered, or comments on tasks performed in task 4.0 Test Day, cold-start and zero-flow baseline

All OK

Date: 01/15/19 Initial: RL

– Hold Point –

Do not proceed unless the following tasks have been completed:

- [x] 1.0 Prerequisites
- [x] 2.0 Documentation of System Setup and Configuration
- [x] 3.0 Pre-test setup and hardware verification
- [x] 4.0 Test Day, cold-start and zero-flow baseline

Confirm that the water pump has been shut off. Confirm that the valves are oriented in the prescribed positions (2 pneumatic valves in the loop and 8 manual valves in the risers).

I verify that the tasks above have been completed according to the written procedure, and that they were done so in a manner that is consistent with the scope of the test objective. I also verify that unless otherwise stated, these were performed while the facility was in a cold state (surrounding metal and insulation is, within reasonable judgment, near ambient temperatures). Any deviations from the written test procedure have been approved by the lead experimenter and documented.

Lead experimenter signature

01/16/2019 08:23
Date/Time

This area intentional left blank

5.0 Test day starting procedures

5.1 Building & administrative tasks

5.1.1 Notify building occupants (METL & USV), directory, and manager of 308

5.1.2 Inspect test area to ensure no combustibles are present.

5.1.3 Post 'WARNING – HOT SURFACE' warning signs around test and heater area

5.1.4 Post "ACCESS CONTROL - TEST IN PROGRESS" over DAQ and heater panel

5.1.5 Post "NO UNAUTHORIZED PERSONNEL" signs over 308 pit staircase

5.1.6 Verify railings are in place to prevent access to 240 / 480 VAC power leads

Date: 01/16/19 Initial: QL

5.2 LabVIEW logging tasks

5.2.1 Initialize data logging on LabVIEW

5.2.1.1 Enter test name, 'dataQuality%0NN%_%date%'

5.2.1.2 Specify recording interval of '2 seconds', enable logging

5.2.1.3 Verify data file was created and is being appended

5.2.2 Verify '0' power signal to all 40 Eurotherm modules

5.2.3 Define trip override temperature for heater banks, '650°C'

5.2.4 Signal to personnel to enable 20 main and 20 guard contactors

5.2.4.1 Verify 240V line voltage across guards

5.2.4.2 Verify 480V line voltage across mains

Date: 01/16/19 Initial: QL

5.3 Power-on initialization

5.3.1 Initialize power ramp in LabVIEW

5.3.1.1 Enter desired power on 'Heaters' tab, 72 kW_e (suggested). The desired thermal power is 51.6 kW_t, and the operator may adjust the electrical power as necessary.

5.3.1.2 Check 'Ramping', specify desired ramp up time period, 90 min

5.3.1.3 Enable 'Power On' button

5.3.2 Monitor & observe power ramp operation

5.3.2.1 Ensure power ramp executes and completes as intended

Date: 01/16/19 Initial: QL

5.4 Document any abnormalities, deviations, other findings discovered, or comments on tasks performed in task 5.0 Test day starting procedures

All OK

Date: 01/16/19 Initial: RL

6.0 Monitoring procedures during test

6.1 After completion of power ramp, and after thermal power in test section exceeds 25 kWt, enable **low power heat removal** loop by completing the following sequence. These steps will prevent the liquid inventory temperature from overshooting the target set point of 30°C while the facility and structure approach thermal equilibrium

6.1.1 Open chiller valves VH-05 and VH-06

6.1.2 On chiller front control panel, adjust process water set point to 70°F (~27°C)

6.1.3 Start chiller via front control panel switch

6.1.4 Open tank discharge port valve VT-01, tank sparger return port valve VT-03

6.1.5 Open HXG supply valve VH-01, close valve VH-02

6.1.6 Open HXG return valve VH-03, close valve VH-04

6.1.7 Supply 60 psig nitrogen to pneumatic HXG throttle valve VP-03

6.1.8 Actuate VP-03 to 14mA open set point via LabVIEW

6.1.9 Power on HXG pump PUMP-02; verify flow and check for any leaks

6.1.10 Adjust VP-03 until desired flow rate is achieved

Date: 01/16/19 Initial: RL

WATER NSTF BASELINE TEST PROCEDURE FOR DATA COLLECTION (NQA-1, TYPE A)	Identifier: ANL-NSTF-000000-TEST-021 Revision: 02 Effective Date: January 14th 2019	Page 15 of 24

6.2 Acceptance Criteria #1 – Test facility thermal equilibrium

6.2.1 Monitor system for steady state thermal operation, which is defined as a thermal power within the test section equal to the target ~~34.4 kW$_t$~~ 51.6 kW$_t$ +/-20% QL, 01/16/19

6.2.2 Adjust HXG flow loop parameters as necessary to maintain nominal liquid temperatures near 30°C. Do not allow liquid temperatures to fall below 20°C or above 50°C.

Thermal equilibrium acceptance criteria: Thermal power stable at ~ 51.8 kW$_t$
Riser inlet temperature stable at ~30.4°C

Time and date met: 7:00 am 01/17/2019

Lead experimenter signature: [signature] 01/17/19

6.3 Acceptance Criteria #2 – Test facility and heat removal steady-state

6.3.1 Adjust the HXG flow loop until power removed equals the thermal power within the test section via the following two parameters:

6.3.1.1 Gradually adjust VP-03 between 10% and 100% open

6.3.1.2 Adjust chiller process set point between 40°F and 80°F.

6.3.2 Continue to adjust HXG loop and monitor system until steady state acceptance criteria is met. This condition is defined by below variables that remain within the stated tolerance across a 2-hour period.

6.3.2.1 Inlet temperature of 30°C, maximum variation +/-1°C

6.3.2.2 Thermal power in test section equal to target ~~34.4~~ kW$_t$, 51.6 kW$_t$ maximum variation +/-20% QL, 01/16/19

6.3.2.3 Flow rate (value independent), maximum variation +/-10%

Steady-state acceptance criteria: Riser inlet temperature ~ 30.4°C within ±1°C
Thermal power ~ 51.8 kW$_t$ within ±20%
Flow rate ~ 1.34 kg/s within ±10%.

Time and date met: 11:30 am 01/17/2019

Lead experimenter signature: [signature] 01/17/19

6.4 Safe operating limits

6.4.1 Heater surface temperature. Monitor heater surface temperatures and ensure that the safety trip point of 650°C is not met. If these are approached, it will be up to the lead experimenter and project manager to use their discretion if testing shall resume as planned, conditions adjusted, or all-together cancelation of heater-power and conclusion of test. Enabling of forced pump may be initiated if deemed necessary to protect safety of structural components.

6.5 Logging of data

6.5.1 Ensure, at intervals of no more than 6 hours apart, that data logging file is being written. This can be verified by the "last modified" date in Windows Explorer or by checking that the file size is increasing with time. If any abnormalities are discovered, best efforts must be made to mitigate the situations without interrupting the quality of the test data. Document these, if any, discovered during testing.

6.6 Unexpected event response

6.6.1 In the event of non-emergency, unexpected events, document these in writing and take best-approach actions to mitigate the situations. Inform lead operator and test manager.

6.6.2 If thermal conditions on heated plate, heated plate thermocouples, or ceramic heaters are seemed unsafe during either axial cosine or radial azimuthal power shaping, lead operator may use discretion and return to linear power profile

6.7 Emergency event response

6.7.1 In the event of site-wide emergency (e.g. tornado or snow warming), proceed as expected and no human intervention is required

6.7.2 In the event of local, building 308 emergencies make best efforts to ensure safety of all personnel, and if deemed necessary, power down heaters and/or drain the entire loop.

6.7.3 In the event of loss of 120VAC power, resume test operations if local UPS back-ups are successfully able to maintain active power to ALL test related systems for the period of power outage. If 120VAC power is lost for a period greater than the capacity of UPS systems, active in-site monitoring may take place for a period of no more than 60 minutes. After this point, manual power down of heaters must be performed to prevent unmonitored damage to heater system.

6.7.4 In the event of 240/480 VAC power loss, test will be concluded and documented as unsuccessful.

6.7.5 In the event of water leakage, perform local mitigation is leak size is small (~0.25" diameter port); otherwise initiate emergency dump of loop inventory

6.8 Document any abnormalities, deviations, other findings discovered, or comments on tasks in 6.0 Monitoring procedures during test (if additional lines requirement, document continuation and location)

On 1/16/2019, at 17:50:37, observed partial load failure on heater zone Main 4-S

Total heater power reduced by ~1 kW

Date: 1/17/19 Initial: QL

WATER NSTF BASELINE TEST PROCEDURE FOR DATA COLLECTION (NQA-1, TYPE A)	Identifier: ANL-NSTF-000000-TEST-021 Revision: 02 Effective Date: January 14th 2019	Page 18 of 24

7.0 Test-day power down

7.1 LabVIEW power ramp

7.1.1 Initialize power ramp in LabVIEW

7.1.1.1 Enter desired power on 'Heaters' tab, '8 kW'

7.1.1.2 Enable 'Ramping'

7.1.1.3 Specify desired ramp up time period, '~~90~~ 120 minutes' DL, 01/17/2019

7.1.1.4 Enable 'Power On' button

7.1.2 Monitor & observe power ramp operation

7.1.2.1 Ensure power ramp executes as intended

7.1.2.2 Verify power ramp completes as intended

7.1.3 Upon conclusion of ramp, verify '0 W' power from controllers and then turn off electric heater power

7.1.4 Upon conclusion of ramp, turn off HXG system

7.1.5 Keep LabVIEW logging enabled an additional 4 hours

Date: 1/17 Initial: DL

7.2 Building and administrative tasks

7.2.1 Disable 20 Main and 20 Guard contactors

Date: 1/17 Initial: DL

7.3 Document any abnormalities, deviations, other findings discovered, or comments on tasks in task 7.0 Test-day power down

All okay

Date: 1/17 Initial: DL

8.0 **Post-test data achieve** *(to be performed within 4 hours after test conclusion)*

8.1 LabVIEW logging closure

8.1.1 Conclude logging on LabVIEW

8.1.2 Verify that all expected data files have been written (1 excel file per day)

Date: 1/17 Initial: DL

8.2 Backup and archive

8.2.1 Launch SyncToy and perform data sync. Verify that all appropriate test files have been copied onto remote system

Date: 1/17 Initial: DL

8.3 Document any abnormalities, deviations, other findings discovered, or comments on tasks in task 8.0 Post-test data archive

All okay

Date: 1/17 Initial: DL

9.0 Post-test, cold and zero-flow verification and survey

9.1 Physical configuration verification

9.1.1 Visually inspect the flange connections for evidence of leakage

9.1.2 Verify that all differential pressure taps, flow meter connections, and other visually viewable wiring or components remained in position

9.1.3 Confirm position of valves, and return them to fully open positions if not already

9.1.4 Perform general inspection for other abnormalities

Date: 1/21/19 Initial: QL

9.2 Verify that instrumentation did not exceed designed operating limits

9.2.1 Type-K thermocouples: 1,350°C

9.2.2 Type-T thermocouples: 400°C

9.2.3 RTDs: 350°C

9.2.4 Series 3051S2CA2A absolute pressure transmitters: 1,500 psia

9.2.5 Series 3051S2CD1A differential pressure transmitters: 2,000 psi

9.2.6 Series 3051S2CD2A differential pressure transmitters: 3,626 psi

9.2.7 Khrone 4000 flow meter: 65°C (ambient), 180°C (process)

Date: 1/21/19 Initial: QL

9.3 Continuity and general instrument check

9.3.1 Using LabVIEW, check for continuity on all 40 heater banks

9.3.2 Document any thermocouples or devices with saturated or '0' voltage signals

Date: 1/21/19 Initial: QL

9.4 Zero-flow post-check

9.4.1 Close the pneumatic valve at water tank outlet

9.4.2 Turn on the circulation pump to establish isothermal condition

9.4.3 Monitor thermocouples within LabVIEW. Verify that all read values nominally near ambient (variations should be minimal with isothermal condition reached). Document any abnormalities, and if open TC detected, document the location and channel

9.4.4 After confirming isothermal condition, turn off the circulation pump and reopen the pneumatic valve at water tank outlet

9.4.5 Establish zero-flow condition by closing riser inlet throttle valve

9.4.6 Monitor flow meter and differential pressure. Verify that readings are within 2% of pre-test ranges

Date: 1/24/19 Initial: QL

9.5 Repeat Section 8.0 Post-Test data archive to include cold and zero-flow survey data

Date: 1/24/19 Initial: QL

9.6 Document any abnormalities, deviations, other findings discovered, or comments on tasks in task 9.0 Post-test, cold and zero-flow verification and survey

New open TC Mini 8-2.25 (TC for guard 6-N)

ΔP1 has a change of ~ 1"WC from pre-test result

Date: 1/24/19 Initial: QL

10.0 Test Conclusion

Test Series & No: Data Quality 052

Test Dates: 1/16/2019 - 1/17/2019

Suggested Classification:
- [x] Fully within scope and procedures (submit for Type A evaluation)
- [ ] Areas outside scope or procedures (submit for trend evaluation)
- [ ] Failed (data not suitable for evaluation or use)

Date: 1/21/2019 Initial: DL

Work Performed by: Qiuping Lu — Date: 1/21/2019

Paul Growski — Date: 1/21/2019

Date:

Date:

Date:

Date:

Work Approved by: Paul Growski, Facility Manager — Date: 1/21/2019

Attachment documents (record description and page count below, then attached)

NA

Other comments or notes

N/A

Appendix A: Documentation of Test Training

Training shall consist of a complete walk-through of this test procedure with all Involved Personnel. The training is given by the lead experimenter.

Training given by: _____ Date: 1/24/19
Lead Experimenter

Training Recipients

Name (print)	Signature	Date
Dan Lisowski		1/24/19

Appendix B – Preliminary Test Acceptance Report, sample

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Nuclear Engineering Division

Run052 – Preliminary Test Acceptance Report

ANL-NSTF-000000-PTAR-017-NC

January 29th 2019

Prepared by: _____ 01/29/2019
Q. Lv, Lead Experimenter — Date

Reviewed by: _____ 29 JAN 2019
N. Bremer, Test Engineer — Date

Approved by: _____ 01/29/2019
D. Lisowski, NSTF Facility Manager — Date

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REVISION HISTORY

Rev	Date	Purpose	Authorization
0	01/29/2019	ANL-NSTF-000000-PTAR-017 release	D. D. Lisowski

Executive summary

The following preliminary test acceptance report (PTAR) provides a summary of the operating parameters, including results, of NSTF's Run052. The test objective was to conduct a single-phase baseline test case with a parametric variation of increased decay heat load. Previous test Run051 was performed at the full scale 'normal operation' power of 1.4 MW_t, while this test Run052 was performed at the full scale 'accident scenario' power of 2.1 MW_t.

The facility was setup at baseline geometry configurations: 80% initial tank inventory, riser discharge into tank center port, and 34.05-inch riser tube to heated wall setback distance. The testing parameters defined a nominal decay heat load of 2.1 MW_t, or 51.6 kW_t for the NSTF scale. The heater power was applied across a 90-minute power ramp, facility allowed to reach thermal equilibrium, and then the single-phase heat removal network was cycled until the test loop reached steady-state thermal and hydraulic flow conditions.

The operating window for active test operations (powered heaters) began at 08:22 on January 16th 2019 and spanned a period of 29 hours and 4 minutes. Two acceptance criteria were defined for the test:

1. Test facility thermal equilibrium
    a. Measuring test section energy balance within 20% of the target 51.6 kW_t goal
    b. Liquid inventory temperatures within 20 – 50 °C
2. Test facility and heat removal steady-state
    a. Riser inlet temperature of 30±1°C
    b. Measured system flow parameters remained within 10% of a mean value
    c. Thermal power within 20% of target 51.6 kW_t goal

All five-acceptance criteria were met across a period of at least 2 hours during stable, steady-state conditions, and observed between the hours of 07:30 and 11:30 on January 17th 2019.

One off-normal event occurred on the 1st day of heating; loss of heated zone Main4S. Primary measured parameters were monitored closely in the hours following, however the 2% reduction in power level proved to incur a negligible influence on the facility behavior, and moreover, negligible influence on the heated plate temperature profile. Thus, the impact onto the test objectives was non-significant and the lead experimenter deemed the test able to continue.

With completion of post-test data verification procedures and review of generated data sets, the test was found to be fully within the defined scope and set of procedures and thus is classified as successful and will be submitted for qualification for Type-A data.

Initial Operating Conditions

The operating state for the test, hereby referred to power modified baseline conditions, defines the configuration of facility in terms of a select number of user-adjustable components. The values for Test052 are summarized below in Table 1. Quality measurements of liquid inventory were made on test day and also provided in the table below.

Table 1: Initial boundary and operating conditions for Run052

Facility geometry	
Heated – riser spacing	34.05 inch
Chimney-tank inlet position	Center tank
Heat load:	
Power control	Burst firing
Distribution	Linear / uniform across 40 zones
Power level	71 kW_e
Valves	
Tank outlet:	Open
Loop inlet throttle:	Open
Riser(s) inlet:	All eight open
Differential pressure	
ΔP-01	Test section, ($DP_{20} – DP_{44}$)
ΔP-02	Lower chimney, ($DP_{22} – DP_{20}$)
ΔP-03	*n/a*
ΔP-04	Upper chimney, ($DP_{25} – DP_{22}$)
ΔP-05	Full loop ($DP_{25} – DP_{40}$)
Liquid Inventory	
Inventory fill amount	80% tank level, ~1,004 gal
Inventory fill level	84.25" (sight glass), 105.9" (ΔP)
Liquid conductivity	13.42 μS/cm
pH	7.72 –
Total chlorine	~0 ppm
Total hardness	~50 ppm

Pre-test Instrument verification

All instruments were verified and checked for working operation prior to initiating active heating and test operations. Of the instruments listed in Appendix E, the following were found to be inoperable or out of conformance.

1. Open TC(s)
   - SW6556-TC224
   - NW5616-TC204

Pre-test Facility Characterization and Zero Flow

The facility was configured for isothermal forced circulation by closing the tank outlet valve and enabling the circulation by-pass loop. Flow was established and allowed to circulate for a period of 15 minutes. Averaged facility parameters from measured instrumentation are provided in Table 2.

Table 2: Pre-test force circulation (isothermal) values for Run052

Flow Meters			Static/Differential Pressure			Liquid/Wall Temperatures	
Loop	2.86	kg/s	Inlet static	37.96	psia	Tank Inlet	22.16 °C
Riser01	0.35	kg/s	Tank gas	14.35	psia	Tank Outlet	22.18 °C
Riser02	0.36	kg/s	Tank level	105.15	inWC	Riser Inlet	22.17 °C
Riser03	0.35	kg/s	ΔP-01	-0.07	inWC	Riser Outlet	22.15 °C
Riser04	0.36	kg/s	ΔP-02	-0.29	inWC	Heater plate	21.76 °C
Riser05	0.36	kg/s	ΔP-04	-0.06	inWC	Ceramic heater	21.64 °C
Riser06	0.35	kg/s	ΔP-05	-0.37	inWC	West wall	22.40 °C
Riser07	0.36	kg/s					
Riser08	0.38	kg/s					

A zero-flow condition was then established by turning off the circulation pump, opening the tank by-pass, and closing the inlet throttle valve. All signals from flow devices were within expected ranges, and temperature gradients across the test structural non-significant, Table 3.

Table 3: Pre-test zero flow system parameters for Run052

Flow Meters			Static/Differential Pressure			Liquid/Wall Temperatures	
Loop	<0.01	kg/s	Inlet static	37.81	psia	Tank Inlet	22.31 °C
Riser01	<0.01	kg/s	Tank gas	14.34	psia	Tank Outlet	22.31 °C
Riser02	<0.01	kg/s	Tank level	105.08	inWC	Riser Inlet	22.11 °C
Riser03	<0.01	kg/s	ΔP-01	0.27	inWC	Riser Outlet	22.26 °C
Riser04	<0.01	kg/s	ΔP-02	-0.22	inWC	Heater plate	21.92 °C
Riser05	<0.01	kg/s	ΔP-04	0.11	inWC	Ceramic heater	21.63 °C
Riser06	<0.01	kg/s	ΔP-05	-0.29	inWC	West wall	22.44 °C
Riser07	<0.01	kg/s					
Riser08	<0.01	kg/s					

Test Log

A dated log of the primary procedural test events is provided below in Table 4. While a bank of heaters failed during the test, immediate measures were taken after the heater failure, and the impact on the test was observed to be negligible. The specific heaters that failed were the center row of Main-4S, and the impact was a reduction in total available heaters from *x*200 to *x*196, or a 2% reduction in available heater power.

Table 4: Procedural event log during Run052

Date	Time	Planned Event
01/15/19	15:21	Isothermal facility characterization
01/15/19	15:52	Zero flow verification
01/16/19	08:23	Start of test operations
01/16/19	08:25	Power-on of electric heaters and start of ramp
01/16/19	09:56	Conclusion of power ramp
01/16/19	13:07	Turning on chiller
01/16/19	17:50	Discovery of heater failure (Main4-S)
01/17/19	02:00 – 04:00	Acceptance Criteria #1 met
01/17/19	07:30 – 11:30	Acceptance Criteria #2 met
01/17/19	11:32	Begin power ramp down
11/29/18	13:26	Test Conclusion

Acceptance criteria

Prior to steady-state heat removal, a thermal equilibrium period was verified for a period of at least 2 hours. The required acceptance criteria (bold and underlined) was verified by confirming primary system variables did not change by more than 5% over this period, Table 5. Upon meeting this criterion, heat removal network was adjusted until the power removed equaled the power within the test section and the NSTF was allowed to naturally respond.

Table 5: Measured values across acceptance criteria window(s) for Run052

		Acceptance Criteria #1 *thermal equilibrium*		**Acceptance Criteria #2** *steady-state heat removal*	
Period Start Time/Date		02:00, 01/17/19		07:30, 01/17/19	
Period Duration		18.5 – 20.5 hr		23 – 27 hr	
Steady-State Parameter		***mean***	***% change***	***mean***	***% change***
Electric Power	kW_e	71.06	0.28%	71.06	0.31%
Heated Plate	°C	403.13	0.15%	403.73	0.06%
Riser Inlet	°C	30.82	1.82%	30.37	0.51%
Flow Rate	*kg/s*	1.34	4.29%	**1.34**	**3.74%**
Heated ΔT	°C	9.20	2.45%	**9.27**	**2.21%**
Thermal Power	kW_t	**51.57**	**3.09%**	**51.81**	**3.02%**

Post-test Instrument verification

All instruments were verified and checked for working operation 48 hours after concluding test operations. Zero flow conditions were re-established, and flow parameters found to be within 10% of pre-test values. Of the instruments listed in Appendix E, and excluding those listing in the pre-test instrument verification section, no new channels were found to be inoperable or out of conformance.

Included Attachments

Appendix A – Filled test procedure and test log, pp. 8 – 32

Appendix B – Software configuration and calibration records, pp. 33 – 35

Appendix C – Data plots, pp. 36 – 56

Appendix D – Design drawings, pp. 57 – 82

Appendix E – DAQ channel listing, pp. 83 – 90

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