Report on Year-3 of Water NSTF Matrix Testing

Two-Phase Parametric Test Series

Nuclear Science & Engineering

About Argonne National Laboratory

Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

DOCUMENT AVAILABILITY

Online Access: U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free at OSTI.GOV (<http://www.osti.gov/>), a service of the US Dept. of Energy's Office of Scientific and Technical Information.

Reports not in digital format may be purchased by the public from the National Technical Information Service (NTIS):

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312
www.ntis.gov
Phone: (800) 553-NTIS (6847) or (703) 605-6000
Fax: (703) 605-6900
Email: **orders@ntis.gov**

Reports not in digital format are available to DOE and DOE contractors from the Office of Scientific and Technical Information (OSTI):

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
www.osti.gov
Phone: (865) 576-8401
Fax: (865) 576-5728
Email: **reports@osti.gov**

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor UChicago Argonne, LLC, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or UChicago Argonne, LLC.

Report on Year-3 of Water NSTF Matrix Testing

Two-Phase Parametric Test Series

prepared by:

Qiuping Lv, Darius Lisowski, Matthew Jasica, Rui Hu, Adam Kraus, Zhiee Jhia Ooi,
Nathan Bremer, and Mitch Farmer

Nuclear Science & Engineering, Argonne National Laboratory

September 2021

Executive Summary

The Natural convection Shutdown heat removal Test Facility (NSTF) is large scale test facility constructed at Argonne National Laboratory to generate NQA-1 qualified validation data for passive decay heat removal systems in advanced reactor concepts. With support from the Department of Energy (DOE) offices of Advanced Reactor Technologies (ART) and Advanced Reactors Regulatory Development (RD), this facility reflects key features of a ½ scale, water-based, Reactor Cavity Cooling System (RCCS) and is intended to study the behavior, bound performance, and ultimately guide design decisions for passive decay heat removal systems. Since the facility also retains all aspects common to a fundamental boiling water thermosiphon, the generated experimental data sets are well poised to advance the understanding of fundamental natural circulation boiling and two-phase flow phenomena

This report serves as a summary of the experimental activities conducted during the programs third year of water-based test operations. Two-phase testing performed in prior years was conducted using a transient mode of facility operation, where the test progression results in a gradual reduction of system level due to loss of inventory from the system by natural boil-off. In this year's testing, a static mode of facility operation was introduced where the system level was maintained at a constant level by continuous refill of boil-off condensate back into the system. This modification allowed the facility to reach a true steady-state mode of operation where single-parameter variations could be studied for their influence on liquid temperatures, system pressures, flow behaviors, and other system parameters. With established confidence in the ability to repeat test conditions and maintain steady-state mode of facility operation, this third year of testing then embarked on a number of two-phase parametric test cases to further understand the thermal hydraulic behavior, two-phase instability phenomena, and decay heat removal performance of this scaled water-based RCCS test facility. Over a 12-month period, 250 hours of active heating was logged and 11 total matrix tests attempted; eight classified as *Successful* per NQA-1, and three as *Trending*.

In continuation from the previous year's campaign, testing was first performed within the inventory parametric series to examine the role of tank level. Testing resulted in the generation of experimental data at two-phase flow conditions with starting inventory levels of 80%, 70%, and 60%. A fourth test was performed using an initial inventory level of 55%, and through an accelerated drain process, allowed to extend into a depleted condition in an attempt to observe potential flow stagnation and cessation of heat removal function. Due to large voiding in the chimney and swelling of the heated leg, flow of the primary coolant continued to function even as the tank level fell 35-inches below the chimney discharge port within the tank. The test series examining the role of system pressures was then initiated, which varied the system pressure by altering the resistance of the steam discharge line off the gas space of the primary tank. Testing within the power parametric series was also performed which examined the role of integral power at levels corresponding to various ranges of prototypic decay heat loads in a prototypic full-scale reactor.

Finally, investigations were made on the role of loss coefficients along the primary piping, where a throttling valve was used to impose varying degrees of flow restriction at the inlet to the heated test section. With the facility operating in a static mode of operation with continuous refill of condensed boil-off, flow restrictions of up to 83% of the nominal flow area were imposed on the loop while operating at steady-state two-phase conditions. Initially, the increasing restriction at the header inlet resulted in a stabilization of system flow oscillations, however with further reduction in flow area, was followed by the onset of unstable Type-II density wave oscillations. As the flow area continued to be reduced, a second period of stability was reestablished. With the final round of late-stage restrictions imposed on the loss coefficient of the inlet header at levels above 80% of the initial flow area, highly unstable flow behavior was reintroduced with parallel channel interactions (PCI) and geysering flow phenomena.

Table of Contents

Executive Summary	i
1. Introduction.....	7
1.1. Program Objectives.....	9
1.2. Quality Assurance Program Plan	10
1.3. Previous Water Testing Accomplishments	10
2. Facility Design.....	11
2.1. Instrumentation	14
2.2. Facility Upgrades	17
2.2.1. Condensate Refill System	17
2.2.2. Upgrades for Pressure Parametric Testing	19
2.2.3. Upgrades for Accelerated Inventory Drain	21
2.3. Faulted Heaters in FY21	22
3. Testing Objectives	25
4. Testing Results.....	27
4.1. Inventory Parametric.....	27
4.2. Depleted Inventory Scenario.....	33
4.3. Pressure Parametric.....	41
4.4. Power Parametric	54
4.5. Refill Tests	62
4.6. Loss Coefficient Parametric.....	70
4.7. Summary of Completed Runs	86
5. Stability Analysis	88
5.1. Flow Instability Mechanisms	88
5.2. Hydraulic Analysis.....	89
5.2.1. Oscillation Period.....	89
5.2.2. Transit Times	93
5.3. Stability Mapping.....	96
6. Path Forward.....	98
Acknowledgements.....	99
References.....	100

List of Figures

Figure 1: Solid model render of complete water NSTF in laboratory high-bay	8
Figure 2: Cross section of single subassembly cooling panel unit.....	11
Figure 3: As-built dimensions of water NSTF, front (East facing) view	12
Figure 4: As-built dimensions of water NSTF, side (South facing) view	13
Figure 5: Location of void fraction sensors along upper chimney network.....	14
Figure 6: Gamma densitometer (top) and twin tip optical probe (bottom)	14
Figure 7: Overview of instrumentation locations on water NSTF	16
Figure 8: Illustration of condensate refill system.....	18
Figure 9: Condensate injection location and wash nozzle used. All dimensions are in units of in.....	18
Figure 10: Steam exit throttling valve location (left) and cross-section showing x_{13} turns closed (right). 19	
Figure 11: Projected valve flow area vs valve position, linear scale (top) and log scale (bottom).....	20
Figure 12: Accelerated inventory drain system	21
Figure 13: Location of faulted heater zones Guard-6N and Guard-2S	22
Figure 14: Temperatures of heated plate at baseline conditions with two faulted heaters.....	23
Figure 15: CAD drawing of water tank with levels shown for various fill levels. Dimensions in inches ..	27
Figure 16: Comparison of total loop flow rate for the inventory parametric series	30
Figure 17: Comparison of liquid riser inlet temperature for the inventory parametric series.....	30
Figure 18: Comparison of heated plate temperature for the inventory parametric series	31
Figure 19: Tank inventory at normal levels; low with flow due to swelling; Depleted with stagnation	33
Figure 20: Configuration of heat removal system during boil-off with external drain.....	34
Figure 21: Inventory removal rates due to natural boil-off and external drain, DataQuality069.....	36
Figure 22: Time history of flow rate and inventory level (relative to chimney inlet center), DataQuality069	36
Figure 23: Major events during DataQuality069. a) Start-up oscillations, b) Closed loop breaks and level falls below the chimney inlet, c) New instability mode with high frequency oscillations, d) Detail view of high frequency	37
Figure 24: Time history of heated section temperature rise; Front surface of heated plate	37
Figure 25: Time history of test section and tank inlet and outlet liquid temperatures, DataQuality069.....	38
Figure 26: Time history of differential pressure measurements, DataQuality069	38
Figure 27: Phase portraits of differential pressure vs flow rate, DataQuality069.....	39
Figure 28: Time history of void fraction, DataQuality069	40
Figure 29: Relationship between inventory level, relative to chimney inlet, and system flow rate.....	40
Figure 30: Steam throttle position: x_{12} turns closed with 11.3% remaining available flow area in Run067 (left), and x_{13} turns closed with 5.4% remaining available flow area in Run068 (right)	41
Figure 31: System pressure for the pressure parametric tests	43
Figure 32: Leveling off of tank gas space pressure in Run068.....	43
Figure 33: Triggering interval of condensate transfer pump, Run068.....	44
Figure 34: Tank level, steeper slope indicating increased steam generation rate, Run068.....	44
Figure 35: Comparison of total loop flow rate for the pressure parametric series	46
Figure 36: Comparison of void fraction for the pressure parametric series.....	46
Figure 37: Comparison of header inlet pressure for the pressure series	47
Figure 38: Comparison of liquid riser inlet temperature for the pressure series.....	47
Figure 39: Comparison of riser tube temperature for the pressure parametric series	47
Figure 40: Comparison of riser fin temperature for the pressure parametric series.....	48
Figure 41: Comparison of heated plate temperature for the pressure series	48
Figure 42: Comparison of ceramic heater temperature for the pressure series	48

Figure 43: Comparison of tank inventory level for the pressure parametric series	49
Figure 44: Total loop flow rate in Run066	53
Figure 45: Tank gas space pressure in Run066.....	53
Figure 46: Liquid RTD temperatures in Run066	53
Figure 47: Comparison of total loop flow for the power parametric series	56
Figure 48: Comparison of tank gas pressure for the power parametric series	56
Figure 49: Comparison of header inlet pressure for the power parametric series.....	56
Figure 50: Comparison of liquid riser inlet temperature, power parametric.....	57
Figure 51: Comparison of heated section ΔT , power parametric	57
Figure 52: Comparison of riser wall temperature, power parametric	57
Figure 53: Comparison of riser fin temperature, power parametric.....	57
Figure 54: Comparison of heated plate temperature, power parametric	58
Figure 55: Comparison of ceramic heater temperature, power parametric.....	58
Figure 56: Comparison of void fraction, power parametric.....	58
Figure 57: Comparison of tank inventory level, power parametric	58
Figure 58: Issues with DP measurement in Run065	61
Figure 59: Comparison of total electric power for the refill tests	64
Figure 60: Comparison of heated plate temperature for the refill tests.....	64
Figure 61: Comparison of liquid riser inlet temperature for the refill tests	64
Figure 62: Comparison of tank gas space pressure for the refill tests.....	65
Figure 63: Comparison of header inlet pressure for the refill tests.....	65
Figure 64: Comparison of total loop flow for the refill tests. Data for Run071 in the right plot is shifted in time to aid in comparison.....	65
Figure 65: Corrected tank inventory level in Run064.....	66
Figure 66: As-measured and temperature compensated level from static inlet pressure, Run064	66
Figure 67: As-measured and temperature compensated level from static inlet pressure, Run071	67
Figure 68: Tank level corrected for influences from added gas space pressure, Run064.....	67
Figure 69: Tank level corrected for influences from added gas space pressure, Run071	68
Figure 70: Throttle valve at inlet header, full-bore 4.0" ball valve.....	70
Figure 71: Jamesbury valve flow area and C_v versus valve handle position in degrees	71
Figure 72: Rate of boil-off generation and condensate refill flow rate during DataQuality071	71
Figure 73: Throttle stages during DataQuality071.....	73
Figure 74: Time history of flow rate and valve position at throttling stages 1-10, DataQuality071	74
Figure 75: Heated plate versus flow area restriction.....	77
Figure 76: Loop flow and heated section ΔT versus flow area restriction.....	78
Figure 77: Mean and variation in flow rates of eight riser channels versus flow area restriction,	78
Figure 78: Chimney void fraction versus available flow area, DataQuality071	79
Figure 79: Stages of throttling in DataQuality071, detail of system loop flow rate	80
Figure 80: Stages of throttling in DataQuality071, detail of individual riser flow	81
Figure 81: Stages of throttling in DataQuality071, detail of chimney liquid temperatures	82
Figure 82: Stages of throttling in DataQuality071, detail of differential pressure.....	83
Figure 83: Stages of throttling in DataQuality071, detail of chimney void fraction	84
Figure 84: Contour plots of test section fluid temperatures across full length and width of 8-riser tube cooling panel. A. referenced to Stage 1, B.E. referenced to PCI instabilities in Stage 10.....	85
Figure 85: Loop flow oscillation period comparison for inventory parametric	91
Figure 86: Loop flow oscillation period comparison for pressure parametric.....	91
Figure 87: Loop flow oscillation period comparison for power parametric	91
Figure 88: Loop flow oscillation period comparison for refill tests	91
Figure 89: Fundamental frequencies in the upper chimney pressure drop, inventory parametric tests	92

Figure 90: Fundamental frequencies in the upper chimney pressure drop, pressure parametric tests	92
Figure 91: Fundamental frequencies in the upper chimney pressure drop, power parametric tests	92
Figure 92: Fundamental frequencies in the upper chimney pressure drop, refill tests.....	92
Figure 93: Fluid transit time in the channel vs oscillation period, inventory parametric tests	94
Figure 94: Fluid transit time in the channel vs oscillation period, pressure parametric tests	94
Figure 95: Fluid transit time in the channel vs oscillation period, power parametric tests.....	94
Figure 96: Fluid transit time in the channel vs oscillation period, refill tests	94
Figure 97: Fluid transit time of system vs period, inventory parametric	95
Figure 98: Fluid transit time of system vs period, pressure parametric	95
Figure 99: Fluid transit time of system vs period, power parametric	95
Figure 100: Fluid transit time of entire system vs oscillation period, refill tests.....	95
Figure 101: Subcooling and Phase Change stability mapping, stages in DataQuality071.....	97

List of Tables

Table 1: Summary of instrumentation on water-based NSTF	14
Table 2: Matrix tests affected by heater fault, Year-3	24
Table 3: Inventory volumes at fill levels	27
Table 4: Liquid height in tank at fill levels	27
Table 5: Initial boundary and operating conditions for inventory parametric testing.....	29
Table 6: Comparison of acceptance criteria for the inventory parametric series.....	31
Table 7: Summary of primary measurements across inventory parametric tests, average over 6-min window toward the end of the 4-hour acceptance period	32
Table 8: Initial boundary and operating conditions for pressure parametric testing.....	42
Table 9: System pressure for the pressure parametric testing.....	42
Table 10: Comparison of acceptance criteria for the pressure parametric series.....	50
Table 11: Summary of primary measurements across pressure parametric tests, average over 6-min window toward the end of the 4-hour acceptance period	51
Table 12: Initial boundary and operating conditions for power parametric testing	54
Table 13: Comparison of acceptance criteria for the power parametric series	59
Table 14: Summary of primary measurements across power parametric tests, average over 6-min window toward the end of the 4-hour acceptance period	60
Table 15: Comparison of acceptance criteria for the refill tests	68
Table 16: Summary of primary measurements in refill tests, average over 2-hour acceptance period	69
Table 17: Summary of restricted inlet test cases performed in Year 3	72
Table 18: Summary of stages for restricted inlet throttle, DataQuality071	73
Table 19: Summary of loop parameters during throttling of DataQuality071.....	77
Table 20: Summary of testing performed on water-based NSTF during Year 3 of program activities	87
Table 21: Summary of the leading frequencies, upper chimney ΔP Fast Fourier Transform.....	90

1. Introduction

The Natural convection Shutdown heat removal Test Facility (NSTF) at Argonne National Laboratory (Argonne), Figure 1, is a large-scale test facility designed and constructed to study the thermal hydraulic performance of passive safety systems for advanced nuclear reactor concepts. This Department of Energy-sponsored program was first initiated in 2005 and has included both experimental and computational activities. The first iteration of the facility, running from 2010 through 2016, focused on the behavior and performance of an air-based Reactor Cavity Cooling System (RCCS) concept [1]. This design of the NSTF reflected a ½ scale and 19° sector slice of the design proposed by General Atomics for use in their 350 MW_t MHTGR. Over this period, the program completed over 2,250 hours of active test operations and 16 successful test runs. Details of the air-based program, including design bases testing results, and project conclusions, can be found in previously published reports [2]. 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. This water-based design was designed to align with major features of the Framatome (formerly AREVA) 625 MW_t SC-HTGR RCCS. Details of the design bases for the conceptual prototype, along with scaling and preparation tasks, can be found in earlier reports [3], [4]. A design report of the as-built, water-based facility, along with new program requirements and testing plan can similarly be found in previous reports [5].

In this report, accomplishments and results from the experimental testing performed between 2020 and 2021 (Year-3 of the water-based program) are presented. An introduction and background are first presented in brief, followed by a high-level description of the test facility design and instrumentation relevant to the results presented, followed by an overview of the testing objectives for the third year of the program. The results from the completed test cases are then presented in detail, including description of preparation activities, overview of the specific test procedure, as-measured system parameters, and observed facility behavior. A large focus has been placed on the quantification and understanding of the stability while operating in a two-phase mode of flow operation, thus an analysis is also provided on the initiating mechanisms and resulting phenomena associated with these instabilities. This generated data, presented results, and supporting analysis, are intended to advance the knowledge of the instability mechanisms, and ultimately, to predict the performance of a full-scale RCCS system.

Figure 1: Solid model render of complete water NSTF in laboratory high-bay

1.1. Program Objectives

Since 2005, the NSTF program has supported the DOE vision to provide US vendors with data suitable for characterizing the RCSS concept for passive decay heat removal. During that time the facility has addressed both air-based and water-based RCCS concepts. The program also aims to advance the basic understanding of natural phenomena, which is an integral feature of many advanced safety concepts. By coupling large scale, integral-level observations with local high-resolution measurements, the NSTF intends to create a shift from uncertainty to predictability, allowing industry realization of a successful decay heat removal solution.

The purpose of the generated data is centered on two industry needs: validation of codes that can be used in licensing and optimization of the advanced conceptual designs. These demand a diverse set of requirements for the experimental capabilities and operating conditions, and furthermore, create a need for applicability to full scale systems if the data is to be relevant. Thus, a rigorous scaling methodology and validation process is required to support the provided data. The scaling basis and similarity relationships have been carefully derived to ensure preservation of key thermal hydraulic behaviors [6] from full scale conditions [7], and are primary driving factors in providing a technical basis for extrapolation of testing results to real conditions. The matrix tests performed in the third year of testing and those planned for future years has been informed by feedback from industry and government stakeholders on key technical needs.

To successfully generate data that is relevant to nuclear codes and industry designers, the data must be produced within a controlled, traceable, and NQA-1 compliant program. Furthermore, the data must encompass a wide range of thermal hydraulic phenomena relevant to potential reactor designs. Measurements of integral behavior such as system flow rate and heated section temperature rise become highly valuable only if they can be coupled with high fidelity measurements of local parameters. Integrated systems codes such as RELAP5 and MELCOR are currently the standard for licensing; however, computational fluid dynamics (CFD) codes continue to mature and are now playing major roles in advancing model development and phenomenological understanding. These advanced codes demand higher-resolution data and must be considered when determining the overall instrumentation suite. Within the NSTF specifically, computational efforts have been active since the program's inception and will remain an area of continued development as experimental data becomes available. Efforts to-date on modeling of the water-based facility can be found in published reports [8] - [11].

Finally, the ability to study design optimization hinges on successful engineering and review processed of facility design. The foresight to include flexibility in facility operation and configuration is a crucial aspect in determining an experimental program's long-term sustainability and relevance. The ability to

adapt to new discoveries, changes in industry requirements and trends, or currently-unforeseen scenarios directly supports this design optimization objective and has been given a high priority in early design stages. Many of the parametric series performed in this third year of testing were enabled by modifications over the past year to the NSTF loop or supporting systems, highlighting the essential role of designed-in flexibility.

1.2. Quality Assurance Program Plan

The research and development activities of this experimental program are under the control of an NQA-1 compliant quality assurance program plan (QAPP). This 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 [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, are conducted on a regular basis throughout the entirety of the water-based testing program.

1.3. Previous Water Testing Accomplishments

Initial operation of the water-based NSTF facility began in 2018, with this first year of testing focused on initial qualification and characterization of the facility. These tests included the completion of four bake-out and shakedown test procedures, six single-phase heated test cases, three isothermal characterization tests, and one two-phase demonstration. The second year of testing saw five matrix tests focused on baseline tests to establish a common reference for two-phase boiling operation. In total, 605 hours of active test operations were logged across 27 separate test operations.

This baseline condition was defined as a nominal decay heat load of 51.6 kW_t, at an initial fill level of 80% of the primary inventory tank (approximately 3800 liters of liquid inventory), riser discharge configured into the tank center port, and a cooling panel to heated wall setback distance of 86.5 cm. Inventory was allowed to boil off through an auxiliary heat removal system into collection reservoirs. To establish the repeatability of the thermal hydraulic behavior of the NSTF system at these conditions, four tests were performed at these standard two-phase baseline conditions. Following these, the first test of a parametric study examining variations in the initial fill level was conducted at a fill level of 70% with boil off. Details of previous tests, including results and observations, from the first [13] and second [14] years of operation be found in previously published reports by the program team. An extension of this series is among those test series conducted in the third year of testing.

2. Facility Design

The water NSTF reflects a $\frac{1}{2}$ axial scale and 12.5° sector slice of the primary design features of a full scale RCCS concept. In its current configuration, the test facility stands at a total height of 59.2-ft (18.1-m). The main components of the facility include an eight-riser cooling panel test section and a water storage tank. The test section extends 30-ft (9.2-m) in total length, constructed from eight 1.5" Schedule 160 stainless steel 316L pipes that are joined to form the cooling panel by $\frac{5}{16}$ " thick steel fins, Figure 2. The fins extend only along a 6.75-m length, reflecting the portion located within bounds of the heated cavity. The tank features a height-to-diameter ratio of 2, is able to hold a minimum 1,000-gallon capacity, includes dual side inlet port locations, and can be pressurized to 2 atmospheres (gauge). The test section and the water tank are connected through 4.0" Schedule 40 stainless steel 316L piping. The as-build NSTF is shown in Figure 3 and Figure 4, with details of the facility and design available in previous reports [5], [14].

Figure 2: Cross section of single subassembly cooling panel unit

Figure 4: As-built dimensions of water NSTF, side (South facing) view

2.1. Instrumentation

A suite of sensors within the water NSTF allow measurement of pertinent thermal hydraulic behaviors 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. Two devices are used for quantitative measurement of the void fraction, and include both point (local) and bulk (volumetric) void fraction, Figure 5 and Figure 6. Both are installed on the vertical chimney section, immediately prior to the inlet of the water storage tank, in a best attempt to capture the full network two-phase flow patterns. A third device, a transparent sight glass, Model 255 from Ernst Co., is planned and will provide means for visual or qualitative observation of the two-phase flow regimes. At the time of this report, installation of the sight glass has been delayed due to concerns of personnel safety and co-located equipment. A high-level summary of all the employed sensors is provided in Table 1, a facility diagram of installed locations in Figure 7, and complete details in previous reports [5].

Figure 5: Location of void fraction sensors along upper chimney network

Figure 6: Gamma densitometer (top) and twin tip optical probe (bottom)

Table 1: Summary of instrumentation on water-based NSTF

<u>Measurement</u>	<u>Sensor Type</u>	<u>Location</u>	<u>Qty.</u>	<u>Mfg.</u>	<u>Model</u>	<u>Range</u>
Flow rate	Magnetic	Inlet header	x1	Krohne	Optiflux 4000	± 5 kg/s
Flow rate	Magnetic	Inlet riser	x8	Krohne	Optiflux 4000	± 1 kg/s
Flow rate	Gear type	Refill line	X1	Bell Flow	MC5-SS-HP-2	0 – 0.30 GPM
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	± 25 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

Figure 7: Overview of instrumentation locations on water NSTF

2.2. Facility Upgrades

To support the planned objectives and test conditions in Year-3 of the water-based testing program, a number of facility modifications and upgrades were performed. To support two-phase flow operation at true steady-state thermal and hydraulic conditions, a condensate refill system was designed and added to allow continuous replenishment of lost inventory due to boil-off. For the pressure parametric test cases, a new gate-style throttle valve was added to the steam line off the dome of the primary storage tank. Finally, to accelerate the total rate of inventory loss, an external drain system was incorporated to provide a low-flow rate means for liquid removal from the primary storage tank. Details of these are included in the following section, which describe the various equipment and control systems integrated into the test facility.

2.2.1. *Condensate Refill System*

A condensate refill system was designed and integrated into the NSTF, Figure 8. The generated steam is first routed to the heat exchanger/condenser, where it is condensed into liquid. To avoid back pressure caused by the condensate slug, the condensate free falls to an intermediate tank that is located right underneath the heat exchanger/condenser, connected through a rigid 1-inch clear PVC pipe. The intermediate tank is connected to the atmosphere through a HEPA filter to maintain a constant pressure boundary. The condensate is then transferred from the intermediate tank back to the NSTF water tank by a DC-powered pump that is equipped with a drive for flow adjustment. During the test, the condensate refill flow rate is constantly adjusted to maintain a constant level in the intermediate tank, and thus constant level in the NSTF water tank. The liquid level in both the intermediate tank and NSTF water tank are monitored through differential pressure level sensors. The lower inlet port of the water tank corresponding to 5% inventory level is utilized as the injection port, with a ½” stainless steel tubing penetrating through the covering blind flange, Figure 9. At this location within the tank is a wash nozzle with several 0.07” diameter to gradually disperse the refill flow, minimizing impact to the system and facilitating mixing with the tank bulk inventory.

Figure 8: Illustration of condensate refill system

Figure 9: Condensate injection location and wash nozzle used. All dimensions are in units of in.

2.2.2. Upgrades for Pressure Parametric Testing

To perform the pressure parametric testing proposed in the test matrix, upgrades were made to adjust and control the system pressure of NSTF. Accumulators are typically used to pressurize and maintain pressure of hydraulic systems. However, considering the low-pressure range (up to 2 bar above atmospheric pressure) involved in the NSTF, accumulators were not considered a good option. Instead, a throttling valve was employed in the steam exit line to adjust the resistance for the steam flow, which allows control of the amount of steam able to escape the primary tank into the heat exchanger loop, and thus varying the NSTF system pressure. A full port gate valve was installed prior to the inlet of the heat exchanger, Figure 10. The gate valve features a total of $\times 15\frac{5}{6}$ turns from fully open to fully close position. With the first $\times 1\frac{1}{2}$ and last $\times 1\frac{1}{2}$ turns not effectively changing the gate position relative to the flow path, the total turns available for reducing the flow area from full open to full closed is approximately $\times 13$. Considering the dimensions and position of the gate and internal bore, hand calculations were used to find the intersection areas and determine the area available for flow as a function of valve position, Figure 11. During a test, the throttling valve was preset to a partially closed position before start of heating, and the system pressure would be let naturally build up once boiling started, to minimize external disturbances to the system.

In addition to the upgrade of the steam exit throttling valve, the as-built NSTF was thoroughly reviewed to ensure the system could withstand the elevated pressure and temperatures. As per the as-installed design and as a safeguard against accidental overpressure, a pressure relief valve set to 1 bar above atmospheric pressure was installed in the steam line. If higher pressures were needed, this could be exchanged with a pressure relief valve rated for higher pressure. For the major components including the test section, water tank, and connecting piping, the elevated pressure and temperatures were already considered during design phase. Therefore, the focus was on the instrumentations and accessory parts. Upon completion of the review, only the sight glass for the side view port of the water tank was identified and upgraded.

Figure 10: Steam exit throttling valve location (left) and cross-section showing $\times 13$ turns closed (right)

Figure 11: Projected valve flow area vs valve position, linear scale (top) and log scale (bottom)

2.2.3. Upgrades for Accelerated Inventory Drain

One of the proposed matrix tests is a tank inventory depletion test to investigate the system performance of NSTF as the inventory level continuously drops. Due to the large capacity of the primary water tank (1000-gallon), the process would be time consuming if solely relying on natural boil-off. Therefore, an accelerated inventory drain was proposed for such a testing, and an upgrade for that was integrated into NSTF this past year. The accelerated inventory drain system draws near-saturated water inventory from the primary water tank through its lower inlet port. The hot inventory is cooled inside a plate-type heat exchanger to approximately room temperature before entering the drain system, Figure 12. The heat exchanger uses the building chilled water as the cooling fluid, approximately 10°C, which is controlled by a manual ball valve and monitored through a digital turbine flow meter. For the hot side, the inventory drain flow is driven and controlled by a DC-powered pump and monitored by a turbine flow meter. This accelerated inventory drain system was proven to function well during the inventory depletion test Run069.

Figure 12: Accelerated inventory drain system

2.3. Faulted Heaters in FY21

While conducting test operations for DataQuality065, a fault was observed that resulted in the failure of control zones Guard-2S and Guard-6N, Figure 13. The loss of these zones affected the total power delivery by approximately 800W, or 1.12% percent. Operators first noticed the issue by discrepancies in the impedance measured in two of the forty power controllers. The operators were able to make corrections and maintain the total power by enforcing adjustments on the remaining distribution to account for the affected zones. Following test conclusion and power shutdown, facility was placed into a maintenance configuration with 240/480VAC systems de-energized and electrical systems opened for access. It was determined that the two affected heaters were operable, but their power leads had shorted to ground. Given the extended insulation paneling covering the heaters and power leads, the location or source of fault could not be located. The event likely occurred during or after the shutdown process of DataQuality064, however the exact cause is still not known.

Figure 13: Location of faulted heater zones Guard-6N and Guard-2S

The effort to dismantle, expose, repair, and re-assembly would require an extended period, thus a consideration was made to evaluate the feasibility of continued testing without the use of these two heater zones. At baseline test conditions, the supplied electric power totals 72.0 kW_e and is delivered to 200 individual heaters that are grouped within 20 control zones. Of the individual heaters, 160 are grouped within the Main zones, and 40 within the Guard zones. Based on observations from early bake-out and shakedown testing, the Guards are adjusted to deliver only 50% of the power that is sent to any given Main heater, and furthermore, the upper guards are adjusted to power only 40% power. This adjusted distribution ensures a uniform temperature across the width of the heated plate. Thus, the overall impact from the loss

of two Guard zones is minor and considerations were made to continue test operations with the remaining heater banks. With the affected Guard-2S and Guard-6N zones accounting for <2% of the total power delivery, the remaining zones could be adjusted to maintain equal integral power levels as previous test scenarios, thus preserving the programmatic requirement. However, there was an additional concern of maintaining sufficient temperature uniformity across the front of the heated plate, which stems from programmatic requirements to represent prototypic boundary conditions. Lastly, there were structural concerns of material warping or cracking that could damage the 1-inch steel plate.

As part of this evaluation, a dry heat-up test was performed to assess the impact of the faulted heater zones, and if the heated plate could still able to maintain adequate uniformity of its thermal profile. Testing was completed over the course of several days at varying power levels, and the team were able to confirm that at steady-state, the heated plate maintained adequate temperature uniformity within acceptable tolerances <15°C across the width, Figure 14. A minor modification to the testing procedure has been proposed, which extends the initial power-on heating duration from 90 minutes to 150 minutes. This extended ramp up period provides a slower rate of heat application and thus allows more time for conduction across the cold spots.

Figure 14: Temperatures of heated plate at baseline conditions with two faulted heaters

With confirmation that continued testing without the use of the two Guard zones would be acceptable, testing continued along the planned matrix series. A summary of the affected matrix tests conducted in Year 3 of the NSTF program is provided in Table 2. Given the facility has operated for nearly 3 years with the current infrastructure, a partial disassembly, inspection, and maintenance period is timely and required. This shutdown, anticipated to extend 4-months, will be used to repair the faulted Guard heaters, examined the cavity interior, and collect emissivity measurements of the test section and heated surfaces.

Table 2: Matrix tests affected by heater fault, Year-3

Test	Dates	Conducted with faulted heaters?
DataQuality061	09/23 – 24/2020	No
DataQuality062	11/12 – 13/2020	No
DataQuality063	12/10 – 11/2020	No
DataQuality064	01/12 – 13/2021	No
DataQuality065	02/03 – 04/2020	Yes
DataQuality066	03/10 – 11/2021	Yes
DataQuality067	04/07 – 08/2021	Yes
DataQuality068	05/06 – 07/2021	Yes
DataQuality069	06/10 – 11/2021	Yes
DataQuality070	07/07 – 08/2021	Yes
DataQuality071	08/11 – 12/2021	Yes

3. Testing Objectives

Having established confidence in the operator and facility's ability to repeat baseline conditions, the third year of testing explored a range of two-phase parametric tests to more fully understand the thermal hydraulic phenomena that may develop in a water-based RCCS. This baseline "accident scenario" is based off a heat load that matches vendor specific power levels anticipated during transient, design basis accident conditions [7]. The initial baseline scenario established in year two of testing corresponds to a full-scale decay heat load of 2.1 MW_t into the RCCS; at the reduced scale for NSTF this heat load is 51.6 kW_t. A primary inventory tank initial level of 80% was established as the baseline condition in year two of testing. The piping network configuration remained unchanged from the two previous years.

Two-phase tests can be divided into two categories with respect to the inventory level—static or dynamic tests. In the static condition, an initial tank level is set and maintained throughout the test (such as through the condensate refill system, Section 2.2.1). A dynamic, or transient, test will begin with a set inventory level but will allow that level to change, either through natural boil-off or accelerated draining (Section 2.2.3). Steam condensate is typically collected throughout the test to track the steam generation rate and inventory loss. During the static test, the overarching operational objective is to approach true steady-state thermal and hydraulic natural circulation conditions. In a dynamic test, where true steady-state is not achievable due to the constantly-changing tank inventory level, the operational objective is a quasi-steady-state of sustained stable operation. Stable operation is indicated by measurements such as flow rate, rate of change in the tank level, or condensate generation. In either case, two-phase instabilities may or may not be suppressed, depending on the operating parameters. In general, the target minimum period of operation was four hours to allow for true or quasi-steady conditions to develop before introducing variations, as in some parametric tests.

This third year of matrix testing in the water-based NSTF introduced a range of parametric tests designed to expand the applicability of NSTF-generated data to a broad set of scenarios and to better understand operating regimes of stability and instability. The starting inventory level tests were continued from year two of testing, generating data on starting inventory levels of 80%, 70%, and 60%. An additional test was starting at an initial inventory level of 55% and with an accelerated drain (Section 2.2.3) was conducted to model a scenario where the inventory continues to deplete without intervention, attempting to observe potential flow stagnation. A pressure parametric series comprising of four pressures was conducted by altering the resistance of the steam line with a gate valve. A new two-phase baseline at the same power parameters but at a tank inventory level of 70% was used to adjust the duration of two-phase oscillations. A third series of tests, also at the 70% tank inventory baseline, examined variations in power level of the cavity heaters, corresponding to different decay heat loads or accident scenarios in a full-scale reactor.

These series all fell into the transient test category. In addition, two successful static inventory level tests at the 70% tank inventory level baseline were conducted employing the condensate refill system described in Section 2.2.1. Confirmation of the successful operation of the refill system enabled one more parametric series investigating variations of the loss coefficient in the primary inventory loop, accomplished by adjusting the position of the inlet header throttling valve.

The inherent sensitivity of natural circulation systems can invoke a wide range of thermal hydraulic phenomena with minimal variations in operating conditions. This is due to the complex and uncertain thermal hydraulic behavior commonly associated with two-phase phenomena. Thus, attention was given to limiting deviations to single parameters and otherwise repeating exact test conditions as well as the ability to generate similar results. Note that results were not expected to be identical across repeated tests, instead, analysis was used to establish statistically significant similarity and confidence in achieving similar operation and behavior across separate data sets.

4. Testing Results

In the third year of testing, eleven DOE matrix tests were conducted on the NSTF, DataQuality061 - DataQuality071, and are described in detail in the following section. Eight of these tests were conducted in a transient inventory mode and represent a range of parametric studies including inventory loss, pressurization, heating power, and loss coefficient, while three of these tests explored steady-state inventory conditions utilizing the inventory refill system. Note, the terms *DataQualityNNN* and *RunNNN* used interchangeably throughout the context of this report, including associated figures and tables.

4.1. Inventory Parametric

As proposed in the original test matrix [15], the inventory parametric series include three subcategories: a) Varying initial tank volumes; b) Accelerated tank inventory loss; and c) Full tank depletion. In FY20, the effort on the inventory parametric was focused on subcategory a), with one initial tank inventory parametric test case conducted (Run060), along with two reference baseline tests (Run057 and Run059). The baseline tests Run057 and Run059 employed an initial tank inventory level of 80%, while test Run060 was a repeat of the baseline with a reduced initial tank inventory of 70%, as shown in Figure 15 and itemized in Table 3 and Table 4. The details of the test results and comparison can be found in previously works [14].

Figure 15: CAD drawing of water tank with levels shown for various fill levels. Dimensions in inches

Table 3: Inventory volumes at fill levels

Tank Fill	Inventory, gal	
	Tank	Full System
80%	901	1004
70%	788.5	891.5
60%	676	779
50%	563	666
40%	450	550
20%	225	321

Table 4: Liquid height in tank at fill levels

Tank Fill	Level Reference, inch	
	Sight Glass	ΔP Level
80%	84.5	106.0
70%	73.0	94.5
60%	61.5	83.0
50%	50.0	71.5
40%	38.5	60.0
20%	15.5	37.0

In this year of testing, the investigation into the inventory parametric series was continued with test Run061, starting at a tank inventory of 60%. The same procedure as in the previous inventory parametric tests was followed, with the system configuration set at baseline conditions. The heater power was applied across a 90-minute automatic power ramp and then maintained constant to allow heating up of the NSTF facility and water inventory. Upon reaching saturation, boiling/flashings of water was first observed in the upper chimney region, and sustained for over 4 hours, followed by power ramp down.

The effects of the initial tank inventory level on the system performance is examined by a comparison of Run059, Run060 and Run061 results, Figure 16 - Figure 18. As the initial tank inventory increases, and thus the associated thermal inertia, more energy is deposited into the liquid inventory, causing a delay in the initiation of two-phase boiling/flashings, Figure 16. In addition, the two-phase flow oscillations damp out quicker with less initial tank inventory. The initial tank inventory does not significantly affect the single-phase flow prior to initiation of boiling, with a standard deviation less than 6% over 2 – 10 hours of the transient, Figure 16. As seen, the detected initiation of the natural circulation does not exhibit a definitive dependence on the initial tank level, Figure 16, which could be due to the difference in the initial liquid temperature profiles in the vertical legs. In addition, the EM flowmeter used for the system flow measurement has a minimum uncertainty of 1 mm/s, making detection of small flows intrinsically not as reliable as measurement of developed flows.

The initial tank inventory affects the hydrostatic head within the loop, and thus the saturation temperature of the liquid when boiling/flashings initiates. However, for the present inventory parametric series, the difference in the initial tank inventory is not sufficient to cause an appreciable effect in liquid saturation temperature. Plotted in Figure 17 are the liquid riser inlet temperatures for the three inventory parametric tests, with x axis normalized to the time of initiation of boiling/flashings. As seen, despite of the difference in the initial inventory temperature (lowest in Run059), the liquid temperature upon initiation of boiling/flashings increases to a common value between the three runs. For the heated plate, its temperature is more sensitive to the power source instead of the heat sink temperature [13]. Upon initiation of boiling/flashings, the heated plate temperature shows a slight positive correlation with the starting inventory level; however, the deviation is within 1% over the entire transient (0 - 15 hours) when the initial difference is accounted for, Figure 18. The measured system values during the two-phase quasi-steady state for the inventory parametric tests are summarized in Table 6 and Table 7.

Table 5: Initial boundary and operating conditions for inventory parametric testing

Facility geometry	Run057	Run059	Run060	Run061
Heated – riser spacing	34.05 inch			
Chimney-tank inlet position	Center tank at 50"			
Heat load:				
Power control	Burst firing			
Distribution	Linear / uniform across 40 zones			
Power level	72 kW _e			
Valves				
Tank outlet:	Open			
Loop inlet throttle:	Open			
Riser(s) inlet:	All eight open			
Riser(s) outlet:	All eight open			
Differential pressure				
ΔP-01	Test section, (DP ₂₀ – DP ₄₄)			
ΔP-02	Lower chimney, (DP ₂₂ – DP ₂₀)			
ΔP-03	Mid chimney, (DP ₂₃ – DP ₂₂)			
ΔP-04	Upper chimney, (DP ₂₅ – DP ₂₃)			
ΔP-05	Full loop/water tank (DP ₂₅ – DP ₄₀)			
Liquid Inventory				
Tank fill, inches	105.94-in	105.64-in	94.50-in	82.91-in
Total system inventory	~1,004 gal	~1,004 gal	~879 gal	~676 gal
Liquid conductivity	~ 31 μS/cm	~ 46 μS/cm	~ 29 μS/cm	~ 28.2 μS/cm
pH	7.02	6.81	7.01	8.20

Figure 16: Comparison of total loop flow rate for the inventory parametric series

Figure 17: Comparison of liquid riser inlet temperature for the inventory parametric series

Figure 18: Comparison of heated plate temperature for the inventory parametric series

Table 6: Comparison of acceptance criteria for the inventory parametric series

		Run059, 80%			Run060, 70%			Run061, 60%		
Period Start Time/Date		08:30, 03/05/20			09:00, 06/26/20			09:30, 09/24/20		
Period Duration		13.3 – 17.3 hr			12.45 – 14.85 hr			11.04 – 12.08 hr		
Loop Flow		<i>max</i>	<i>min</i>	<i>mean</i>	<i>max</i>	<i>min</i>	<i>mean</i>	<i>max</i>	<i>min</i>	<i>mean</i>
Oscillation period (peak-to-peak)	sec	205.0	156.0	183.5	195.0	137.0	170.6	176.0	115.0	153.7
Average flow (per cycle)	kg/s	2.90	2.21	2.55	3.12	2.28	2.78	3.23	2.59	2.92
Oscillation amplitude (peak – average)	kg/s	3.75	0.69	1.82	4.55	0.02	1.22	3.42	0.10	1.26
Two-phase Boil-Off										
Maximum void fraction	%	64.4			69.2			62.1		
Average condensate rate	gpm	0.263			0.257			0.259		
Generated condensate volume	gal	83.83			66.84			63.33		
Post Loop Cool Down										
Starting tank inventory level	inWC	105.64			94.50			82.91		
Ending tank inventory level	inWC	91.51			87.08			74.03		
Estimate total inventory loss	gal	~138			~115			~116		

Table 7: Summary of primary measurements across inventory parametric tests, average over 6-min window toward the end of the 4-hour acceptance period

		Run057	Run059	Run060	Run061	
	Test date	11/2019	03/2020	06/2020	09/2020	
	Full power reference	2.1	2.1	2.1	2.1	
Static pressure	Inlet header	39.94	39.75	39.33	38.83	MW_t
	Tank basin	17.57	17.32	17.18	17.21	psia
	Tank water level	100.55	100.44	89.51	77.99	psig
Differential pressure	$\Delta P01$, Test Section	13.55	13.54	12.65	11.63	inWC
	$\Delta P02$, Low chimney	2.08	2.13	2.02	1.76	inWC
	$\Delta P03$, Mid chimney	4.26	4.13	4.06	3.89	inWC
	$\Delta P04$, Up chimney	5.93	6.00	6.68	7.97	inWC
	$\Delta P05$, Tank	2.44	2.42	2.32	1.86	inWC
RTD Energy Balance Temp.	Tank inlet	107.22	106.90	106.23	105.31	$^{\circ}C$
	Tank outlet	105.39	105.08	104.98	104.86	$^{\circ}C$
	Header inlet	105.32	105.00	104.91	104.80	$^{\circ}C$
	Header outlet	109.06	108.81	108.21	107.60	$^{\circ}C$
HXG Loop	Hot supply	100.03	99.74	99.78	99.77	$^{\circ}C$
	Hot return	23.55	22.76	22.79	24.02	$^{\circ}C$
	Cold supply	18.17	18.21	18.14	18.12	$^{\circ}C$
	Cold return	23.00	23.46	23.47	23.50	$^{\circ}C$
	HXG flow rate	NA	NA	NA	NA	GPM
Piping Flow Rates	Primary loop	2.96	2.94	3.25	3.79	kg/s
	Riser 01	0.362	0.360	0.398	0.463	kg/s
	Riser 02	0.365	0.364	0.404	0.477	kg/s
	Riser 03	0.360	0.357	0.396	0.464	kg/s
	Riser 04	0.372	0.369	0.410	0.485	kg/s
	Riser 05	0.375	0.373	0.413	0.483	kg/s
	Riser 06	0.366	0.362	0.404	0.473	kg/s
	Riser 07	0.375	0.372	0.415	0.485	kg/s
	Riser 08	0.393	0.391	0.435	0.507	kg/s
Test Section Surface	Tubes, hot side	113.57	113.36	112.79	112.08	$^{\circ}C$
	Tubes, cold side	107.51	107.23	106.89	106.49	$^{\circ}C$
	Fins, hot side	136.61	136.12	135.26	134.37	$^{\circ}C$
	Fins, cold side	136.92	136.57	135.71	134.83	$^{\circ}C$
Heated Cavity Surface	Cavity cold walls	117.90	116.19	118.16	117.22	$^{\circ}C$
	Cavity north wall	220.32	218.83	220.74	216.44	$^{\circ}C$
	Cavity south wall	223.09	223.42	225.92	222.64	$^{\circ}C$
Heaters	Heater plate, front	409.16	409.33	409.93	408.29	$^{\circ}C$
	Ceramic heaters	550.91	550.74	550.33	548.87	$^{\circ}C$
Power	Electric supplied	71.96	71.96	71.96	71.96	kW_e
	Riser panel thermal	46.51	47.05	45.44	44.70	kW_t
	HXG thermal	NA	NA	NA	NA	kW_t
	Thermal efficiency	65%	65%	63%	62%	%

4.2. Depleted Inventory Scenario

As a continuation of the inventory parametric series, a test case was established where the liquid inventory level within the facility would fall to a low level and result in the stagnation of primary system flow. Due to large voiding in the chimney and swelling of the heated leg, flow of the primary inventory continues to function as the level falls below the elevation of the chimney inlet. As the system continues to operate and the level is further reduced, a threshold level is met and the loop ultimately experiences flow stagnation, Figure 19. This scenario is reflective of a *depletion* state, where the heat removal is severely degraded and the facility is no longer able to perform its safety related function. To reach such a depleted liquid level, analytical modeling predicted that the level would need to fall to a level approximately 16-inches below the chimney inlet into the tank, or 38% of the available inventory in the NSTF. At this level, it was predicted that the continuity of the flow loop will break and the system will experience flow stagnation.

Figure 19: Tank inventory at normal levels; low with flow due to swelling; Depleted with stagnation

Planning for the actual experiment began by establishing the initial liquid inventory at the start of the test. To ensure correct start-up behavior reflective of normal operation, it would be necessary that the initial fill fully cover the chimney inlet, approximately 52% inventory. To reach the target 38% level using natural boil-off as the sole means for inventory removal, approximately 0.25 GPM based on previous testing, it would require operating the facility at two-phase conditions for a period of at least 15-hours. Given the availability of project staff, an external drain feature was implemented to accelerate the rate of total inventory loss and allow the test to be conducted within allowable hours. The external drain was implemented by drawing inventory from a side port on the primary storage tank, which utilized ½" diameter

high temperature lines, a separate heat exchanger to ensure safe transfer of the removed liquid, throttle valves to adjust the flow rate, and a flow meter to monitor the drain rate, Figure 20.

Figure 20: Configuration of heat removal system during boil-off with external drain

To ensure that the drain did not influence the integral system behavior or introduce unwanted affects, a relatively slow drain rate of 0.5 GPM was selected. The combined rate from boil-off and external drain, expected to total approximately 0.75 GPM, would allow the facility to reach depleted conditions in approximately 5 hours past the start of boiling.

With completed preparations and establishment of initial conditions, test operations for DataQuality069 began on June 10th 2021. The test facility was filled to an initial level of 55% or approximately 6-inch above the centerline of the chimney inlet. A power ramp to 72 kW_e over a 150-minute period, extended due to the faulted Guard heater zones, was then initiated. Boiling was first observed approximately 11-hours after the start of the power ramp, with boiling and flashing beginning in the upper chimney region. Following, the facility was allowed to continue normal two-phase operation with natural boil-off for a period of 30 minutes to allow any residual start-up effects to decay. Then, the accelerated inventory drain system was enabled and two-phase operation with both natural boil-off and accelerated drain continued for the remainder of the

test. The facility was allowed to operate without adjustment until the tank level dropped to approximately 35-inches below the centerline of the chimney, after which the test concluded and power-ramp initiated.

The total test duration for DataQuality69 extended 22 hours and 15 minutes, including 11-hours of heat up to saturation, approximately 9.5 hours of test observation with boiling, and the remaining 1.5 hours for power ramp down and cold inventory refill. During the period of boiling, the volume removed from the system by natural boil-off and external drain was maintained at a nearly constant 0.27 GPM and 0.51 GPM, respectively, resulting in a total inventory drain rate of approximately 0.78 GPM. The time history of the drain rates, system flow and tank inventory across the test duration are shown in Figure 21 and Figure 22. A number of discrete events occurred during this time, Figure 23, beginning with the inception of boiling at approximately 11-hours, followed shortly by the brief period of start-up oscillations from 11.2 to 11.4-hours. Unlike previous tests that began at 80%, 70%, or even 60% initial tank inventory levels, the starting 55% level resulted in only 4 – 5 large oscillations before the system transitioned to a stable and continuous mode of two-phase flow.

Near the 12.7-hour mark, an abrupt spike in the flow rate was measured and upon review of the tank level at the time of observation, indicates that the level had reached the perimeter of the chimney inlet pipe, thus introducing an air pocket to horizontal section of the chimney. The flow rate continues to gradually increase until the 11.8-hour mark, when the flow rate peaks and begins a reduction. This inflection point corresponds to the centerline of the chimney inlet to the tank, where the cold driving head and heated buoyancy pressure are no longer coupled by a common elevation. At approximately 16-hours into the test, a new instability mode is introduced and the flow shifts away from stable continuous two-phase flow and into a regime of moderate amplitude, high-frequency oscillations that averaged 16-seconds between peaks. By 18-hours, these oscillations dampened and the facility returned to a more stable flow state for the remainder of the test window.

As the test progressed, most liquid and structural temperatures across the facility exhibited a continuous increase. The temperature difference of the fluid entering and exiting the test section averaged 2°C shortly after boiling inception, increasing to just over 2°C by the test conclusion, Figure 24 *left*. Similarly, the averaged surface temperature of the heated plate measured ~392°C at the start of boiling, increasing to ~411°C after 10 hours, Figure 24 *right*. However, the temperatures of fluid at the tank inlet, tank outlet, and riser inlet reached a steady-state period once the ~16-hour mark was reached, remaining a near-constant 105°C for the remainder of the testing window, Figure 25

Figure 21: Inventory removal rates due to natural boil-off and external drain, DataQuality069

Figure 22: Time history of flow rate and inventory level (relative to chimney inlet center), DataQuality069

Figure 23: Major events during DataQuality069. a) Start-up oscillations, b) Closed loop breaks and level falls below the chimney inlet, c) New instability mode with high frequency oscillations, d) Detail view of high frequency

Figure 24: Time history of heated section temperature rise; Front surface of heated plate

Figure 25: Time history of test section and tank inlet and outlet liquid temperatures, DataQuality069

At approximately 18 hours into test operations, differential pressure transducers ΔP_{04} and ΔP_{05} , which measure the pressure drop across the upper chimney and tank, respectively, became saturated at their upper range limit of 25-inWC, Figure 26. Both of these transducers had one side of their imposing tubing connected to port DP₂₅, located at the short horizontal piping of the chimney segment that connected to the tank inlet. As the tank inventory continued to decrease, this section of piping became fully voided and emptied of liquid. Thus, the pressure drop signals recorded by ΔP_{04} and ΔP_{05} were not correctly captured after the 18-hour mark. However, no impacts on the system operations were caused during this period.

Figure 26: Time history of differential pressure measurements, DataQuality069

Figure 27: Phase portraits of differential pressure vs flow rate, DataQuality069

The void fraction, as measured from a bulk volume shortly prior to the tank inlet along the upper portion of the chimney region, peaked at an average value of 70% by 18-hours, and remained at this mean value until approximately 19-hours, Figure 28. However, after 19-hours it experienced a reduction down to an average void fraction of approximately 62%. The exact reason is not fully known, as it would be expected that with falling system levels the void fraction would continue to increase until reaching nearly 100% or fully voided. The likely cause is a stabilization of the boiling front and change from unstable flow excursions, as measured from the flow rate measurement during the regime of moderate amplitude, high-frequency oscillations which were observed between 16 and 18-hours into the test. After these windows, the facility stabilized and returned to the continuously boiling, stable two-phase mode of flow operation. The relationship between flow rate, including amplitude of flow oscillations, and the system level is provided by Figure 29.

Figure 28: Time history of void fraction, DataQuality069

Figure 29: Relationship between inventory level, relative to chimney inlet, and system flow rate

4.3. Pressure Parametric

The pressure parametric tests conducted in FY2021 include three tests, namely, Run062, Run067, and Run068. For the pressure parametric series, test Run060 with 70% starting tank inventory has been selected as the new baseline due to the appropriate duration of two-phase flow oscillations during the 4-hour acceptance criteria examination window for this test. In the baseline Run060, the generated steam was routed to the HXG/condenser for condensation and eventually collected in the two holding tanks. System pressure was allowed to develop naturally with the steam experiencing flow resistance mainly in the HXG/condenser when leaving the system. In test Run062, the generated steam was directly discharged to atmosphere. Due to the smaller flow resistance of the steam discharge port than the HXG/condenser, lower system pressure was developed during the two-phase operation in Run062. However, as a consequence of discharging to atmosphere, no data could be measured about the condensate generation rate or total condensate collected. For tests Run067 and Run068, a full-port gate valve installed upstream of the HXG/condenser was utilized to throttle the steam flow, and thus affecting the system pressure. The steam throttling valve was set at $x12$ and $x13$ turns closed, reducing the available flow areas for exiting steam to 11.3% and 5.4% of the fully open 1.0" bore, Figure 30. The system configurations for the pressure tests are summarized in Table 8.

Figure 30: Steam throttle position: $x12$ turns closed with 11.3% remaining available flow area in Run067 (left), and $x13$ turns closed with 5.4% remaining available flow area in Run068 (right)

Table 8: Initial boundary and operating conditions for pressure parametric testing

Facility geometry	Run060	Run062	Run067	Run068
Heated – riser spacing	34.05 inch			
Chimney-tank inlet position	Center tank at 50"			
Heat load:				
Power control	Burst firing			
Distribution	Linear / uniform across 40 zones			
Power level	72 kW _e			
Valves				
Tank outlet:	Open			
Loop inlet throttle:	Open			
Riser(s) inlet:	All eight open			
Riser(s) outlet:	All eight open			
Differential pressure				
ΔP-01	Test section, (DP ₂₀ – DP ₄₄)			
ΔP-02	Lower chimney, (DP ₂₂ – DP ₂₀)			
ΔP-03	Mid chimney, (DP ₂₃ – DP ₂₂)			
ΔP-04	Upper chimney, (DP ₂₅ – DP ₂₃)			
ΔP-05	Full loop/water tank (DP ₂₅ – DP ₄₀)			
Liquid Inventory				
Inventory fill amount	70% tank level, ~879 gal			
Inventory fill level, ΔP	94.50"	94.46"	94.52"	94.48"
Liquid conductivity	29 μS/cm	30.4 μS/cm	27.7 μS/cm	28.3 μS/cm

The system pressure achieved near the end of the 4-hour acceptance criteria window is shown in Figure 31, and summarized in Table 9. For tests Run060, Run062, and Run067, the system pressure developed naturally without external interference with the initial configuration. In test Run068, from approximately 15.52 to 16.80 hours into the test, the steam throttling valve was gradually opened by approximately 1 turn (~6% area reduction per turn) to avoid over-pressurization of the system. This led to the system pressure leveling off, Figure 32, accompanied by increased rate of steam generation, Figure 33 and Figure 34.

Table 9: System pressure for the pressure parametric testing

	Run060	Run062	Run067	Run068
Scenario	Baseline	Reduced pressure	Elevated pressure	Elevated pressure
Pressure regulation	None	Direct to atmosphere	Gate valve	Gate valve
Gate valve flow area	100%	>100%	11.3%	5.4%
Resulting system pressure	17.2 psia	16.1 psia	18.8 psia	25.5 psia

Figure 31: System pressure for the pressure parametric tests

Figure 32: Leveling off of tank gas space pressure in Run068

Figure 33: Triggering interval of condensate transfer pump, Run068

Figure 34: Tank level, steeper slope indicating increased steam generation rate, Run068

The pressure parametric test results compared as shown in Figure 35 - Figure 43. For better comparison, the test results have been aligned at the time of the third peak of the two-phase flow. The system pressure is notably affecting the two-phase flow oscillation characteristics. With higher system pressure, the two-phase flow oscillation is suppressed in the amplitude but has a longer oscillation period, Figure 35. The suppression of the flow oscillation amplitude is likely a result of the suppression of the vapor generation rate or the void fraction at higher system pressure, Figure 36. As two-phase boiling/flashing starts, system pressure starts to build up. With varying steam exiting resistance in the four tests, the tank gas space pressure and thus the header inlet pressure start to deviate, Figure 37. Since the liquid is always heating up to approach saturation, the higher header inlet pressure results in higher saturation temperatures, which in turn leads to higher riser liquid temperature, Figure 38. As discussed in [13], the riser structure temperatures are more sensitive to the riser liquid temperatures due to the low thermal resistance associated with the convective heat transfer on riser inner surface. However, the heater structure temperatures are more sensitive to the source power than the riser liquid temperature because of the much larger thermal resistance for the cavity internal heat transfer (radiation and natural convection). Therefore, the effect of system pressure on the riser liquid temperatures propagates to the riser structures, Figure 39 and Figure 40, but not the heater structures, Figure 41 and Figure 42.

The effect of the system pressure on the two-phase boil-off is shown in Figure 43. As boiling/flashing initiates, the system pressure starts to build up. During the first phase, the system pressure is continuously ramping up, leading to higher liquid saturation temperature and thus continuous heating up of the system. During this transient, more sensible heat is used for system heating up at higher system pressure, leading to smaller steam generation rate and thus inventory loss rate, as seen in Figure 43. As the system gradually approaches thermal equilibrium, most of the heat deposit to the system contributes to steam generation, reflected as similar inventory loss rate toward the end of the transient for all four tests, Figure 43. The measured system values during the acceptance criteria window for the pressure parametric tests are summarized in Table 10, and the full system parameters near the end of the period in Table 11.

Figure 35: Comparison of total loop flow rate for the pressure parametric series

Figure 36: Comparison of void fraction for the pressure parametric series

Figure 37: Comparison of header inlet pressure for the pressure series

Figure 38: Comparison of liquid riser inlet temperature for the pressure series

Figure 39: Comparison of riser tube temperature for the pressure parametric series

Figure 40: Comparison of riser fin temperature for the pressure parametric series

Figure 41: Comparison of heated plate temperature for the pressure series

Figure 42: Comparison of ceramic heater temperature for the pressure series

Figure 43: Comparison of tank inventory level for the pressure parametric series

Table 10: Comparison of acceptance criteria for the pressure parametric series

		Run060 (reduced)			Run062 (baseline)			Run067 (moderate)			Run068 (high)		
Inventory Fill		70%											
Ending System Pressure		17.2 psia			16.1 psia			18.8 psia			25.5 psia		
Period Start Time/Date		09:00, 06/26/20			09:30, 11/13/20			08:05, 04/08/21			08:59, 05/07/21		
Period Duration		12.45 – 14.85 hr			12.2 – 14.6 hr			12.3 – 16.9 hr			13.08 – 17.12 hr		
Loop Flow		max	min	mean	max	min	mean	max	min	mean	max	min	mean
Oscillation period (peak-to-peak)	sec	195.0	137.0	170.6	193.0	130.0	174.9	225.0	121.0	174.6	286.0	131.0	191.4
Average flow (per cycle)	kg/s	3.12	2.28	2.78	3.00	2.39	2.68	3.03	1.77	2.63	3.14	1.54	2.43
Oscillation amplitude (peak – average)	kg/s	4.55	0.02	1.22	3.54	0.03	1.55	3.96	0.09	1.30	2.77	0.10	1.68
Two-phase Boil-Off													
Maximum void fraction	%	69.2			66.7			66.8			57.5		
Average condensate rate	gpm	0.257			--			0.225			0.148		
Generated condensate volume	gal	66.84			--			100.0			33.6		
Post Loop Cool Down													
Starting tank inventory level	inWC	94.50			94.46			94.52			94.48		
Ending tank inventory level	inWC	87.08			82.43			77.63			84.47		
Estimate total inventory loss	gal	~115			~104			~167.5			~99.2		

Table 11: Summary of primary measurements across pressure parametric tests, average over 6-min window toward the end of the 4-hour acceptance period

		Run060	Run062	Run067	Run068	
	<i>Test date</i>	06/2020	11/2020	04/2021	05/2021	
	<i>Full power reference</i>	2.1	2.1	2.1	2.1	
Static pressure	Inlet header	39.33	38.14	41.17	47.91	MW_i
	Tank basin	17.18	16.12	18.76	25.47	$psia$
	Tank water level	89.51	89.26	89.84	91.89	$psig$
Differential pressure	$\Delta P01$, Test Section	12.65	12.45	14.00	16.64	$inWC$
	$\Delta P02$, Low chimney	2.02	1.92	2.23	2.72	$inWC$
	$\Delta P03$, Mid chimney	4.06	3.90	4.33	5.06	$inWC$
	$\Delta P04$, Up chimney	6.68	6.21	6.44	7.43	$inWC$
	$\Delta P05$, Tank	2.32	2.11	2.59	3.36	$inWC$
RTD Energy Balance Temp.	Tank inlet	106.23	104.09	109.04	118.02	$^{\circ}C$
	Tank outlet	104.98	102.89	107.92	117.05	$^{\circ}C$
	Header inlet	104.91	102.82	107.79	116.95	$^{\circ}C$
	Header outlet	108.21	106.21	111.21	120.12	$^{\circ}C$
HXG Loop	Hot supply	99.78	NA	99.45	99.81	$^{\circ}C$
	Hot return	22.79	NA	21.54	19.69	$^{\circ}C$
	Cold supply	18.14	NA	18.21	18.23	$^{\circ}C$
	Cold return	23.47	NA	22.88	22.69	$^{\circ}C$
	HXG flow rate	NA	NA	NA	NA	GPM
Piping Flow Rates	Primary loop	3.25	3.16	3.07	3.19	kg/s
	Riser 01	0.398	0.386	0.377	0.390	kg/s
	Riser 02	0.404	0.396	0.387	0.402	kg/s
	Riser 03	0.396	0.386	0.377	0.390	kg/s
	Riser 04	0.410	0.403	0.394	0.408	kg/s
	Riser 05	0.413	0.401	0.391	0.405	kg/s
	Riser 06	0.404	0.392	0.383	0.398	kg/s
	Riser 07	0.415	0.403	0.393	0.406	kg/s
Test Section Surface	Riser 08	0.435	0.422	0.413	0.425	kg/s
	Tubes, hot side	112.79	110.52	115.47	124.16	$^{\circ}C$
	Tubes, cold side	106.89	104.79	109.71	118.61	$^{\circ}C$
	Fins, hot side	135.26	133.26	137.91	146.03	$^{\circ}C$
Heated Cavity Surface	Fins, cold side	135.71	133.77	138.52	146.65	$^{\circ}C$
	Cavity cold walls	118.16	115.84	117.59	117.92	$^{\circ}C$
	Cavity north wall	220.74	214.16	214.90	212.40	$^{\circ}C$
Heaters	Cavity south wall	225.92	221.07	223.39	221.21	$^{\circ}C$
	Heater plate, front	409.93	407.59	409.21	409.04	$^{\circ}C$
Power	Ceramic heaters	550.33	549.13	544.31	544.45	$^{\circ}C$
	Electric supplied	71.96	71.96	71.97	71.98	kW_e
	Riser panel thermal	45.44	45.17	44.38	42.99	kW_t
	HXG thermal	NA	NA	NA	NA	kW_t
	Thermal efficiency	63%	63%	62%	60%	%

Failed and Trending Attempts

Prior to its use in the pressure parametric tests, the flow resistance characteristics of the steam exit throttling valve and its impact on the NSTF system as it closes were not known. To induce sufficient system pressure difference compared to the baseline while not over pressurizing the system, the proper closing position of the steam throttling valve needed to be determined. Therefore, an NSTF two-phase parametric test with reduced initial tank inventory of 70%, direct condensate refill, and steam exit throttling (Run066) was conducted. The general idea for this test was similar to the header inlet throttling test. First, a true two-phase steady state was established by directly refilling the generated condensate back to the system. Following, the steam exit throttling valve was gradually closed to develop the correlation between the system pressure and the steam exit throttling valve position.

The test began at 20:00 on March 10th 2021 and spanned a period of 21 hours 58 minutes. At ~ 12.8 hours into the test, boiling/flashing initiated and was first observed in the upper chimney, Figure 44. At ~ 13.2 hours, the condensate refill system was started. A constant inventory level inside the water tank was maintained by manually adjusting the refill rate to match the steam/condensate generate rate. The NSTF eventually reached a two-phase steady-state operation (in terms of the average of the system parameters) with condensate refill, which was maintained for over 2 hours (~ 15.3 – 17.3 hours), Figure 44. Following that, the steam exit throttling was applied by gradually closing the throttling valve. From ~ 17.3 – 19.6 hours the steam exit throttling valve was gradually closed to x12.5 turns or 8% remaining available flow area, and the system pressure was seen responding, Figure 45. At ~ 19.6 hours, the system pressure and fluid temperatures increased to a point that raised concerns for integrity of the sight glass window on the side of water tank, Figure 45 and Figure 46. Therefore, it was decided to conclude the steam exit throttling. The throttling valve was gradually reopened, followed by power ramp down and test conclusion. Following this test, a sight glass rated to a higher temperature and pressure sufficient to meet the new system requirements replaced the one installed on the water tank. The peak system pressure achieved was approximately 19.2 psia, partially meeting the initial test objective. Therefore, this test was classified as *Trending*.

Figure 44: Total loop flow rate in Run066

Figure 45: Tank gas space pressure in Run066

Figure 46: Liquid RTD temperatures in Run066

4.4. Power Parametric

In FY19, power parametric testing was performed to investigate the effect of total heat load on the NSTF single-phase performance [13]. In FY21, this work was extended to the two-phase testing of the NSTF. Per the proposed test matrix [15], the power parametric series include 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). With Run060 selected as the baseline for the power parametric series, which corresponds to the full-scale power of 2.1 MW_t and has an initial tank fill of 70%, two additional tests were conducted in FY21. The first test simulates the case of “Elevated” full scale power of 2.8 MW_t (Run065), while the second the “Normal” full scale power of 1.4 MW_t (Run070). However, due to the issue of faulted heaters in Run065, this test was classified as Trending, and will be discussed in following sections.

Table 12: Initial boundary and operating conditions for power parametric testing

Facility geometry	Run060	Run070
Heated – riser spacing Chimney-tank inlet position	34.05 inch Center tank at 50"	
Heat load:		
Power control Distribution	Burst firing Linear / uniform across 40 zones	
Electric Power level	72 kW _e	48 kW _e
Target thermal pwore	51.6 kW _t	34.4 kW _t
Full-scale Decay Heat Equiv.	2.1 MW _t	1.4 MW _t
Valves		
Tank outlet:	Open	
Loop inlet throttle:	Open	
Riser(s) inlet:	All eight open	
Riser(s) outlet:	All eight open	
Differential pressure		
ΔP-01	Test section, (DP ₂₀ – DP ₄₄)	
ΔP-02	Lower chimney, (DP ₂₂ – DP ₂₀)	
ΔP-03	Mid chimney, (DP ₂₃ – DP ₂₂)	
ΔP-04	Upper chimney, (DP ₂₅ – DP ₂₃)	
ΔP-05	Full loop/water tank (DP ₂₅ – DP ₄₀)	
Liquid Inventory		
Inventory fill amount	70% tank level, ~879 gal	70% tank level, ~879 gal
Inventory fill level	73.56" (SG), 94.50" (ΔP)	73.44" (SG), 94.53" (ΔP)
Liquid conductivity	~ 29 μS/cm @ 26.0°C	~ 26 μS/cm @ 26.3°C
pH	7.01 –	7.73

The two successful power parametric tests, Run060 and Run070, were configured at baseline geometry as summarized in Table 12. A total electric power of 72 kW_e was applied across a 90-minute automatic ramp in Run060. In Run070, due to the two faulted guard heaters (2S and 6N), a power signal of 48.6 kW_e was sent to the heater controllers in order to achieve the desired total power of 48 kW_e. In addition, the

power ramp was extended to 10 minutes. Following the power ramp, the NSTF facility and water inventory gradually heated up and eventually led to two-phase boiling/flashings. The stable two-phase operation was maintained for over 4 hours, followed by power ramp down to conclude the test.

The power parametric tests results are shown in Figure 47 - Figure 57. Except for the left plot in Figure 47, which plots the data at the actual run time, all Run070 data is shifted earlier in time to better compare the two-phase flow and system response. The total power affects the total loop flow in a few aspects. First, the transient flow development with lower power is delayed, including both the initiation of the natural circulation and initiation of two-phase boiling/flashings, Figure 47. Natural circulation was first detected at ~ 0.65 hours into test for Run060, while ~ 1.16 hours for Run070. In addition, boiling/flashings started at ~ 11.8 hours for Run060, but ~ 17.2 hours for Run070. Second, higher power in Run060 led to higher single-phase natural circulation flow, which was attributed to the larger hot-and-cold leg temperature difference as indicated by the first hour of time in Figure 51. For two-phase operation, the higher power input in Run060 led to the higher void fraction, Figure 56, and thus higher average total loop flow rate as well bigger flow oscillations, Figure 47. However, the flow oscillations sustained longer in Run070 with lower power, Figure 47. Toward the end of the 4-hour window for the two-phase operation, a higher riser liquid temperature increase of $\sim 3.83^{\circ}\text{C}$ was achieved in Run70 than the $\sim 3.3^{\circ}\text{C}$ in Run060, Figure 51, in contrast to the total flow comparison, Figure 47. The reason for that is, during two-phase operation, the dominant driving force for the natural circulation flow is the void generation in the hot leg, Figure 56, instead of the temperature induced liquid density difference.

In tests Run060 and Run070, as boiling/flashings initiates, pressure starts to build up due to steam generation. The higher power in Run060 led to faster steam generation, as indicated by the tank inventory level in Figure 57, and thus higher system pressure, Figure 48 and Figure 49. Therefore, some observations from the pressure parametric testing are also applicable here. As the system approached the quasi-steady state (at ~ 16.5 hours), higher fluid and riser structure temperatures were achieved partially due to the higher system pressure. However, unlike the pressure parametric testing where the riser structure temperatures did not start to diverge between tests until boiling/flashings started (Figure 39 and Figure 40), riser fin temperature started to separate during the single-phase heat up in the present case, Figure 53. In addition, different heater structure temperatures were achieved in the power parametric testing, Figure 54 and Figure 55, while similar heater structure temperatures were obtained in the pressure parametric testing, Figure 41 and Figure 42. Both of these two differences were attributed to the varying power applied in the power parametric testing. The measured system values during the acceptance criteria window for the power parametric tests are summarized in Table 13, and the full system parameters near the end of the period are summarized in Table 14.

Figure 47: Comparison of total loop flow for the power parametric series

Figure 48: Comparison of tank gas pressure for the power parametric series

Figure 49: Comparison of header inlet pressure for the power parametric series

Figure 50: Comparison of liquid riser inlet temperature, power parametric

Figure 51: Comparison of heated section ΔT , power parametric

Figure 52: Comparison of riser wall temperature, power parametric

Figure 53: Comparison of riser fin temperature, power parametric

Figure 54: Comparison of heated plate temperature, power parametric

Figure 55: Comparison of ceramic heater temperature, power parametric

Figure 56: Comparison of void fraction, power parametric

Figure 57: Comparison of tank inventory level, power parametric

Table 13: Comparison of acceptance criteria for the power parametric series

		Run060			Run070		
Inventory Fill		70%					
Total Electric Power		72 kW _e			48 kW _e		
Period Start Time/Date		09:00, 06/26/20			09:31, 07/08/21		
Period Duration		12.45 – 14.85 hr			17.7 – 23.7 hr		
Loop Flow		max	min	mean	max	min	mean
Oscillation period (peak-to-peak)	sec	195.0	137.0	170.6	287.0	231.0	262.4
Average flow (per cycle)	kg/s	3.12	2.28	2.78	1.90	1.69	1.79
Oscillation amplitude (peak – average)	kg/s	4.55	0.02	1.22	2.09	0.29	1.09
Two-phase Boil-Off							
Maximum void fraction	%	69.2			44.7		
Average condensate rate	gpm	0.257			0.151		
Generated condensate volume	gal	66.84			53.6		
Post Loop Cool Down							
Starting tank inventory level	inWC	94.50			94.53		
Ending tank inventory level	inWC	87.08			86.45		
Estimate total inventory loss	gal	~115			~80.1		

Table 14: Summary of primary measurements across power parametric tests, average over 6-min window toward the end of the 4-hour acceptance period

		Run060	Run070	
	<i>Test date</i>	06/2020	07/2021	
	<i>Full power reference</i>	2.1	1.4	<i>MW_i</i>
Static pressure	Inlet header	39.33	37.49	<i>psia</i>
	Tank basin	17.18	15.31	<i>psig</i>
	Tank water level	89.51	91.24	<i>inWC</i>
Differential pressure	ΔP01, Test Section	12.65	13.98	<i>inWC</i>
	ΔP02, Low chimney	2.02	2.26	<i>inWC</i>
	ΔP03, Mid chimney	4.06	4.08	<i>inWC</i>
	ΔP04, Up chimney	6.68	3.81	<i>inWC</i>
	ΔP05, Tank	2.32	2.81	<i>inWC</i>
RTD Energy Balance Temp.	Tank inlet	106.23	103.75	°C
	Tank outlet	104.98	101.67	°C
	Header inlet	104.91	101.48	°C
	Header outlet	108.21	105.24	°C
HXG Loop	Hot supply	99.78	99.72	°C
	Hot return	22.79	21.29	°C
	Cold supply	18.14	18.29	°C
	Cold return	23.47	21.19	°C
	HXG flow rate	NA	NA	<i>GPM</i>
Piping Flow Rates	Primary loop	3.25	1.69	<i>kg/s</i>
	Riser 01	0.398	0.214	<i>kg/s</i>
	Riser 02	0.404	0.213	<i>kg/s</i>
	Riser 03	0.396	0.209	<i>kg/s</i>
	Riser 04	0.410	0.219	<i>kg/s</i>
	Riser 05	0.413	0.214	<i>kg/s</i>
	Riser 06	0.404	0.212	<i>kg/s</i>
	Riser 07	0.415	0.216	<i>kg/s</i>
	Riser 08	0.435	0.228	<i>kg/s</i>
Test Section Surface	Tubes, hot side	112.79	108.35	°C
	Tubes, cold side	106.89	103.61	°C
	Fins, hot side	135.26	122.86	°C
	Fins, cold side	135.71	124.30	°C
Heated Cavity Surface	Cavity cold walls	118.16	106.54	°C
	Cavity north wall	220.74	180.40	°C
	Cavity south wall	225.92	185.65	°C
Heaters	Heater plate, front	409.93	341.22	°C
	Ceramic heaters	550.33	455.14	°C
Power	Electric supplied	71.96	48.03	<i>kW_e</i>
	Riser panel thermal	45.44	26.30	<i>kW_t</i>
	HXG thermal	NA	NA	<i>kW_t</i>
	Thermal efficiency	63%	55%	%

Failed and Trending Attempts

In addition to the successful power parametric tests Run060 and Run070, there was a high-power attempt, Run065. This test was configured at baseline geometry, with a reduced initial tank inventory of 70% and an increased electrical power of 82 kW_e corresponding to the full-scale power of 2.8 MW_t. The test began at 22:00 on February 3rd 2021 and spanned a period of 17 hours 40 minutes. Shortly after the power ramp up was initiated, the operator identified two faulty guard heaters 2S and 6N by noticing the abnormal impedance measurements in these two zones. Considering that the resulting power adjustment due to these alleviation actions was less than 1% of the total power, the impact to the overall system was negligible, and it was decided to continue the test.

At ~ 11.6 hours into the test, a minor leak in a ΔP impulse tube occurred, and as a precaution, all the ΔP ports were closed at ~ 12 hours, and no ΔP measurements were available beyond that time. In light of these issues, it was decided to continue the test as an informal reference but to classify this test as *Trending*. This test will be repeated after the two faulted guard heaters are fixed in FY22.

Figure 58: Issues with DP measurement in Run065

4.5. Refill Tests

For header inlet throttling parametric testing, the strategy of repeating baseline test with varying initial header inlet throttling would require a high number of repeat test cases for each change in imposed loss coefficient. In addition, the relationship between the flow resistance or flow coefficient and the valve opening is not linear for the header inlet throttling valve. Therefore, it is difficult to accurately predict the minimum valve closing at which appreciable effects on the NSTF system performance start to appear. Therefore, it was decided to establish a true two-phase steady state with direct condensate refill, after which the header inlet throttling valve could be gradually adjusted in multiple steps to investigate its effect on the system performance.

In FY21, two successful refill tests were conducted, namely, Run064 and Run071. Run071 was a repeat of Run064 with the difference that power ramp was applied over 150 minutes instead of 90 minutes, due to the malfunctioning of two guard heaters 2S and 6N. Following the power ramp, the heater power was maintained constant to allow heating up of the NSTF facility and water inventory. Upon reaching saturation, boiling/flashing of water was first observed in the upper chimney region. The condensate refill system was subsequently started to maintain a constant inventory level inside the water tank by manually adjusting the refill rate to match the steam/condensate generation rate. The NSTF eventually reached a two-phase steady-state operation with condensate refill, which was maintained for over 2 hours. Following, variations of the header inlet throttle valve position were performed to examine its effect on the NSTF operation. The following acceptance criteria were defined for the refill test, which established intended steady-state operating conditions over the course of the stated evaluation period:

1. Average system flow rate maximum variation $\pm 10\%$
2. Tank inventory level maximum variation $\pm 10\%$
3. Intermediate tank condensate level maximum variation $\pm 10\%$
4. Average fluid RTD temperatures maximum variation $\pm 10\%$
5. Position of inlet throttle valve remained within $<1\%$ of a mean value
6. Average system thermal power remained within 3% of a mean value

In this section, results of only the steady-state operation will be presented, with the header inlet throttling testing discussed in details in Section 4.6. The total electrical power applied in tests Run064 and Run071 are shown in Figure 59. The power ramp extended over a longer period in Run071 than in Run064. Thus, the heater structure temperatures and fluid temperatures developed faster in Run064 than in Run071, despite that the starting temperatures were similar in the two tests, Figure 60 and Figure 61. However, as the two-phase operation progressed and the system approached the steady state, a higher fluid temperature was

achieved in test Run071, Figure 61. This was attributed to the higher steady-state system pressure and thus header inlet pressure achieved in test Run071, Figure 62 and Figure 63. A throttling valve was installed in the steam transfer line for the pressure parametric testing, which occurred between tests Run064 and Run071. Although a full port gate valve was used to minimize the impact, it had still caused an increase in the steam line total flow resistance even at fully open position for the valve.

The total loop flow is compared for the two tests, Figure 64. Due to the shorter power ramp process, single-phase natural circulation developed faster and boiling/flashings initiated earlier in Run064, Figure 64. The two-phase flow oscillation characteristics are also not identical between the two tests, Figure 64. Due to the difference in power ramp process, different system thermal conditions were achieved when boiling/flashings started in the two tests. In addition, the added steam line throttling valve had also caused higher system pressure in Run071. Both reasons contributed to the difference in the two-phase flow oscillation characteristics.

In lieu of the tank inventory level as measured by the originating pressure transmitter, the system level can be derived based on measurements of the static pressure at the inlet header and tank gas space pressure measured off the dome of the primary tank. Using liquid temperatures along the downcomer and piping, the static inlet pressure was first adjusted for temperature compensation and then converted to units of inWC, Figure 66 and Figure 67. Following, the level was further adjusted to account for the additional pressure generated within the gas space. This result, Figure 68 and Figure 69, provides a secondary means of verification that the system level remained constant within the allowed tolerances. The measured values across the acceptance criteria for the two tests are summarized in Table 15, and the full system steady-state parameters in Table 16.

Figure 59: Comparison of total electric power for the refill tests

Figure 60: Comparison of heated plate temperature for the refill tests

Figure 61: Comparison of liquid riser inlet temperature for the refill tests

Figure 62: Comparison of tank gas space pressure for the refill tests

Figure 63: Comparison of header inlet pressure for the refill tests

Figure 64: Comparison of total loop flow for the refill tests. Data for Run071 in the right plot is shifted in time to aid in comparison.

Figure 65: Corrected tank inventory level in Run064

Figure 66: As-measured and temperature compensated level from static inlet pressure, Run064

Figure 67: As-measured and temperature compensated level from static inlet pressure, Run071

Figure 68: Tank level corrected for influences from added gas space pressure, Run064

Figure 69: Tank level corrected for influences from added gas space pressure, Run071

Table 15: Comparison of acceptance criteria for the refill tests

	Run064		Run071	
<i>Period Start</i>	11:08, 01/13/2021		09:21, 08/12/2021	
<i>Period Duration</i>	14.8 – 16.8 hr		14.1 – 16.1 hr	
	<i>Mean</i>	<i>Period Change</i>	<i>Mean</i>	<i>Period Change</i>
System Flow Rate	2.77 kg/s	2.33%	2.67 kg/s	7.30%
System Level	632.76 inch	0.02%	632.48 inch	0.07%
Condensate Level	11.03 inch	0.05%	8.31 inch	0.06%
Fluid RTD Bulk	104.82 °C	0.17%	104.99 °C	0.41%
Throttle Position	0°	0.00%	0°	0.00%
Thermal Power	44.51 kW _t	1.78%	44.60 kW _t	2.21%

Table 16: Summary of primary measurements in refill tests, average over 2-hour acceptance period

		Run064	Run071	
		Test date	06/2020	08/2021
		Full power reference	2.1	2.1
Static pressure	Inlet header	38.70	38.70	MW_t $psia$
	Tank basin	16.47	16.49	$psig$
	Tank water level	NA	94.36	$inWC$
	Derived total inventory	632.76	632.48	$inch$
Differential pressure	$\Delta P01$, Test Section	13.38	13.04	$inWC$
	$\Delta P02$, Low chimney	2.08	2.08	$inWC$
	$\Delta P03$, Mid chimney	4.07	4.03	$inWC$
	$\Delta P04$, Up chimney	5.59	5.57	$inWC$
	$\Delta P05$, Tank	2.44	2.50	$inWC$
RTD Energy Balance Temp.	Tank inlet	105.08	105.28	$^{\circ}C$
	Tank outlet	103.51	103.62	$^{\circ}C$
	Header inlet	103.41	103.49	$^{\circ}C$
	Header outlet	107.27	107.58	$^{\circ}C$
HXG Loop	Hot supply	99.61	99.75	$^{\circ}C$
	Hot return	22.62	22.58	$^{\circ}C$
	Cold supply	18.20	18.22	$^{\circ}C$
	Cold return	22.49	22.40	$^{\circ}C$
	HXG flow rate	NA	NA	GPM
Piping Flow Rates	Primary loop	2.77	2.67	kg/s
	Riser 01	0.340	0.331	kg/s
	Riser 02	0.347	0.338	kg/s
	Riser 03	0.339	0.329	kg/s
	Riser 04	0.353	0.345	kg/s
	Riser 05	0.351	0.340	kg/s
	Riser 06	0.346	0.335	kg/s
	Riser 07	0.352	0.343	kg/s
	Riser 08	0.369	0.360	kg/s
Test Section Surface	Tubes, hot side	111.66	111.83	$^{\circ}C$
	Tubes, cold side	105.61	105.81	$^{\circ}C$
	Fins, hot side	134.23	134.45	$^{\circ}C$
	Fins, cold side	134.82	136.83	$^{\circ}C$
Heated Cavity Surface	Cavity cold walls	114.54	115.53	$^{\circ}C$
	Cavity north wall	212.24	211.32	$^{\circ}C$
	Cavity south wall	219.73	217.74	$^{\circ}C$
Heaters	Heater plate, front	407.53	403.99	$^{\circ}C$
	Ceramic heaters	548.47	541.03	$^{\circ}C$
Power	Electric supplied	71.96	71.97	kW_e
	Riser panel thermal	44.51	44.60	kW_t
	HXG thermal	NA	NA	kW_t
	Thermal efficiency	62%	62%	%

4.6. Loss Coefficient Parametric

To investigate the role of flow area restrictions at the inlet to the heated section, two-phase testing was performed which utilized the throttling capability of loop control valve positioned on the primary loop. This valve, a 4.0-inch nominal sized Jamesbury® Series 9000 full-bore ball valve, Figure 70, is installed along the downcomer piping immediately prior to the inlet header. An intelligent valve controller, Neles model ND9103, provides precise adjustment of the ball position with a 4-20mA signal input and position indicator output. At the fully open position (normal operation), this valve has a C_v value of 2,200 and a K value of 0.05 [16]. C_v represent the flow of water at 60°F through the valve in U.S. gallons per minute at a pressure drop of 1 psi, while K is an industry standard flow resistance coefficient. The valve can be proportionally controlled across the entire range of positions, from fully open (0° valve angle, 100% open position), to fully closed (90° valve angle, 0% open position). Additionally, a position indicator provides a signal of the actual valve position. Due to the geometry of the internal ball, the flow area for passing fluid is not linearly relative to the valve angle or position. The relationship for these parameters, as a function of valve angle, is shown in Figure 71.

Figure 70: Throttle valve at inlet header, full-bore 4.0" ball valve

Figure 71: Jamesbury valve flow area and C_v versus valve handle position in degrees

In order to ensure high confidence in isolating the role of inlet throttling on the various loop parameters during two-phase flow conditions, it was required that loop operate at a true thermal and hydraulic steady-state mode of operation. Unlike testing performed at baseline conditions, which exhibit a quasi-steady mode of operation given the continuous loss of inventory due to boil-off, testing performed within this parametric series utilized a continuous refill of boil-off condensate back into the loop. The rate of refill was adjusted based on the dynamic rate of boil-off, controlled by a DC water pump which was fitted with a high resolution, low range flow meter, Bell Flow Systems, Model MC5-SS-HP-2. The flow rate of condensate refill for DataQuality071, one of the inlet throttling parametric tests conducted, is shown in Figure 72.

Figure 72: Rate of boil-off generation and condensate refill flow rate during DataQuality071

Two-phase matrix testing conducted within the restricted inlet parametric series in Year 3 of the NSTF experimental program included DataQuality064, DataQuality067, and DataQuality071, Table 17. In this section, detailed results will be provided for DataQuality071, which captures the complete range of inlet throttling tested and was successfully conducted at a ‘data-quality’ rigor.

Table 17: Summary of restricted inlet test cases performed in Year 3

Test No.	Dates	Duration	Refill?	Classification	Purpose	Throttle Range (% closed)
064	01/12-13/21	20h34m	Yes	Data-quality	Low range throttle	0% ... 55%
067	04/07-08/21	21h11m	No	Scoping	High throttling	30% ... 75%
071	08/11-12/21	22h07m	Yes	Data-quality	Repeat; full range	0% ... 75%

The test objective for DataQuality071 was to conduct a two-phase baseline test case with direct condensate refill to establish a steady-state operation, and then vary the header inlet throttling to investigate its effect on the system performance and stability. This test was performed at the full scale ‘accident scenario’ power of 2.1 MW_t, or 51.6 kW_t scaled to the NSTF, and operated in a steady mode of two-phase operation with condensate refill. The facility was setup at baseline geometry configurations with reduced initial tank inventory: 70% initial tank inventory, riser discharge into tank center port, and 34.05-inch riser tube to heated wall setback distance. The heater power was applied across a 150-minute automatic power ramp and then maintained constant to allow heating up of the NSTF facility and water inventory. Upon reaching saturation, boiling/flashings of water was first observed in the upper chimney region. The condensate refill system was subsequently started to maintain a constant inventory level inside the water tank by manually adjusting the refill rate to match the steam/condensate generation rate. During the entire ~8-hour period of boiling and two-phase flow, the tank level was maintained at a constant 94.4±0.3 inch, with an average condensate generate and thus refill flow rate of 0.24 GPM.

After approximately 3-hours at boiling conditions with refill, the NSTF reached a two-phase thermal and hydraulic steady-state condition. During this window of active test operations, ten stages of inlet restriction were imposed on the operating test loop, beginning with fully open (100% available flow area) to severely restricted (17% available flow area). At each stage, the facility was allowed at least 20-minutes for stabilization of system flow rates, liquid temperatures, etc. Increments between stages were coarse at early portions, and more granular during later portions due to the non-linear relationship between valve angle and flow area, Figure 73.

Figure 73: Throttle stages during DataQuality071

The operating window for active test operations (powered heaters) during DataQuality071 began at 19:00 on August 11th 2021 and spanned a period of 22 hours and 7 minutes. The onset of boiling occurred at approximately 12.5-hours into the test, and throttling began near the 15-hour mark. Following, 10 stages of inlet restriction were imposed on the operating test loop, Table 18. Beginning at Stage 1 with a fully opened inlet valve, set to a 0° angle and 100% flow area, the test facility was gradually stepped to a maximum flow restriction during Stage 10 with a mostly closed inlet valve, set to a 68° angle which resulted in a 17% available area for flow. The time history of the flow and throttle restriction is shown in Figure 74.

Table 18: Summary of stages for restricted inlet throttle, DataQuality071

Stage	Averaging Window, <i>hr</i>		Valve Position		Flow Area	C_v	K
	<i>Start</i>	<i>End</i>					
1	15.83	16.13	0°	100%	100%	2,096	0.05
2	16.13	16.50	22°	75%	77%	1,460	0.11
3	16.50	16.85	36°	60%	57%	1,035	0.22
4	16.86	17.17	45°	50%	44%	760	0.41
5	17.26	17.53	54°	40%	33%	509	0.90
6	17.60	17.88	57°	36%	29%	433	1.25
7	17.88	18.23	60°	33%	25%	361	1.79
8	18.31	18.57	63°	30%	22%	293	2.73
9	18.62	18.92	65°	27%	20%	246	3.87
10	19.02	19.26	68°	25%	17%	202	5.72

Figure 74: Time history of flow rate and valve position at throttling stages 1-10, DataQuality071

With the inception of boiling first observed near the 12.5-hr mark, the system experience large amplitude, pure-flashing driven oscillations consistent with start-up instabilities of a natural circulation loop. Peaking at 6.27 kg/s, the facility then continued into a window of sustained flow oscillations at a nominal peak-to-peak period of approximately 170 seconds and peak-to-peak amplitude of approximately 3 kg/s. With continuous condensate refill to maintain a constant system level, these regular flow oscillations continued for approximately 3 hours, the 15.5 hr mark, before gradually reducing to an oscillation period of 160 seconds and peak-to-peak amplitude of 1.5 kg/s. At this portion of the test, the facility had reached steady-state thermal and hydraulic conditions, as evident by the near-zero rate of change in flow parameters, liquid temperatures, and system pressures. This first period, or Stage 1, was used as the reference basis for throttling adjustments. Stages 2 & 3 reduced the flow area to 77% and 56% respectively, during which flow oscillations continued but with minor reductions in their peak-to-peak amplitude. Flashing phenomena, observed during start-up and through Stage 3 of the throttling test, occurs when the flow quality is low and a tall adiabatic chimney is present. The mechanism of this instability is hot liquid from the heater outlet experiences a hydrostatic head pressure decrease as it flows up, at which point it eventually reaches its saturation limit near the exit of the riser causing it to flash void. The increased driving force causes a rise in the flow rate leading to reduced exit temperature and suppression of flashing. This in turn then reduces the driving force and flow causing the exit temperature to increase once again leading to the repetition of the process [20]. The necessary condition for flashing is that the fluid temperature at the inlet of the riser is greater than the saturation temperature corresponding to the pressure at the exit [22] which was determined to have been met during the entire portion of the two-phase testing period in DataQuality071. By Stage 4, a reduction in flow area down to 44% available, the flow restriction caused dampening of the oscillations and the facility began a period of stable two-phase flow. This stable period continued through Stage 5 and 6, which reduced the flow area to 33% and 29% respectively.

Instabilities were re-introduced during Stage 7, at 25% total available flow area, which caused large amplitude flow oscillations, though of a different mechanism from the smooth sinusoidal shaped flashing induced peaks during startup and through Stage 3. These irregular oscillations, observed by jagged curves in the system flow rate and large voiding in the upper chimney, are likely characteristic of Type-II density wave oscillation (DWO) instabilities. This is the most commonly observed form of density wave oscillation, and is due to multiple regenerative feedbacks between the flow rate, vapor generation rate and pressure drop [21]. The system stabilized after reducing the flow area further down to 22% in Stage 8, and continued stable flow at 20% flow area in Stage 9. These stages, similar to those of Stages 4, 5, and 6, allowed the loop to flow in a stable two-phase mode of flow operation without oscillatory or periodic flow excursions. A discussion of the mechanisms driving this sequence of instability and stability follows in Section 5.3.

Instabilities finally returned at the 10th and final stage, where only 17% area was available for flow. At this condition, the flow restriction increased the residence time of fluid in the test section to a level that allowed for local voiding. Unlike previous stages where voiding was driven primarily due to a reduction in hydrostatic head pressure, these low flow rates allowed enough power to enter the local fluid that the saturation temperatures could be reached even before rising in elevation through the chimney. The phenomena drove the onset of the parallel channel instability (PCI) mechanism, which drove out-of-phase voiding and independent flow excursions across the 8 parallel riser tubes. The PCI instability is a unique phenomenon that arise from coupled influences of flashing, boiling, and geysering, that “leads to a very complex dynamic” [29]. The behavior can be chaotic in nature, with random flow reversals in individual channels a common occurrence. In addition to asymmetric flow rates with periodic reversals in adjacent channels, another key indicator is a non-uniform axial temperature distribution within the heated riser tubes. Elements of geysering are also evident, due to the stagnation of system flow, period of quiescence, and sudden eruption due to voiding. The events repeat by a series of three events: an initial period subcooled flow stagnation, incubation and enthalpy addition, and violent ejection of fluid [30]. As the authors can attest, this phenomenon is readily distinguishable by audible events originating from steam eruptions within the heated section.

A summary of selected loop parameters, relevant to the stabilizing role of the inlet throttling, is provided in Table 19. Stages 4, 5, 6, 7, and 8, were classified as stable, and exhibited minor variations in flow, void fraction, and fluid temperatures. Unstable regions, namely Stages 1, 2, 3, 7, and 10, show large variations due to flow, temperature, and void oscillations. Utilizing the flow area restriction as a basis for reference comparisons of the mean heated plate surface temperature, loop flow rate, heated section temperature rise, and individual riser flow rates are shown in Figure 75, Figure 76, and Figure 77, respectively. An enlarged figure of the void fraction including minimum and maximum spans is provided in Figure 78. Detailed subplots, at each of the 10 stages, is provided for the bulk system flow rate, individual riser channel flow rate, chimney liquid temperatures, differential pressures, and void fraction signals in Figure 79, Figure 80, Figure 81, Figure 82, and Figure 83, respectively. Finally, contour plots of the liquid temperatures within the riser tube section during the PCI flow oscillations of Stage 10 are shown in Figure 84.

Table 19: Summary of loop parameters during throttling of DataQuality071.

Stage #	Flow Area % open	Flow Loop, kg/s		Flow Risers, kg/s		Void Fraction, %		Riser Outlet, °C	Plate, °C	Stability -
		Mean	Var.	Mean	Var.	Mean	Var.	Mean	Mean	
1	0%	2.76	60%	0.351	64%	11.4%	310%	107.64	404.2	<i>unstable</i>
2	77%	2.80	55%	0.357	60%	13.1%	269%	107.66	404.6	<i>unstable</i>
3	57%	2.72	53%	0.347	58%	17.2%	258%	107.76	404.9	<i>unstable</i>
4	45%	2.63	8%	0.336	14%	42.1%	36%	107.91	405.2	stable
5	33%	2.24	5%	0.286	11%	55.1%	16%	108.60	405.5	stable
6	29%	2.07	5%	0.265	12%	58.2%	19%	108.98	405.8	stable
7	26%	1.96	56%	0.251	59%	61.4%	67%	109.35	406.0	<i>unstable</i>
8	22%	1.89	11%	0.242	18%	66.2%	37%	109.54	406.3	stable
9	20%	1.71	15%	0.219	21%	68.7%	46%	110.15	406.5	stable
10	19%	1.07	631%	0.138	1143%	27.2%	338%	112.52	406.9	<i>unstable</i>

Figure 75: Heated plate versus flow area restriction

Figure 76: Loop flow and heated section ΔT versus flow area restriction

Figure 77: Mean and variation in flow rates of eight riser channels versus flow area restriction,

Figure 78: Chimney void fraction versus available flow area, DataQuality071

Figure 79: Stages of throttling in DataQuality071, detail of system loop flow rate

Figure 80: Stages of throttling in DataQuality071, detail of individual riser flow

Figure 81: Stages of throttling in DataQuality071, detail of chimney liquid temperatures

Figure 82: Stages of throttling in DataQuality071, detail of differential pressure

Figure 83: Stages of throttling in DataQuality071, detail of chimney void fraction

Figure 84: Contour plots of test section fluid temperatures across full length and width of 8-riser tube cooling panel. A. referenced to Stage 1, B.E. referenced to PCI instabilities in Stage 10

4.7. Summary of Completed Runs

In total, eleven tests were conducted on the NSTF over the past year and summarized in Table 20. Eight of these tests were conducted in a transient inventory mode and represent a range of parametric studies including inventory loss, pressurization, heating power, and loss coefficient. Three of these tests explored steady-state inventory conditions utilizing the inventory refill system. Five tests were conducted as part of a Cooperative Research and Development Agreement (CRADA) with a US-based vendor, however details of these CRADA tests fall outside the scope of this report and are not classified according to the NQA-1 QAPP but are included here for a complete overview of the year's activities.

Table 20: Summary of testing performed on water-based NSTF during Year 3 of program activities

<u>Test</u>	<u>Date</u>	<u>Duration</u>	<u>Purpose</u>	<u>Classification</u>
DataQuality061	09/23 – 24/20	016h55m	Inventory parametric , 60% transient inventory, two-phase, 2.1 MW _t , baseline pressure (17.2 psia).	Accepted
DataQuality062	11/12 – 13/20	018h58m	Pressure parametric , reduced pressure (16.1 psia) vented to atmosphere, two-phase, 2.1 MW _t , 70% transient inventory.	Accepted
DataQuality063	12/10 – 11/20	022h57m	Scoping test of refill system , two-phase, 2.1 MW _t , 70% steady-state inventory, baseline pressure.	<i>Trending</i>
DataQuality064	01/12 – 13/21	020h34m	Loss coefficient parametric , header inlet throttle range 0% - 55% closed; two-phase 2.1 MW _t baseline, 70% steady-state inventory, baseline pressure.	Accepted
DataQuality065	02/03 – 04/20	017h48m	Power parametric , 2.8 MW _t high power, two-phase, 70% transient inventory, baseline pressure.	<i>Trending</i>
DataQuality066	03/10 – 11/21	021h56m	Scoping test of steam throttling valve , two-phase, 2.1 MW _t baseline, 70% steady state inventory; Steam exit throttle x12.5 turns (92% steam flow area reduction), peak pressure 19.2 psia	<i>Trending</i>
DataQuality067	04/07 – 08/21	021h11m	Pressure parametric , elevated pressure (18.8 psia) with steam throttle x12 turns (89% steam flow area reduction), two-phase 2.1 MW _t baseline, 70% transient inventory. Secondary purpose of loss coefficient parametric , header inlet throttling with range of 30% - 75% closed at elevated pressure once quasi-steady state achieved at above conditions.	Accepted
DataQuality068	05/06 – 07/21	019h12m	Pressure parametric , high pressure (25.5 psia) with steam throttle x13 turns (95% steam flow area reduction), two-phase 2.1 MW _t baseline, 70% transient inventory.	Accepted
DataQuality069	06/10 – 11/21	022h15m	Inventory depletion , initial inventory 55%, final inventory 21%, with accelerated drain 0.5 gpm, two-phase, 2.1 MW _t baseline, baseline pressure.	Accepted
DataQuality070	07/07 – 08/21	025h13m	Power parametric , 1.4 MW _t low power, two-phase, 70% transient inventory, baseline pressure.	Accepted
DataQuality071	08/11 – 12/21	022h07m	Loss coefficient parametric , header inlet throttle range 0% - 75 % closed, two-phase, 2.1 MW _t baseline, 70% steady-state tank inventory, baseline pressure.	Accepted

5. Stability Analysis

At the forefront of this program is an objective to provide data that is suitable for supporting the development and validation of passive safety decay heat removal systems for advanced nuclear power plants. Given the complexity inherent to natural circulation system, an integral feature of several advanced safety concepts, there is a need to ensure understanding of the underlying phenomenon that can occur in these two-phase boiling water loops. With more testing performed in FY21, especially the header inlet throttling tests, it is found that violent system flow behaviors and degrade of the system heat removal performance can occur when the boiling boundary propagates to the test section. In addition, the oscillations will pose unique structural challenges for any future implementation. If large magnitude vibrations are sustained, piping supports, bolted mating assemblies, loosened securement hardware, etc. are at risk and must be engineered accordingly. Thus, there continues to be a strong interest in understanding the instability mechanism, which at a minimum will provide a shift away from uncertainty and into predictability. With continued development and further understanding, engineering controls or design features can then be incorporated to allow these systems to operate only in stable regimes.

In an attempt to answer these questions, a cursory analysis of the flow phenomena and instability mechanisms was previously performed in FY20. As the testing program continued and with more testing data acquired in FY21, especially the true two-phase steady-state data from the refill tests, the stability analysis was continued to enhance the understanding of the two-phase boiling phenomenon in natural circulation systems, as well as to potentially provide valuable insight on the stability and performance expected from a full scale installation.

5.1. Flow Instability Mechanisms

Two-phase flow instabilities are not desirable in nuclear systems as they may cause forced mechanical vibrations and deteriorated heat transfers. Boure et al. [23] performed an extensive review of two-phase flow instabilities, and classified the phenomena into different types based on their specific mechanisms and characteristics. For low-pressure boiling systems, typical types of instabilities that should be considered include natural circulation oscillations (also called *thermal hydraulic oscillations* [25], or *hydrostatic head fluctuations* [26]), density wave oscillations (DWO), flow pattern transition instability, and geysering.

Natural circulation oscillations can occur in a loop with a part in which bubbles can accumulate [27], e.g., the Argonne water-based NSTF with both horizontal and vertical chimney sections. This phenomenon usually starts with a perturbation causing insufficient generation of vapor that accumulates in the non-heated horizontal chimney section. As vapor generation continues, accumulated bubbles coalesce with incoming vapor and cause the hydrostatic head to decrease. The decrease of hydrostatic head in the chimney

results in an increase of flow rate, which forces the accumulated bubbles out and subcooled water in. The chimney hydrostatic head is then recovered and the flow is reduced, allowing the process to start again and repeat. One characteristic of this instability is the presence of 2-5 fundamental frequencies in the measured oscillations [28], which will be discussed later.

In boiling systems, density wave oscillations are due to multiple regenerative feedbacks between the flow rate, vapor generation rate, and pressure drop [23]. Their phenomenon stems from a density difference between the inlet and outlet fluid states, which can trigger a delayed and alternating feedback from the subcooled liquid inertia and compressibility of the two-phase mixture. One characteristic of DWO is the oscillation period being approximately 1.5 to 2 times of the fluid transit time in the channel. Flow pattern transition instabilities have been postulated as occurring when the flow conditions are close to the point of transition between bubbly flow and annular flow. In bubbly-slug flow, a temporary increase in bubble population may change the flow pattern to annular flow with decreased pressure drop. The flow rate then increases which may cause insufficient vapor generation and revert the flow pattern to bubbly-slug flow. Lastly, geysering has been observed in a variety of closed end vertical columns of liquid which are heated at the base. The process mainly consists of boiling delay, condensation or expulsion of vapor, and liquid returning.

5.2. Hydraulic Analysis

5.2.1. *Oscillation Period*

The loop flow oscillation periods for all the previous successful tests are summarized in Figure 85 – Figure 88, divided into four groups, namely, the inventory parametric, the pressure parametric, the power parametric, and the refill parametric. Across the inventory parametric tests, higher starting inventory level leads to longer flow oscillation period, Figure 85. For a single test and excluding the first few startup flow oscillations, the oscillation period decreases as the inventory level drops. For the pressure parametric series, it is found that higher system pressure leads to longer flow oscillation period, Figure 86. In contrast, higher total power leads to shorter flow oscillation period, Figure 87. For the refill tests (Run064 and Run071), the constant inventory level results in longer oscillation period compared to the baseline Run060 with decreasing inventory level, Figure 88. In addition, as the system approaches a steady state, a constant oscillation period of ~ 163.8 seconds is achieved.

One characteristic of the natural circulation oscillations is the presence of multiple fundamental frequencies. The presence of additional modes within the larger system oscillation can be examined by a time domain frequency analysis. The fast Fourier transform results of the pressure drop in the upper chimney section (ΔP_4) are shown in Figure 89 - Figure 92. The first fundamental frequency represents the

primary system wide fluctuations, while the additional peaks represent the higher order harmonics (integer products of the fundamental) characteristic of the natural circulation oscillations mechanism. The leading frequencies of the performed tests are summarized in Table 21.

Table 21: Summary of the leading frequencies, upper chimney ΔP Fast Fourier Transform

Leading Frequency, Hz x 1000	
Inventory Parametric	
Run059	5.01
Run060	5.29
Run061	6.31
Pressure Parametric	
Run062	5.27
Run060	5.29
Run067	4.97
Run068	4.76
Power Parametric	
Run060	5.29
Run070	3.72
Refill Parametric	
Run060	5.29
Run064	5.11
Run071	5.20

Figure 85: Loop flow oscillation period comparison for inventory parametric

Figure 86: Loop flow oscillation period comparison for pressure parametric

Figure 87: Loop flow oscillation period comparison for power parametric

Figure 88: Loop flow oscillation period comparison for refill tests

Figure 89: Fundamental frequencies in the upper chimney pressure drop, inventory parametric tests

Figure 90: Fundamental frequencies in the upper chimney pressure drop, pressure parametric tests

Figure 91: Fundamental frequencies in the upper chimney pressure drop, power parametric tests

Figure 92: Fundamental frequencies in the upper chimney pressure drop, refill tests

5.2.2. *Transit Times*

The fluid transit time is an important parameter to consider when determining the two-phase flow instability mechanisms. The DWO features an oscillation period approximately 1.5 to 2 times of the fluid transit time in the channel which is defined as including the full length of the chimney region and half of the heated core/test section.

$$\tau_{Channel} = \frac{V_{Chimney} + 0.5V_{Core}}{\dot{Q}_{bulk}} \quad [4]$$

where V denotes the fluid volume, and $\dot{Q}_{bulk}$ denotes the bulk volumetric flow rate. The two-phase flow oscillation periods are plotted against the fluid transit times in the channel for all the parametric tests, Figure 93 - Figure 96. Although the system behaviors observed in these tests exhibit similar characteristics of DWO, it is believed that natural circulation oscillations is the dominant instability mechanism here. As seen from the plots, only the later period of the examined two-phase window in Run060 lies in the DWO operating zone (between x1.5 and x2 lines). Lisowski et al. [28] identified a different characteristic transit time that could represent the observed flow oscillations during the full growth and decay of oscillations. This transit time accounts for the flow path of the entire system from the tank outlet to inlet, and defined as:

$$\tau_{System} = \frac{V_{DC} + V_{Core} + V_{Chimney}}{\dot{Q}_{bulk}} \quad [5]$$

where the subscript DC denotes downcomer. The fluid transit time in the entire system for the performed tests is shown in Figure 97 - Figure 100. As seen, for all the tests, majority of the potted data consistently lie in between x1 and x1.5 lines, indicating that this new transit time definition may be viewed as a means to further identify the mechanism of natural circulation oscillations observed in the tests.

Figure 93: Fluid transit time in the channel vs oscillation period, inventory parametric tests

Figure 94: Fluid transit time in the channel vs oscillation period, pressure parametric tests

Figure 95: Fluid transit time in the channel vs oscillation period, power parametric tests

Figure 96: Fluid transit time in the channel vs oscillation period, refill tests

Figure 97: Fluid transit time of system vs period, inventory parametric

Figure 98: Fluid transit time of system vs period, pressure parametric

Figure 99: Fluid transit time of system vs period, power parametric

Figure 100: Fluid transit time of entire system vs oscillation period, refill tests

5.3. Stability Mapping

The use of an inlet orifice or throttle valve are common industry practices used to stabilize oscillations in force circulation systems. For single phase flow, this throttling increases the flow friction and thus provides a damping effect on the increasing flow. In two-phase systems, however, increasing the inlet throttling reduces the natural circulation flow rate which causes an increase in channel exit quality and shifts the unstable region to higher inlet subcooling [17]. Since the flow rate decreases, this leads a higher power to flow ratio, or threshold power for triggering an instability, often causing the onset of density wave oscillations. Others have indicated that the effect of inlet restriction remains unknown especially with respect to the boiling natural circulation loop with a long and large diameter chimney comparing to the length and flow area of a heated section such as the natural circulation BWR [18]. Nayak et al. [19] performed loss coefficient analysis of a parallel channel two-phase natural circulation loop for the Indian Advanced Heavy Water Reactor (AHWR). They observed a stable zone of Type-I instability which remained continuous regardless of increases in loss coefficient. For Type-II instabilities, they also observed stability when the inlet loss coefficient was increased, however only until a threshold point of $K = 30$, a value unique from their AHWR facility geometry and test conditions. When they further increased the inlet coefficient past 30, however, they found a decrease in the threshold and thus higher likely hood for the onset of Type-II instability. The authors conclude that for a natural circulation system with multiple channels, increases in orificing of inlet channels does not always increase the stability.

Boure et al. [23] identified the role of inlet subcooling on the stability of a two-phase natural circulation loop. They found that an increase in the inlet subcooling at a channel inlet decreases the void fraction along the loop, which in turn increases the non-boiling length and the fluid transit time. Thus the increase of inlet subcooling stabilizes two-phase boiling flow at medium or high subcooling. At small subcooling, however, an incremental change of transit time is significant in the response delay of void generation from the inlet flow and the increase of inlet subcooling destabilizes the flow. Boure et al. concluded that these stabilizing and destabilizing effects are competing, and insight into the stability regimes requires specific knowledge of the specific geometry and operating conditions. Though in all 10 stages of two-phase flow with restricted inlet observed in DataQuality071 the inlet subcooling, defined as the difference in local fluid temperature from the saturation point at the local pressure, remained a near constant of 10.8°C . This parameter is an important variable that may provide indications for throttling induced stability during other levels of heated power, loop geometry, boundary conditions, etc.

Examining the stability of the two-phase behavior, the flow parameters were used to determine the dimensionless Subcooling (N_{sub}) and Zuber or Phase Change number (N_{ph}) numbers, as defined by Eq. 6 and 7. Note, the Subcooling number, a non-dimensional parameter, should not be confused with inlet subcooling, a dimensioned value with units of °C. Using a stability map for two-phase flow system by Fukuda and Kobori [24] to establish stable and unstable regions, N_{sub} and N_{ph} at each of the ten stages during DataQuality071 are plotted, Figure 101.

$$N_{sub} = \frac{c_{pl}\Delta T_{sub}}{h_{fg}}(\rho_f/\rho_g - 1) \quad [6]$$

$$N_{ph} = \frac{Q}{Wh_{fg}}(\rho_f/\rho_g - 1) \quad [7]$$

Figure 101: Subcooling and Phase Change stability mapping, stages in DataQuality071

6. Path Forward

With completion of matrix testing in FY21, a maintenance period for the experimental test facility has been scheduled and will begin by early FY22. During this window the project team will place the facility into a cold standby mode and perform repair activities for the faulted Guard heaters, examine the cavity interior, collect emissivity measurements of the test section and heated surfaces, and perform other maintenance and upgrade tasks as necessary. To expose the guard heater elements, a significant portion of our outer insulation panels will need to be removed from the heated cavity, thus this maintenance window will likely require an extended duration for disassembly, repair, and reassembly.

With completion of the scheduled maintenance, expected to extend 4 – 6 months, matrix testing will resume and begin with repeat testing to ensure continuity of the facility operation and behavior after repairs and other maintenance work. Following, the power parametric test series will be closed-out by completion of the final very-high power test case, which has been put on-hold due to the faulted heater zones. A prototypic accident scenario test case will then be conducted to examine the heat removal performance over the full extent of a prototypic accident scenario. These conditions will incorporate an extended duration decay heat curve and representative cosine power profile for a design basis accident in a full-scale conceptual reactor design. Based on scheduling and completion of these test cases, off-normal testing will be initiated with new scenarios involving partially and fully closed riser channels.

Acknowledgements

This work was supported by the U.S. Department of Energy Office of Nuclear Energy's Advanced Reactor Technology (ART) and Office of Advanced Reactors Regulatory Development (RD), under contract number DE-AC02-06CH11357. The NSTF program team wishes to extend our gratitude for the funding, support, and guidance from our program sponsor and associated laboratories. We also wish to acknowledge the technical, laboratory, and QA support that has been provided by other Argonne staff including Art Vik, Roberta Riel, and John Woodford.

References

- [1] Lomperski, S., Pointer, W.D., Tzanos, C.P., Wei, T.Y.C., and Kraus, A., 2011. Air-cooled Option RCCS Studies and NSTF Preparation, ANL-GenIV-179. Argonne National Lab. (ANL), Argonne, IL (United States).
- [2] Lisowski, D., Gerardi, C.D., Kilsdonk, et. al., 2016. Final Project Report on RCCS Testing with Air-based NSTF, ANL-ART-47. Argonne National Lab. (ANL), Argonne, IL (United States).
- [3] Lisowski, D., Lee, T., Kilsdonk, D.J., et. al., 2015. Status Report on the Water-Based NSTF RCCS Capability: Preparations and Design for the Transformation of the Natural Convection Shutdown Heat Removal Test Facility (NSTF) From Air to Water-based Cooling, ANL-ART-23. Argonne National Lab. (ANL), Argonne, IL (United States).
- [4] Lisowski, D., 2017. Unpublished information, Argonne National Lab (ANL), Argonne, IL US.
- [5] Lisowski, D., Gerardi, C.D., Hu, R., Kilsdonk, D.J., Bremer, N.C., Lomperski, S.W., Kraus, A.R., Bucknor, M.D., Farmer, M.T., 2017. Water NSTF Design, Instrumentation, and Test Planning, ANL-ART-98. Argonne National Lab. (ANL), Argonne, IL (United States).
- [6] Tzanos, C.P., Farmer, M.T., 2007. Feasibility study for use of the natural convection shutdown heat removal test facility (NSTF) for VHTR water-cooled RCCS shutdown, ANL-GenIV-079. Argonne National Lab. (ANL), Argonne, IL (United States).
- [7] AREVA, No.: 12-9237246-000, “Water-Cooled RCCS RD Designer Observation Report”, Technical Data Record, 2014
- [8] Lv, Q., Kraus, A., Hu, R., Bucknor, M., Lisowski, D., Nunez, D., 2017. Progress Report on Computational Analyses of Water-Based NSTF, ANL-ART-103. Argonne National Lab. (ANL), Argonne, IL (United States).
- [9] Lv, Q., Kraus, A., Hu, R., Bucknor, M., and Lisowski, D., 2019. “Preliminary RELAP5 System Analysis of the Water-Based NSTF Part 1: Model Development”, Proceedings of NURETH-18, 4372-4387
- [10] Lv, Q., Kraus, A., Hu, R., Bucknor, M., and Lisowski, D., 2019. “Preliminary RELAP5 System Analysis of the Water-Based NSTF Part 2: Parametric Study”, Proceedings of NURETH-18, 4388-4405
- [11] Lv, Q., Kraus, A., Hu, R., and Lisowski, D., 2021. “Benchmark of RELAP5 Modeling for the Water-based NSTF Single-phase Operations”, Transactions of American Nuclear Society, 744-747
- [12] ASME NQA-1-2009 (with 1a 2009 addenda), “Quality Assurance Requirements for Nuclear Facility Applications”, 2008
- [13] Lisowski, D., Lv, Q., Hu, R., Kraus, A., Bremer, N., Kilsdonk, D.J., Farmer, M., 2019. RCCS Testing with the Water-based NSTF: Year-1 Single-Phase Results, ANL-ART-175. Argonne National Lab. (ANL), Argonne, IL (United States).
- [14] Lisowski, D., et. al., 2020. Report on Year-2 of Water NSTF Matrix Testing: Two-Phase Baseline & Repeatability, ANL-ART-206. Argonne National Lab. (ANL), Argonne, IL (United States).
- [15] Lisowski et al., 2017. Unpublished information, Argonne National Lab. (ANL), Argonne, IL (United States).
- [16] Flanged Jamesbury Ball Valves ASME Class 150 & 300 Full Bore: 1/2"-24" (DN15-600), Series 9000. Technical Bulletin B107-2EN, 10/2020

- [17] Nayak, A.K., Vijayan, P.K., 2008. Flow Instabilities in Boiling Two-Phase Natural Circulation Systems: A Review. *Science and Technology of Nuclear Installations* 2008, 1-15.
- [18] Furuya, M., Inada, F., Yasuo, A., 2001. Inlet throttling effect on the boiling two-phase flow stability in a natural circulation loop with a chimney. *Heat and Mass Transfer* 37, 111–115.
- [19] Nayak, A.K., Vijayan, P.K., Saha, D., 2000. Analytical Modelling and Study of the Stability Characteristics of the Advanced Heavy Water Reactor (No. BARC/2000/E/011). Bhabha Atomic Research Center, Mumbai, India.
- [20] Vijayan, P.K., Nayak, A.K., 2010. Introduction to Instabilities in Natural Circulation Systems, IAEA Training Course on Natural Circulation Phenomena and Passive Safety Systems. Presented at the Advanced Water-Cooled Reactors, ICTP, Trieste, Italy.
- [21] Furuya, M., 2006. Experimental and Analytical Modeling of Natural Circulation and Forced Circulation BWRs. Tokyo.T
- [22] Jiang, S.Y, Yao, M.S, Bo, J.H and Wu, S.R, 1995, Experimental simulation study on the start-up of the 5 MW nuclear heating reactor, *Nuclear Engineering and Design* 158, pp.111-123
- [23] Boure, J.A., Bergles, A.E., Tong, L.S., 1973. Review of two-phase flow instability. *Nuclear Engineering and Design* 25, 165–192.
- [24] Fukuda, K., and Kobori, T., 1979. “Classification of Two-Phase Flow Instability by Density Wave Oscillation Model”, *Journal of Nuclear Science and Technology*, 16, 95-108
- [25] Wu, C.Y., Wang, S.B., and Pan, C., 1996. “Chaotic Oscillations in a Low Pressure Two-phase Natural Circulation Loop under Low Power and High Inlet Subcooling Conditions”, *Nuclear Engineering and Design*, **162**, 223-232
- [26] Subki, M.H., Aritomi, M., and et al., 2004. “Multi Parameter Effect of Thermohydraulic Instability in a Natural Circulation Boiling Water Reactor During Startup”, *JSME Int. J. B*, 277-286
- [27] Chiang, J.H., Aritomi, M., and Mori, M., 1993. “Fundamental Study on Thermohydraulics During Start-up in Natural Circulation Boiling Water Reactors, (ii) Natural Circulation Oscillation Induced by Hydrostatic Head Fluctuations”, *J. Nucl. Sci. Technol*, **30**, 203-211
- [28] Lisowski, D.D., Omotowa, O., Muci, M.A., Tokuhiro, A., Anderson, M.H., and Corradini, M.L., 2014. “Influences of Boil-off on the Behavior of a Two-phase Natural Circulation Loop”, *International Journal of Multiphase Flow*, **60**, 135-148
- [29] Marcel, C.P. et al., 2010. “Experimental Investigations on Flashing-induced Instabilities in One and Two-parallel Channels: A Comparative Study”, *Exp. Therm. Fluid Sci*, **34**, 879-892
- [30] Kyung, I.S., Lee, S.Y., 1994. Experimental observations on flow characteristics in an open two-phase natural circulation loop. *Nuclear engineering and design* 150, 163-176.

Nuclear Science & Engineering

Argonne National Laboratory
9700 South Cass Avenue, Bldg. 206
Argonne, IL 60439

www.anl.gov

Argonne National Laboratory is a U.S. Department of Energy
laboratory managed by UChicago Argonne, LLC