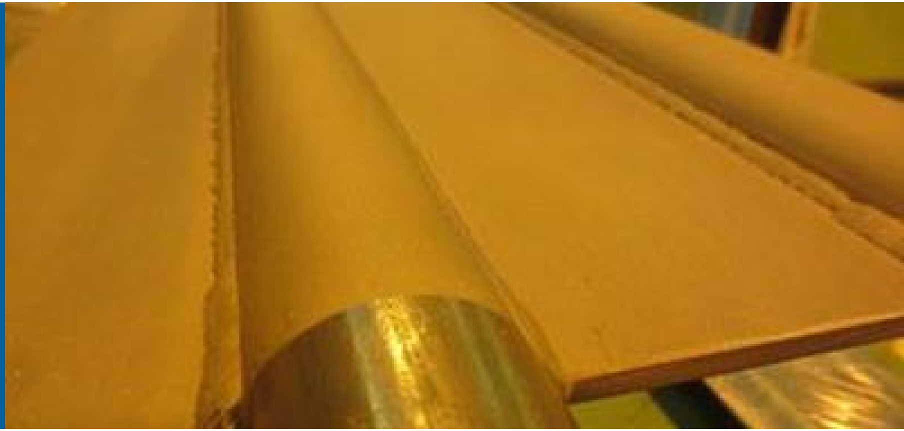
WE START WITH YES.

Argonne NATIONAL LABORATORY

WATER-COOLED NSTF RECENT DATA AND CURRENT STATUS



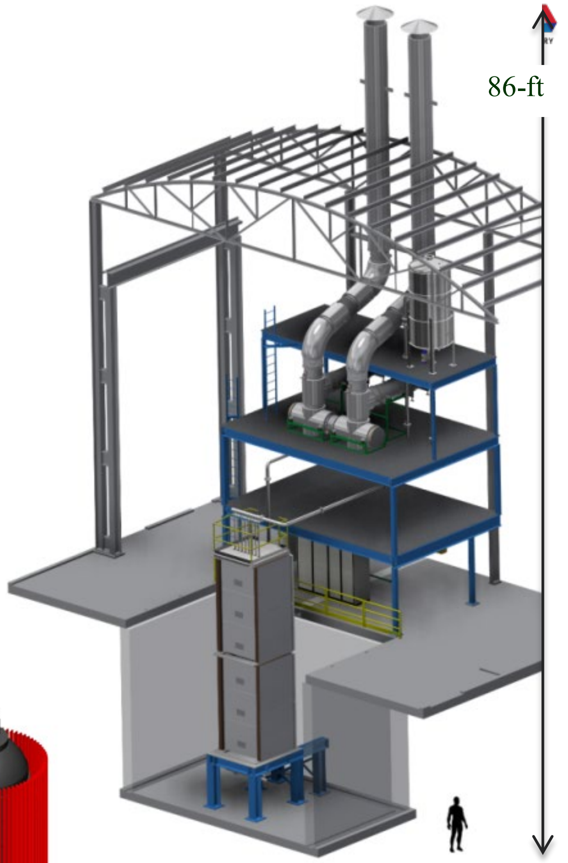
DARIUS LISOWSKI QIUPING LV MATT JASICA MITCH FARMER

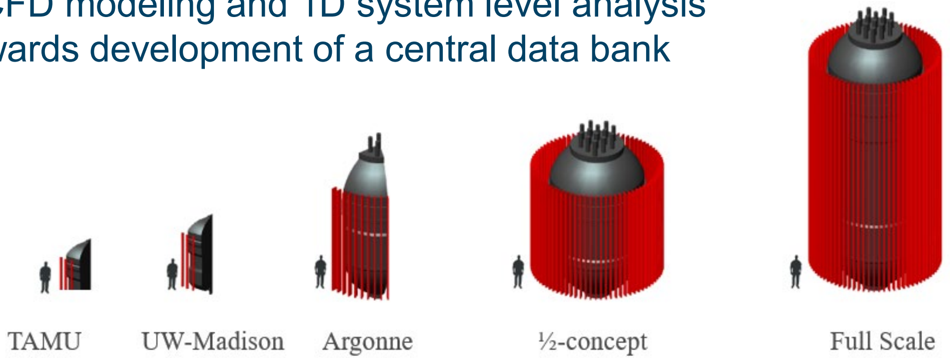
July 13th, 2022

Advanced Reactor Technologies
Gas-Cooled Reactor Program Review

INTRODUCTION

- Natural Convection Shutdown Heat Removal Test Facility (NSTF) was initiated in support of DOE programs: NGNP, SMR, and ART
  - Air-based testing program (completed, FY13 - FY16)
  - Water-based testing program (on-going, FY18 to present)
- Top level objectives of NSTF program at Argonne:
  - passive safety and decay heat removal for advanced concepts
  - generate NQA-1 qualified licensing data for industry
  - provide benchmark data for code V&V
- Concurrent with a broader scope and multiple collaborators
  - Experimental facilities at scales (½, ¼, etc.) for both air and water
  - Complimenting CFD modeling and 1D system level analysis
  - Collaborating towards development of a central data bank





CURRENT PROJECT FOCUS

- With successful conclusion of air-based testing, program has shifted to a water-based operation of the existing test facility
- Water-cooled NSTF based on concept for Framatome 625 MW_t SC-HTGR
  - DOE sponsored HTGR Technology Economic/Business Analysis and Trade Studies
- Program Objectives:
  - Continue RCCS initiative by generating experimental data from ½ scale water test facility
  - Provide data for code qualification
  - Examine heat removal performance of a water-cooled RCCS concept
- Close ties with industry and academia
  - Previous CRADA with Kairos Power;
  - Previous NEUP with TAMU, UW-Madison, etc.
  - Current ARPA-E with Framatome

PROGRAM QUALITY ASSURANCE

- Regular audits, or assessments, maintain compliance to NQA-1
  - Following requirements of ASME NQA-1 2008 with 2009 addendum
  - Small team of dedicated individuals with strong management support
  - Primary purpose is generating and packaging high-quality data

NQA-1 2008/2009a compliant

Date	Audit Type	Lead Auditor
Spring 2014, 03/18 – 20/2014	☐ MA ☐ Internal ☑ **External**	Kirk Bailey (INL)
Winter 2014, 02/16 – 18/2015	☑ **MA** ☐ Internal ☐ External	Roberta Riel (ANL)
Summer 2015, 07/20 – 23/2015	☐ MA ☑ **Internal** ☐ External	Roberta Riel (ANL)
Fall 2015, 11/3 – 5/2015	☐ MA ☐ Internal ☑ **External**	Alan Trost (INL)
Winter 2016, 01/21/2016	☑ **MA** ☐ Internal ☐ External	Roberta Riel (ANL)
Summer 2016, 06/29 – 30/2016	☐ MA ☑ **Internal** ☐ External	Roberta Riel (ANL)
Fall 2016, 11/29 – 30/2016	☑ **MA** ☐ Internal ☐ External	Roberta Riel (ANL)
Fall 2017, 11/07 – 09/2017	☐ MA ☑ **Internal** ☐ External	Roberta Riel (ANL)
Spring 2018, 02/06 – 08/2018	☐ MA ☐ Internal ☑ **External**	Michelle Sharp (INL)
Summer 2018, 05/30/2018	☑ **MA** ☐ Internal ☐ External	Roberta Riel (ANL)
Winter 2019, 01/29 – 30/2019	☐ MA ☑ **Internal** ☐ External	Roberta Riel (ANL)
Winter 2020, 02/18 – 19/2020	☑ **MA** ☐ Internal ☐ External	Roberta Riel (ANL)
Spring 2020, 03/17 – 19/2020	☐ MA ☐ Internal ☑ **External**	R. Dieter (Kairos)
Fall 2020, 08/25 – 27/2020	☐ MA ☑ **Internal** ☐ External	Roberta Riel (ANL)
Summer 2021, 09/07 – 09/2021	☐ MA ☑ **Internal** ☐ External	Roberta Riel (ANL)
Spring 2022, 4/25 – 28/2022	☑ **MA** ☐ Internal ☐ External	Roberta Riel (ANL)
Spring 2023, TBD	☐ MA ☐ Internal ☑ **External**	TBD

FY22 NEW FUNDING & PLUS-UP

- DOE funding

Work Package	Activity	Months Active
AT-22AN060201	Program Administration & NQA-1	12
RD-22AN050201	Experimental Matrix Testing	12
	Computational Analysis	5

- Plus-up in May '22 supported revitalized Computational Analysis activity that was not included in original FY work package due to funding constraints
  - Work scope includes use of existing RELAP5 model as a predictive capability tool to support test planning; and continuation of development to improve modeling accuracy of complex two-phase phenomena

- Additional support via ARPA-E with Framatome "*Digital Twin-Based Asset Performance and Reliability Diagnosis for the HTGR Reactor Cavity Cooling System Using Metroscope*"

FY22 DELIVERABLES

Level	Work Package / Deliverable	Target	Actual	Status
L3	**AT-22AN060201** Complete ‘Accident Scenario’ matrix test & Submit test report	06/30/2022	06/29/2022	**Completed**
L3	**RD-22AN050201** Progress report on RELAP5 modeling of NSTF two-phase experiments	09/15/2022	09/15/2022	*On Schedule*
L2	**RD-22AN050201** Test report detailing experimental results from power parametric, accident scenario, and off-normal test cases	08/01/2022	09/15/2022	*Exp. Late*

- L3 milestone and deliverable completed and submitted on time in late June 2022
- Mid-FY testing schedule was adjusted due to constraints with staffing availability
  - Typical year-end activities (calibration, in-depth analysis, documentation, etc.) were moved up to allow continued progress of the overall program
- For inclusion of full year accomplishments in deliverable report, completion of L2 milestone will be moved to late in FY

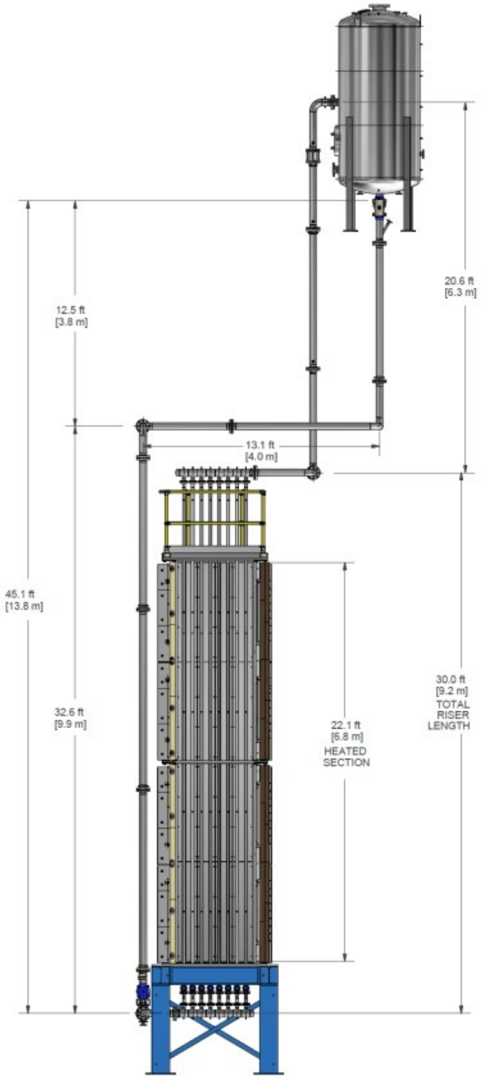
PROGRAM HOSTED REVIEW MEETING, FY22

- Key players joined for 1-day review of the water-based NSTF program, hosted by Argonne and held virtually Nov. 16th 2021
  - Invitation extended to those involved with NSTF and broader RCCS activities
  - Participation and feedback critical in ensuring a level of completeness as the NSTF program continues scheduled water-based matrix test series
- Meeting purpose:
  - Present completed testing and simulation results from NSTF program
  - Jointly discuss the planning for remaining water-based matrix testing
  - Share updates from Industry and Academia
- 43 total participants from DOE, US-NRC, Argonne, INL, Framatome, Kairos Power, X-Energy, UW-Madison, Texas A&M, and Oregon State
- Collaboration of industry, federal, national labs, and universities supports greater goals of the US industry passive decay heat removal initiative

FACILITY OVERVIEW

TEST FACILITY OVERVIEW

- ½ axial scale based off Framatome 625 MW_t SC-HTGR
  - Total height of 18 m (59-ft)
  - Heated length of 6.7 m (22-ft)
- Natural circulation boiling water test loop
  - Operating modes of natural or forced
- 4,260 liter water storage tank
  - H/D ratio of 2.0, rated to 2 bar over pressure
- Heat transfer panel:
  - Eight riser tubes and ten heat transfer panels
  - 316L stainless tubes, 1018 carbon fins
  - Full penetration HLAW weld to risers
- Network piping: 4.0” Sch. 40, 316L stainless



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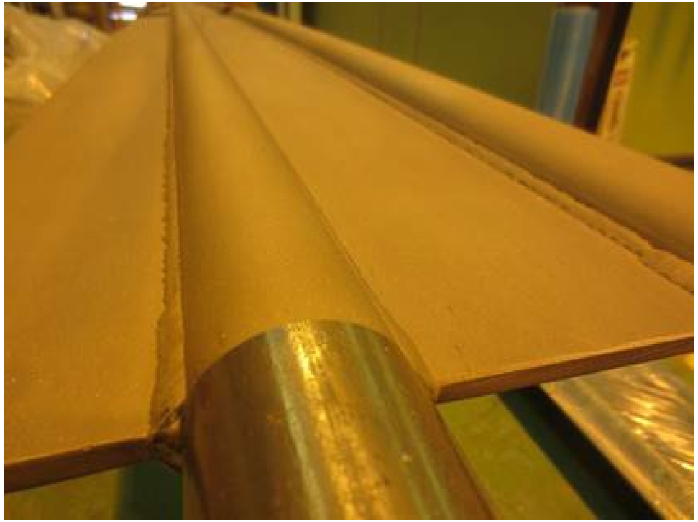
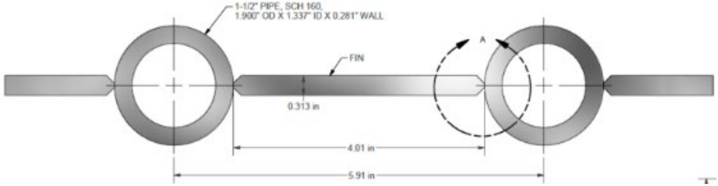
WATER COOLING PANEL TEST SECTION

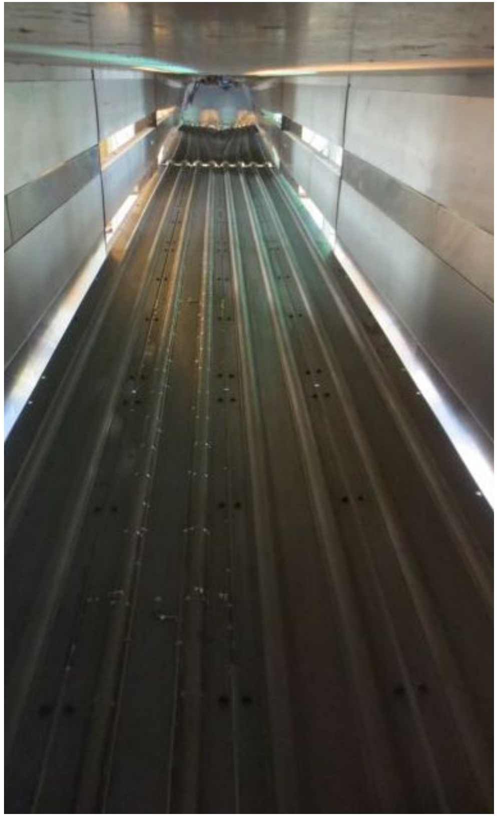


Bead blasted cooling panel surface



Dimensions of single “panel”

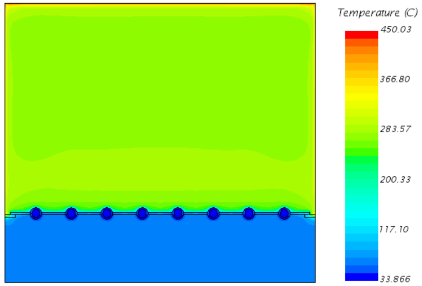
Panel hoisted vertical prior to install

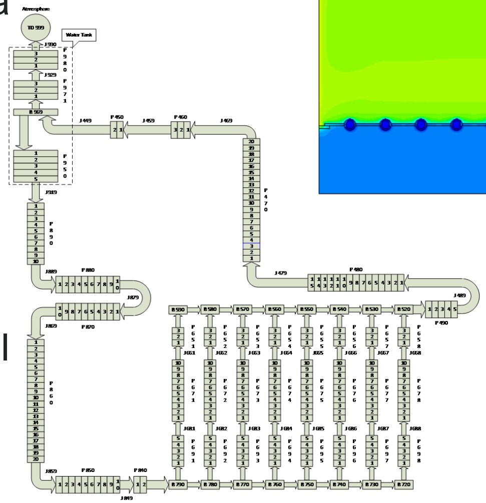


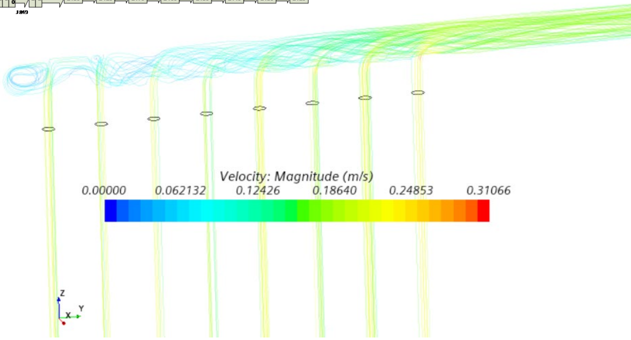
Installed test section, view in heated cavity

COMPUTATIONAL MODELING

- Support NSTF experimental program
  - Aid in corroboration and understanding of experimental data
  - Data vetting for generated sets
  - Predictive capabilities for upcoming / high hazard tests
- Assess code capabilities/limitations in modeling NSTF/ RCCS systems using both system T/H and CFD codes
- System modeling progress using RELAP5-3D (v4.2.1)
  - Parametric studies: power, system pressure, inlet throttling, tank inventory, geometric variation, and test section material
  - Code benchmark using single-phase data
  - Two-phase flow instabilities prediction
- CFD modeling progress using STAR-CCM+ (v15.06)
  - Development of full facility geometry
  - Detailed study of flow distribution
  - Impacts of insulation on flow behavior in the cavity
  - Provide detailed and localized heat transfer data to compare with and expand RELAP modeling
  - Focused on areas with significant 3-D phenomena







FY22 MAINTENANCE PERIOD

FACILITY REPAIRS AND MAINTENANCE

- For the past 36-months, the test facility has been operating on a regular basis, logging over 800-hours of active heating across over 40 test scenarios
  - To address scheduled needs for inspection and maintenance, along with repairs of the faulted heaters, the testing program was paused at end of FY21
- On September 1st, 2021, facility was placed into cold-standby with inventory fully drained and electrical systems de-energized
- Outage extended nearly 5-months, with testing resumed in February of 2022

MAINTENANCE WORK

CAVITY INSPECTION

- Outer insulation panels on heated cavity were removed to allow access to interior
- Initial inspections indicate that all components (e.g. cavity separation insulation, sensors, reflective panels, etc.) have remained in intended positions
- Surface conditions have been visually examined, confirming expected oxidation of carbon steel fins
- Personnel entry for detailed documentation and measurement of emissivity

RECENT TESTING RESULTS

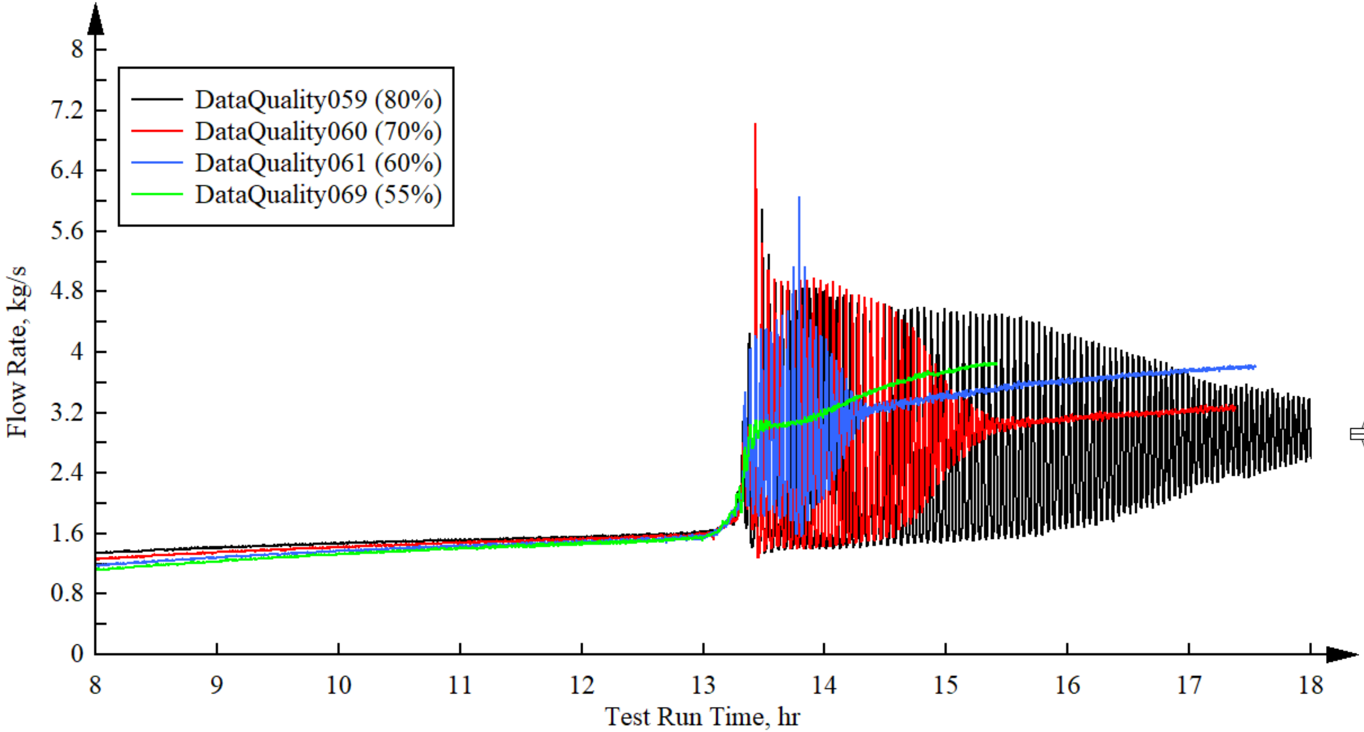
COMPLETED MATRIX TEST CASES

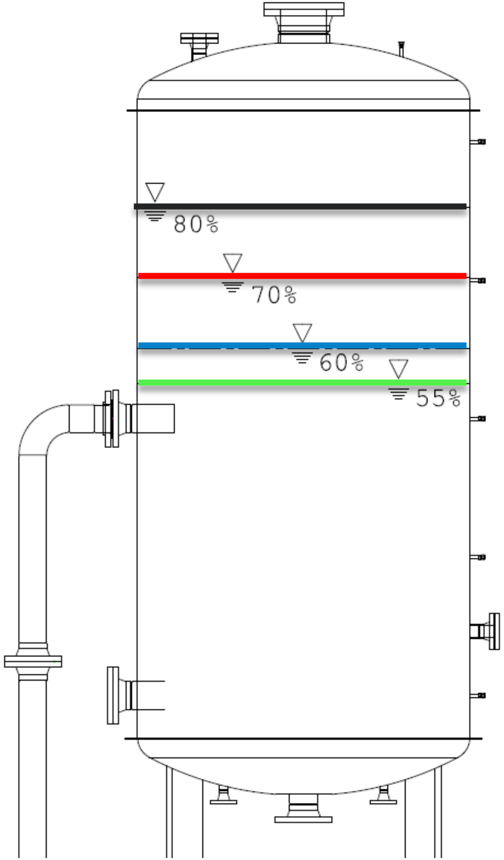
	Test Name	Date	Duration	Purpose	Classification
FY18	BakeOut003	06/01/2018	010h06m	Heater & insulation bake out	☐ Accepted ☐ Trending ☐ failed ☑ **n/a**
	BakeOut004	06/07/2018	007h26m	Heater & insulation bake out	☐ Accepted ☐ Trending ☐ failed ☑ **n/a**
	Shakedown001	07/05 – 06/2018	024h22m	Single-phase demonstration, 60% tank vol.	☐ Accepted ☐ Trending ☐ failed ☑ **n/a**
	DataQuality050	08/03/2019	008h57m	Single-phase, 1.4 MW_t baseline, 80%	☐ Accepted ☐ Trending ☑ **failed** ☐ n/a
FY19	DataQuality051	11/28 - 29/2018	026h53m	Single-phase, 1.4 MW_t baseline, 80%, 15°ΔT	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a
	Characteriz001	01/15/2019	001h26m	Isothermal characterization test	☐ Accepted ☐ Trending ☐ failed ☑ **n/a**
	DataQuality052	01/16 - 17/2019	029h4m	Single-phase, 2.1 MW_t baseline, 80%	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a
	Shakedown002	02/19 – 20/2019	028h29m	Two-phase demonstration, 60% tank vol.	☐ Accepted ☐ Trending ☐ failed ☑ **n/a**
	DataQuality053	03/26 – 27/2019	026h52m	Single-phase, 2.1 MW_t baseline, 80%, riser throttle	☐ Accepted ☑ **Trending** ☐ failed ☐ n/a
	DataQuality054	04/25 – 05/01	177h37m	Transient characterization; Single-phase, 700 kW_t,	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a
	Characteriz002	06/03/2019	003h00m	Isothermal characterization test	☐ Accepted ☐ Trending ☐ failed ☑ **n/a**
	DataQuality055	6/13 – 14/2019	026h01m	Single-phase, 2.8 MW_t baseline, 80%; 42kW_t addt'l	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a
	Characteriz003	07/22/2019	001h28m	Isothermal characterization test	☐ Accepted ☐ Trending ☐ failed ☑ **n/a**
	Characteriz004	08/29/2019	003h03m	Isothermal characterization test, post new riser valves	☐ Accepted ☐ Trending ☐ failed ☑ **n/a**

COMPLETED MATRIX TEST CASES

	Test Name	Date	Duration	Purpose	Classification
FY20	DataQuality056	10/08 – 10/2019	054h14m	Single-phase and two-phase 2.1 MW_t baseline	☐ Accepted ☑ **Trending** ☐ failed ☐ n/a
	DataQuality057	11/07 – 08/2019	020h24m	Two -phase 2.1 MW_t baseline	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a
	DataQuality058	12/12– 13/2019	021hm34	Two -phase 2.1 MW_t baseline (repeatability)	☐ Accepted ☐ Trending ☑ **failed** ☐ n/a
	DataQuality059	03/04 – 04/2020	019h05m	Two -phase 2.1 MW_t baseline (repeatability)	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a
	DataQuality060	06/25 – 26/2020	019h28m	Two -phase 2.1 MW_t baseline, 70% inventory	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a
FY21	DataQuality061	09/23 – 24/2020	016h55m	Two-phase 2.1 MW_t baseline; 60% inventory	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a
	DataQuality062	11/12 – 13/2020	018h58m	Two-phase 2.1 MW_t baseline; Reduced pressure	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a
	DataQuality063	12/10 – 11/2020	022h57m	Two-phase 2.1 MW_t baseline, Steady-state refill	☐ Accepted ☑ **Trending** ☐ failed ☐ n/a
	DataQuality064	01/12 – 13/2021	020h34m	Two-phase 2.1 MW_t baseline; Header inlet throttle	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a
	DataQuality065	02/03 – 04/2020	017h48m	Two-phase 2.8 MW_t High power	☐ Accepted ☑ **Trending** ☐ failed ☐ n/a
	DataQuality066	03/10 – 11/2021	021h56m	Two-phase 2.1 MW_t baseline, Moderate pressure	☐ Accepted ☑ **Trending** ☐ failed ☐ n/a
	DataQuality067	04/07 – 08/2021	021h11m	Two-phase 2.1 MW_t baseline, Moderate pressure	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a
	DataQuality068	05/06 – 07/2021	019h12m	Two-phase 2.1 MW_t baseline, High pressure	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a
	DataQuality069	06/10 – 11/2021	022h15m	Two-phase 2.1 MW_t baseline, 55% inventory	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a
	DataQuality070	07/07 – 08/2021	025h13m	Two-phase 1.4 MW_t Low power	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a
	DataQuality071	08/11 – 12/2021	022h07m	Two-phase 2.1 MW_t baseline; Header inlet throttle	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a
FY22	DataQuality072	02/10 - 11/2022	027h21m	Single-phase, 1.4 MW_t baseline, ARPA-E fault #1,2,&3	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a
	DataQuality073	03/16 - 17/2022	021h02m	Two-phase 2.1 MW_t baseline; Riser outlet throttle	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a
	DataQuality074	04/18 - 21/2022	071h45m	Framatome accident scenario, V.2 scaled x5.2	☑ **Accepted** ☐ Trending ☐ failed ☐ n/a

VOLUME PARAMETRIC





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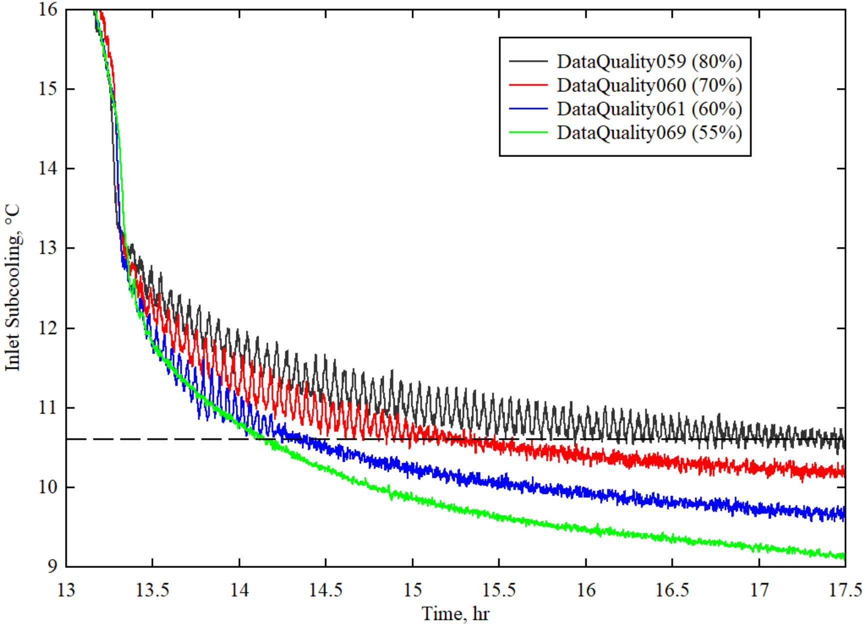
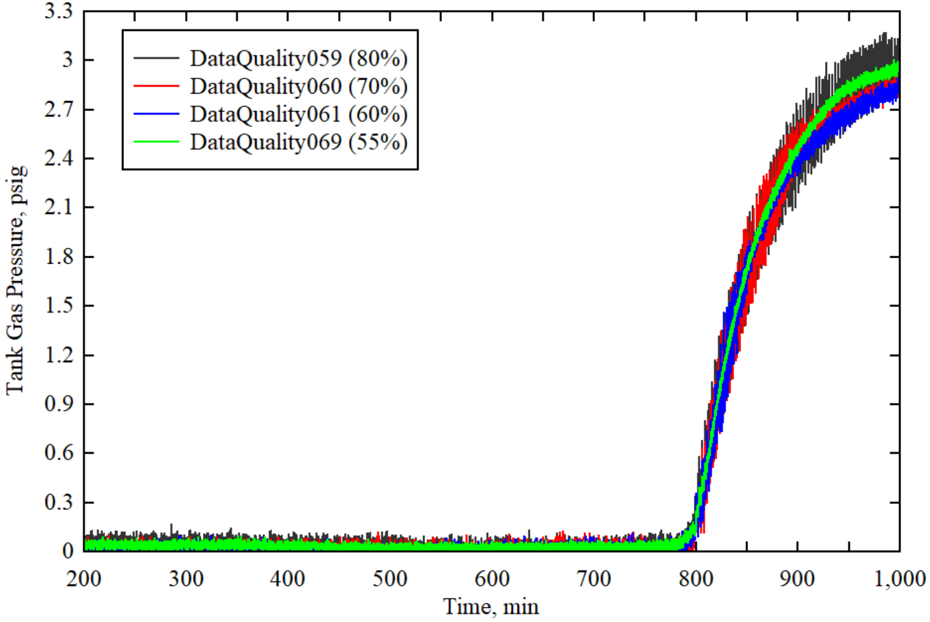
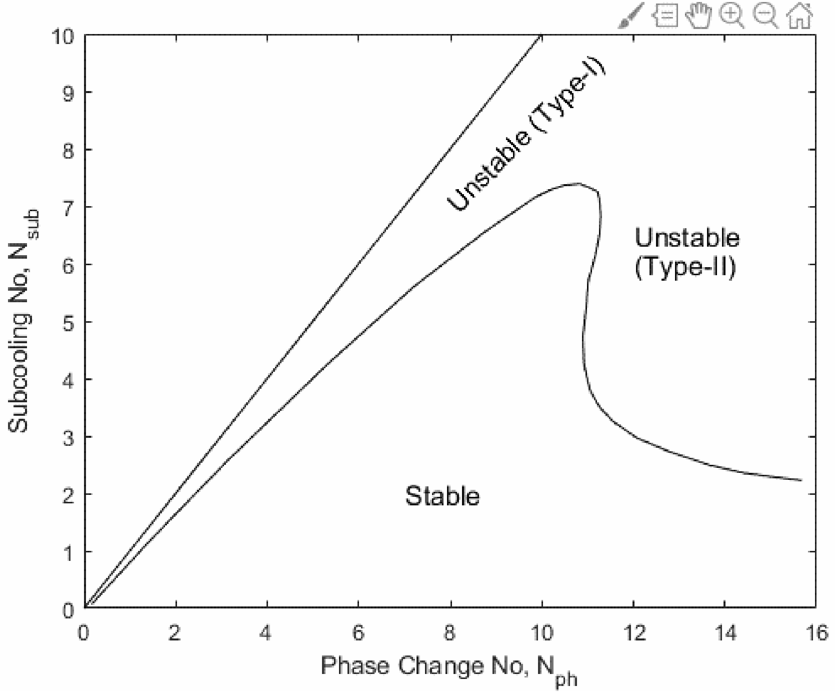
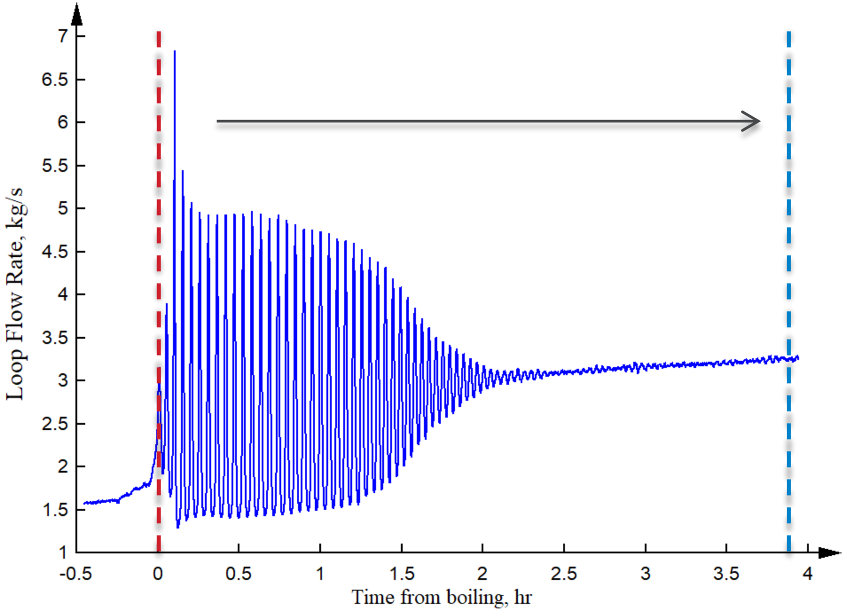




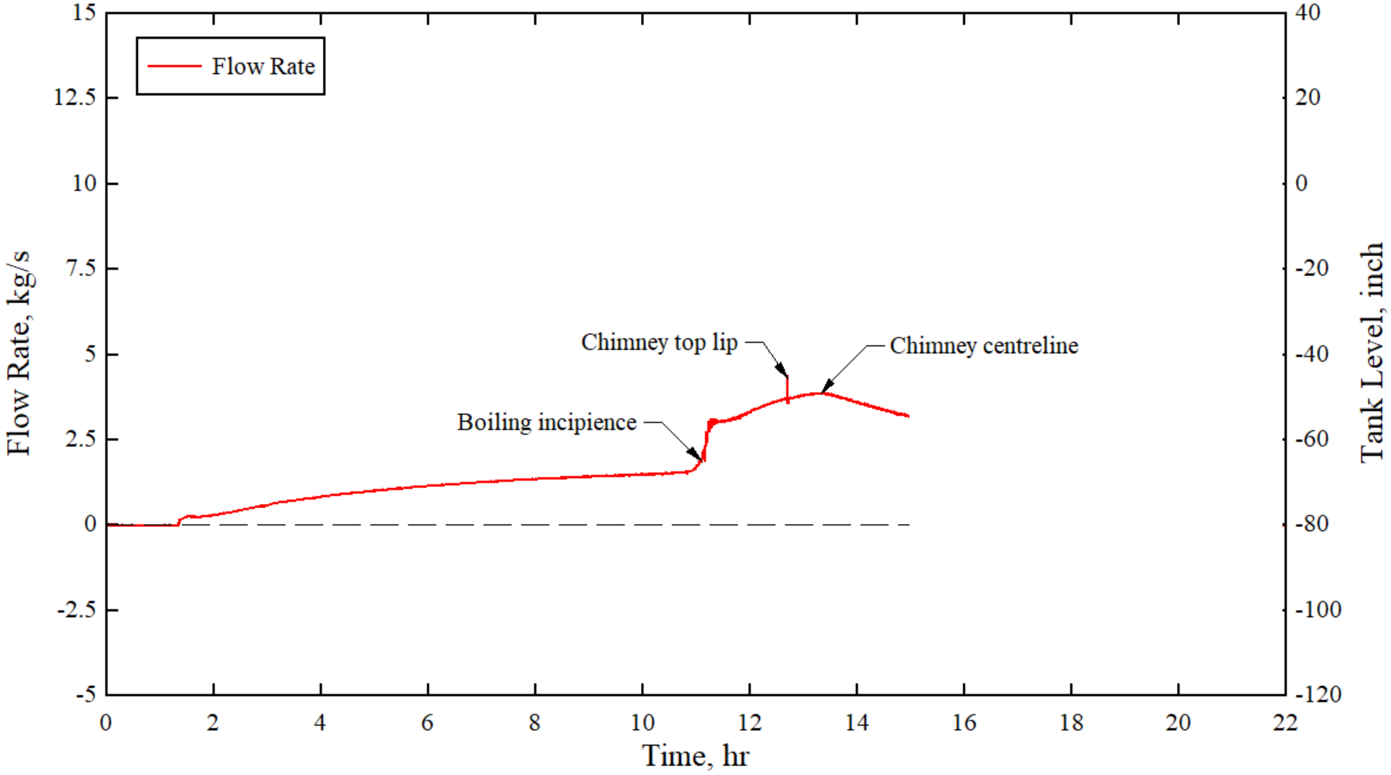
DAMPENING INSTABILITIES

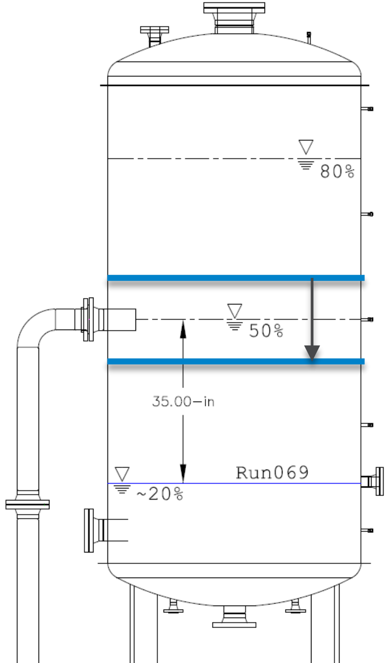
$$N_{sub} = \frac{C_{pl}\Delta T_{sub}}{h_{gl}}(\rho_l/\rho_g - 1) \qquad N_{ph} = \frac{Q}{W}\frac{v_{fg}}{h_{fg}v_f}$$





DEPLETED INVENTORY SCENARIO





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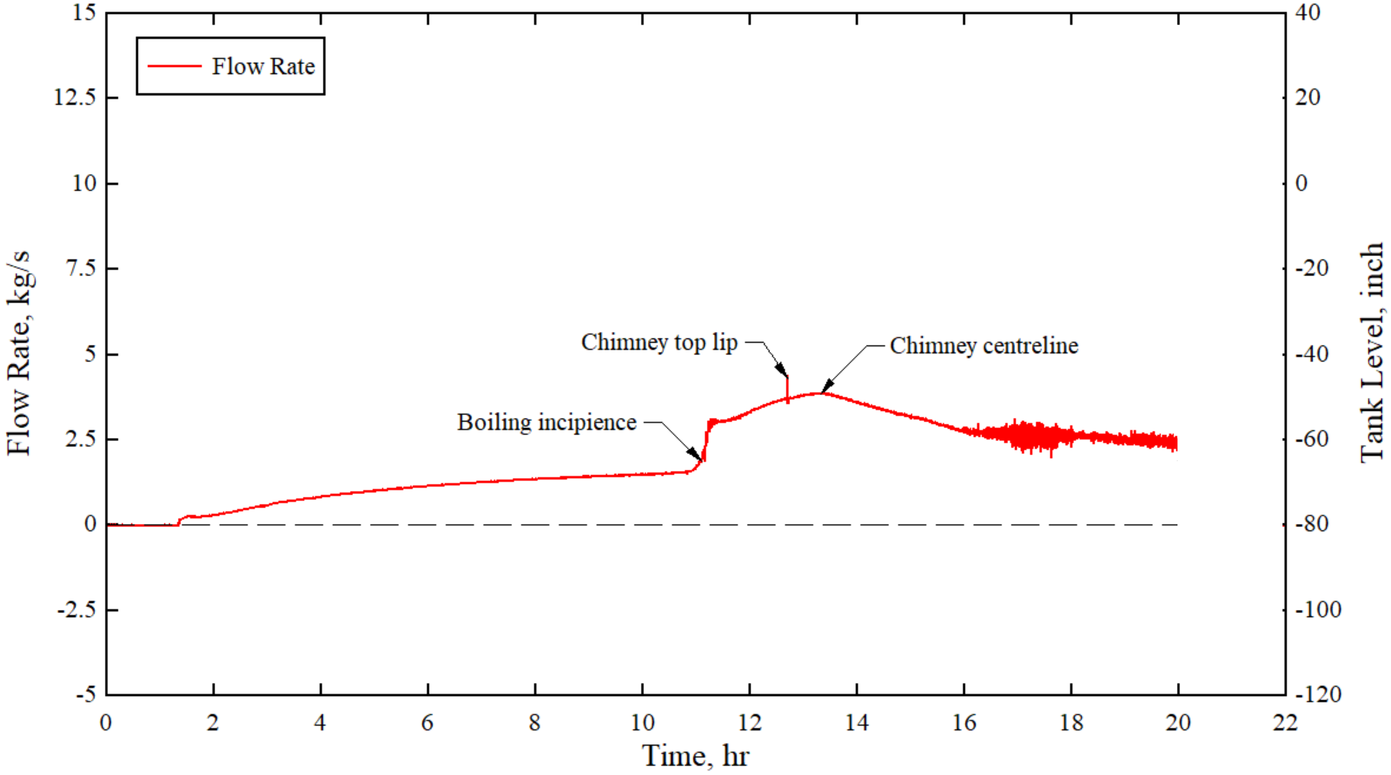

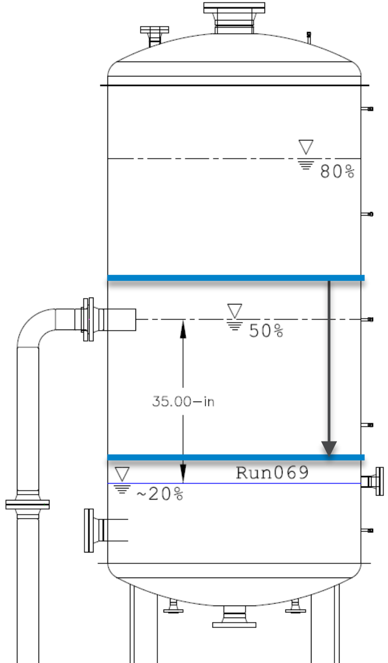

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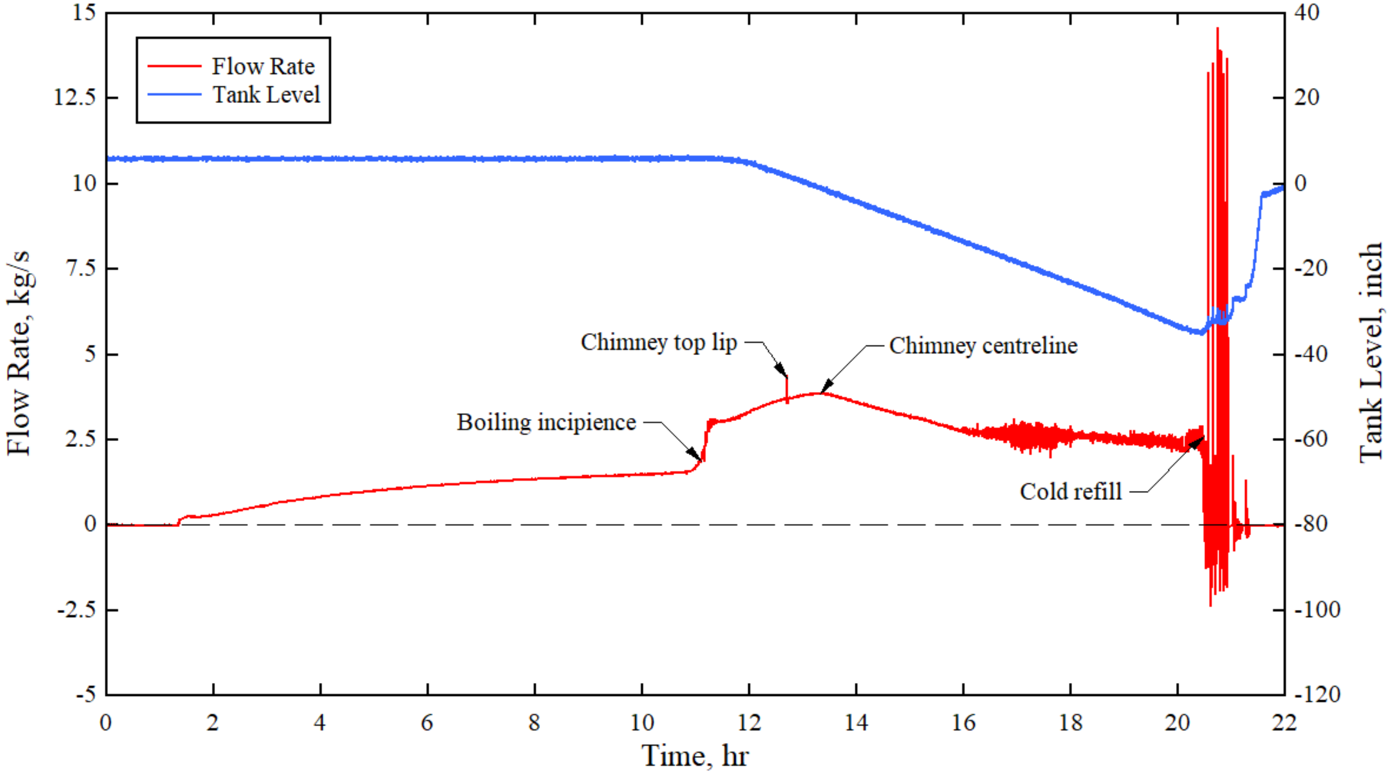

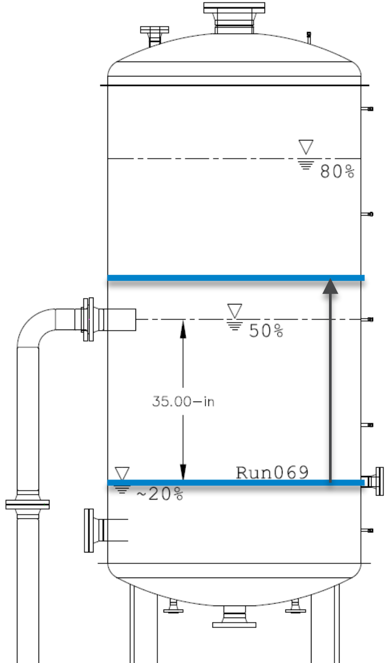

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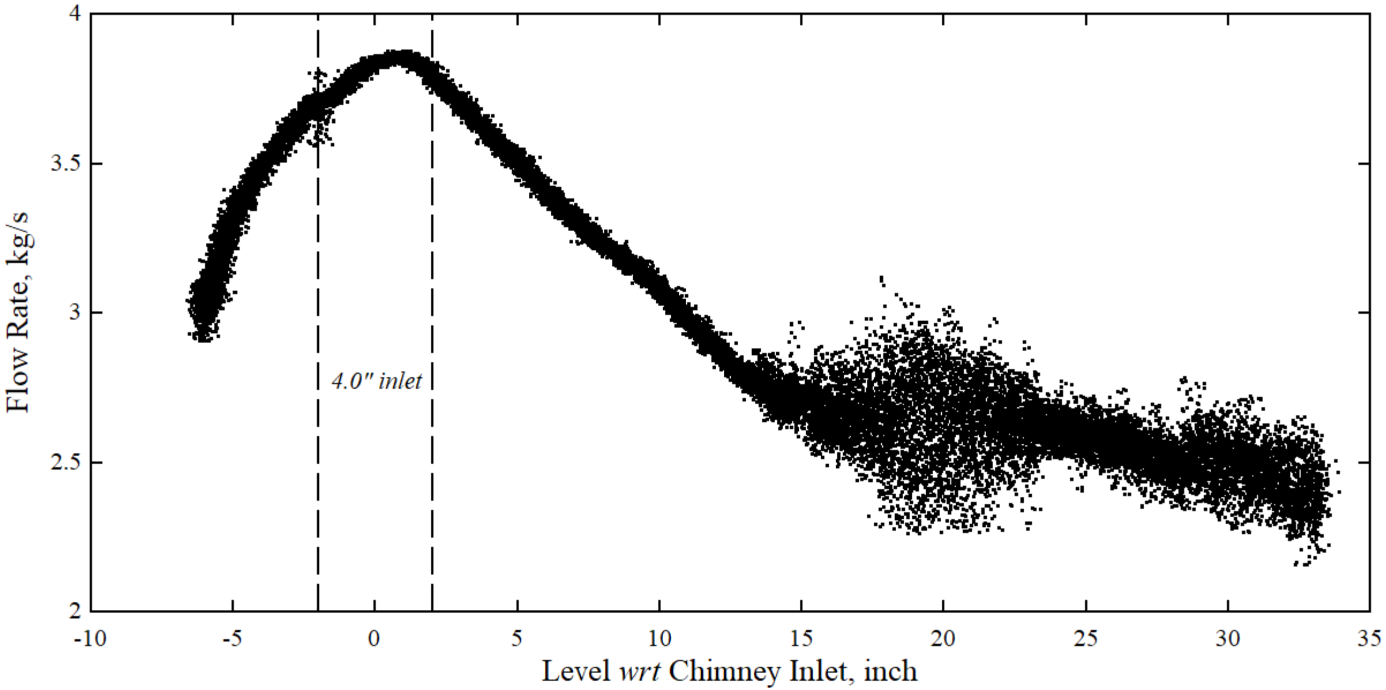
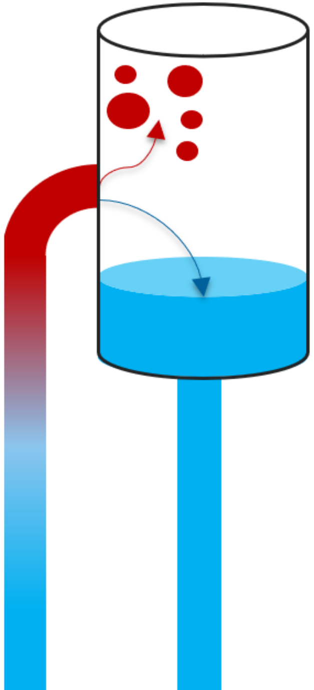
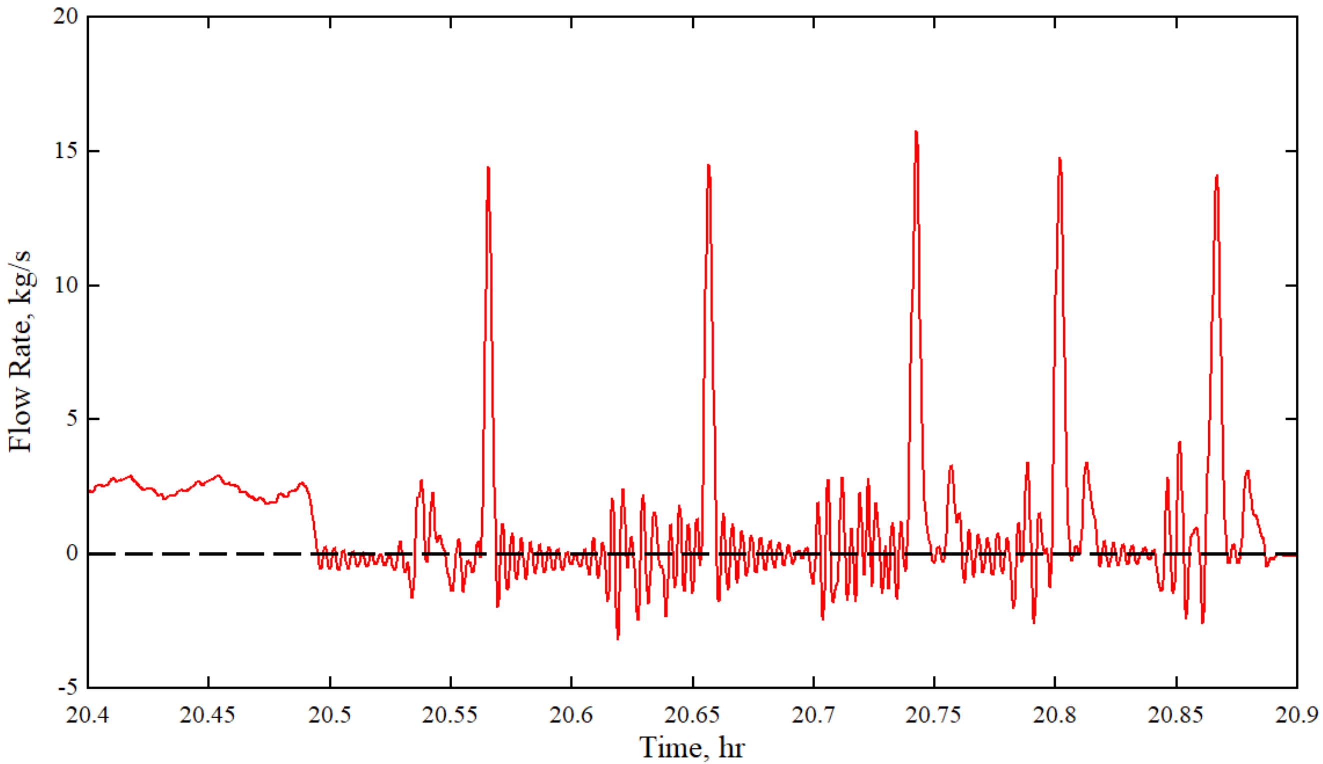
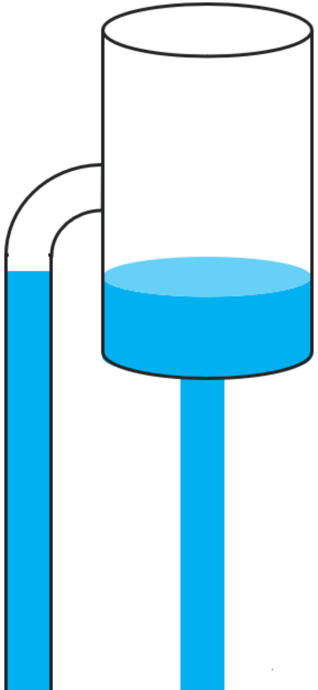




POST-DEPLETION COLD REFILL

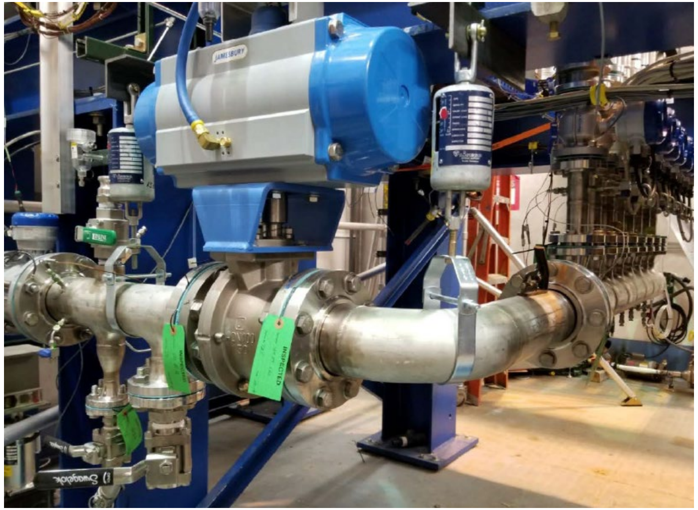
Cold refill → Cessation of loop flow → Quiescent fluid in risers → Geysering

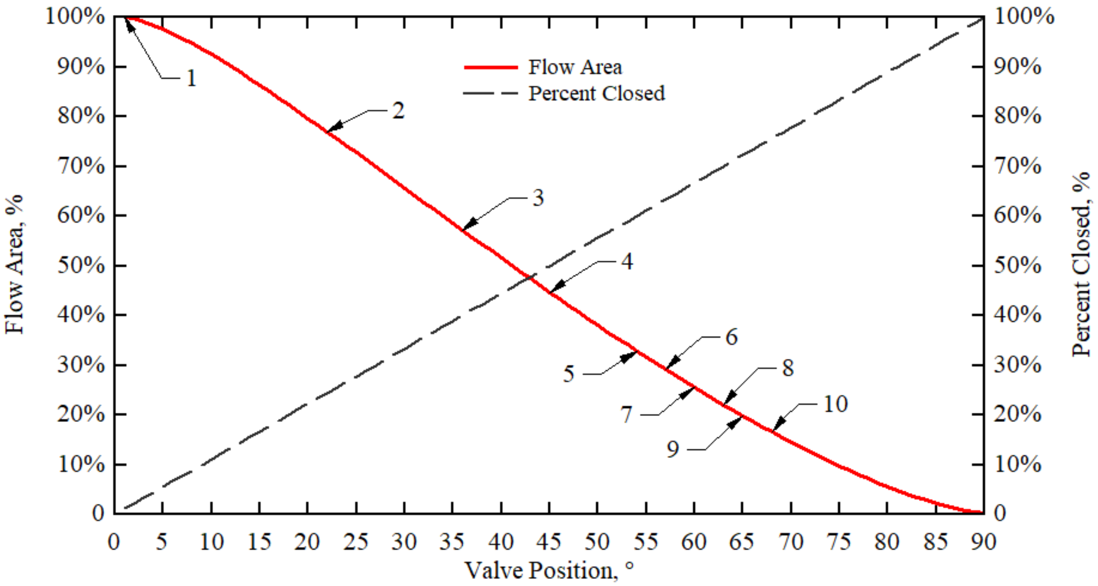




RESTRICTED FLUID INLET PARAMETRIC

- Test facility was allowed to reach true steady-state two-phase flow mode of operation (baseline test conditions with addition of condensate refill)
- In 20-minute increments, inlet throttle valve was adjusted from 100% to 17% available flow area





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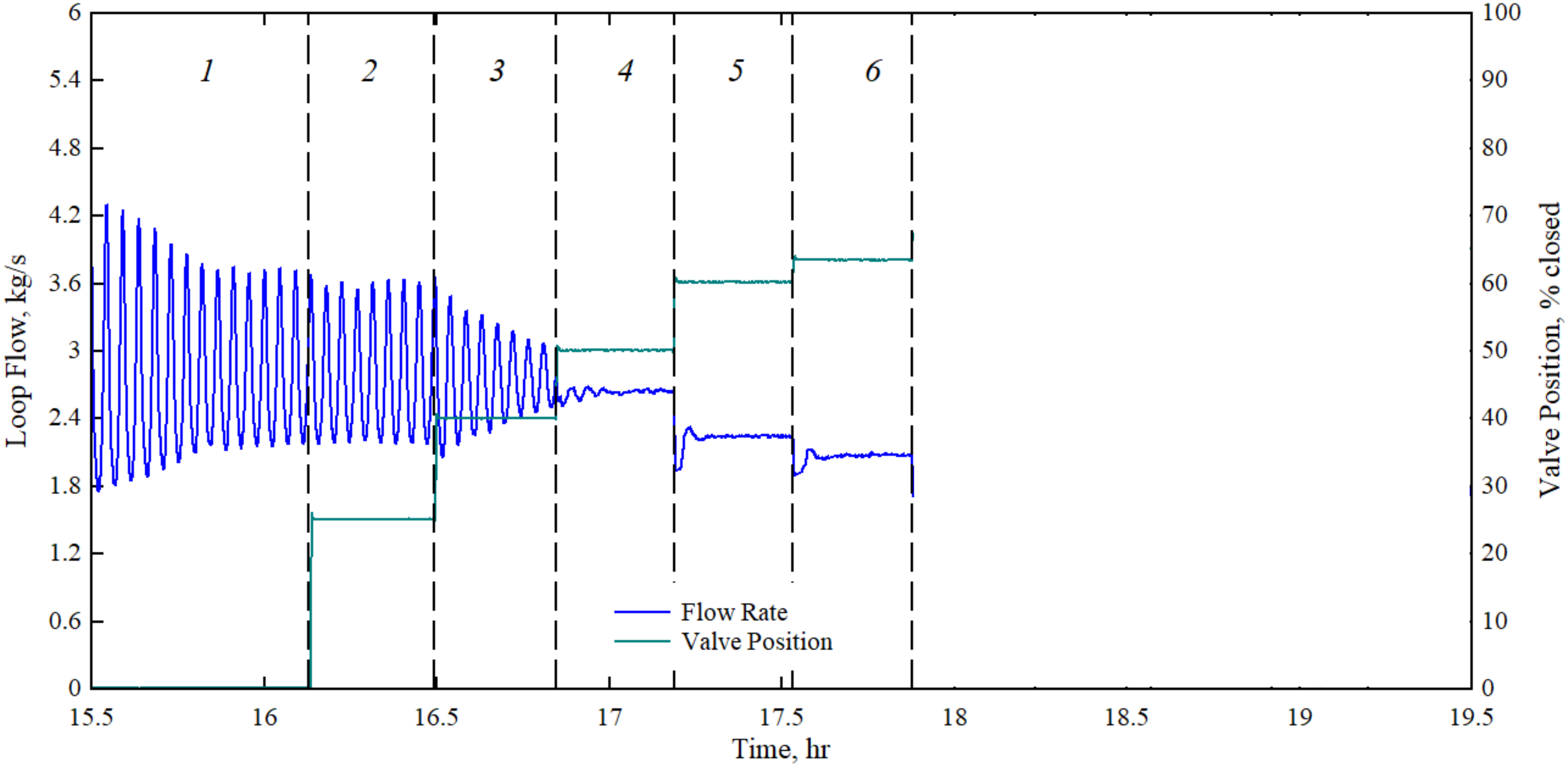

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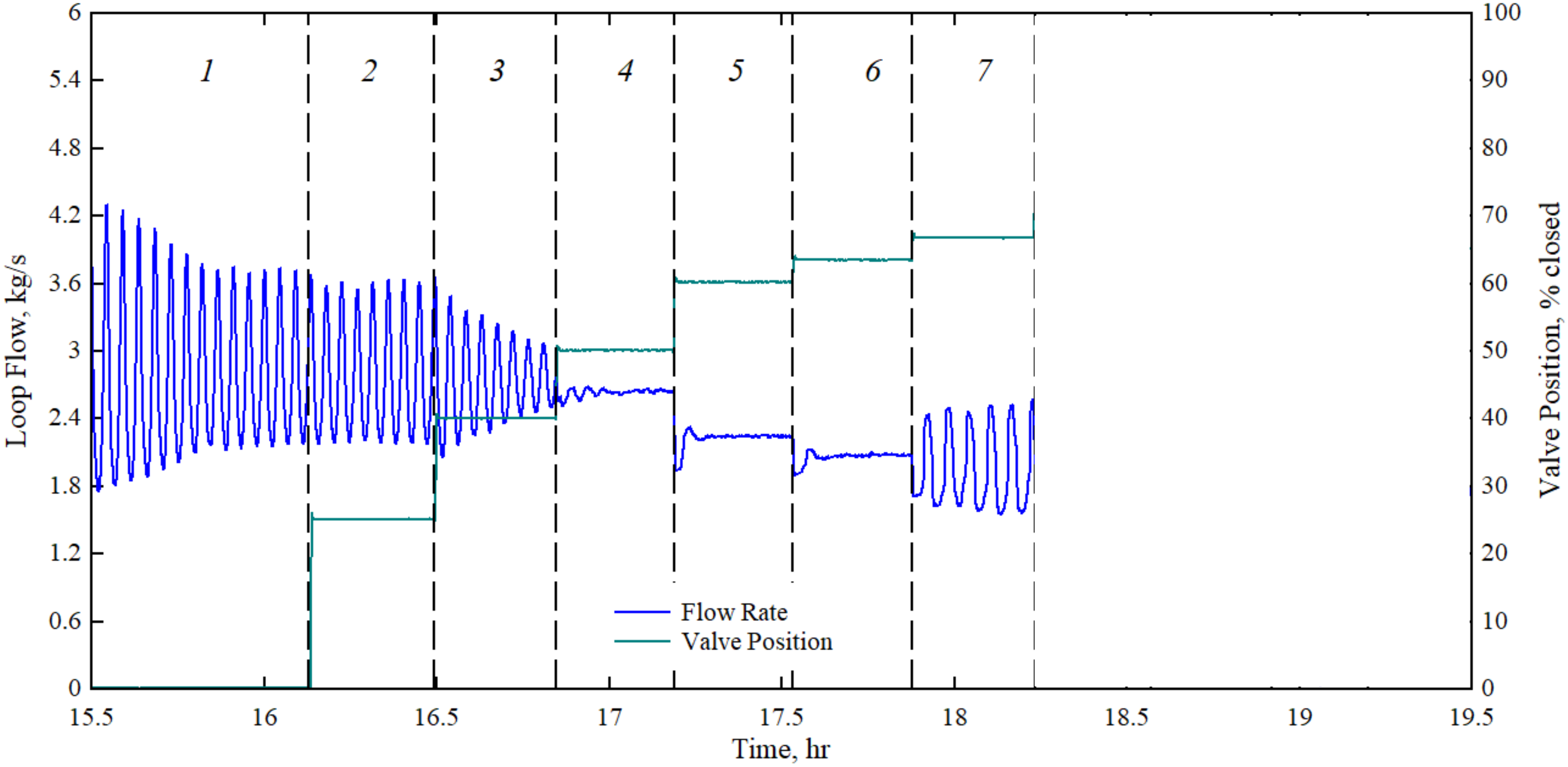

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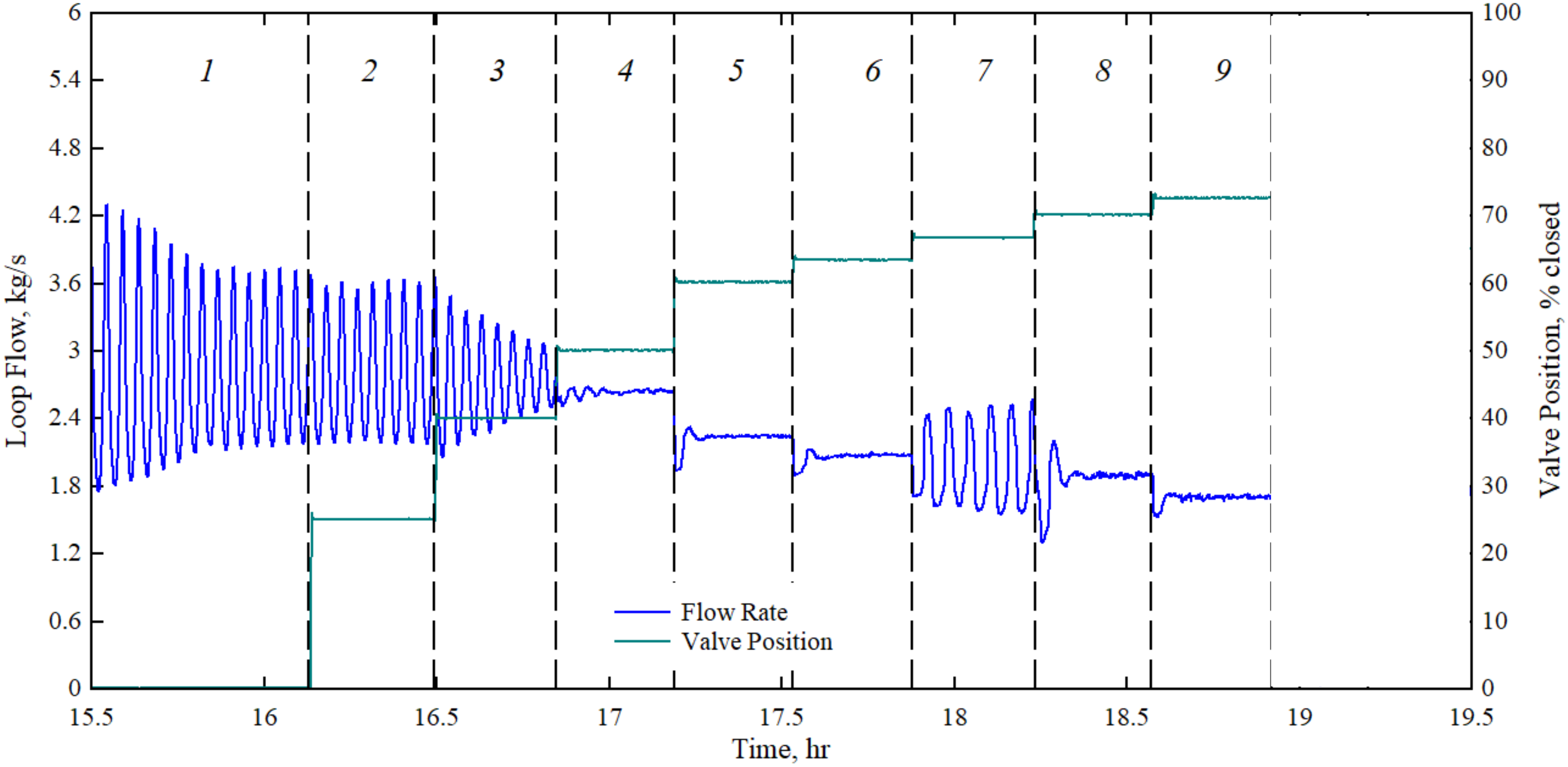
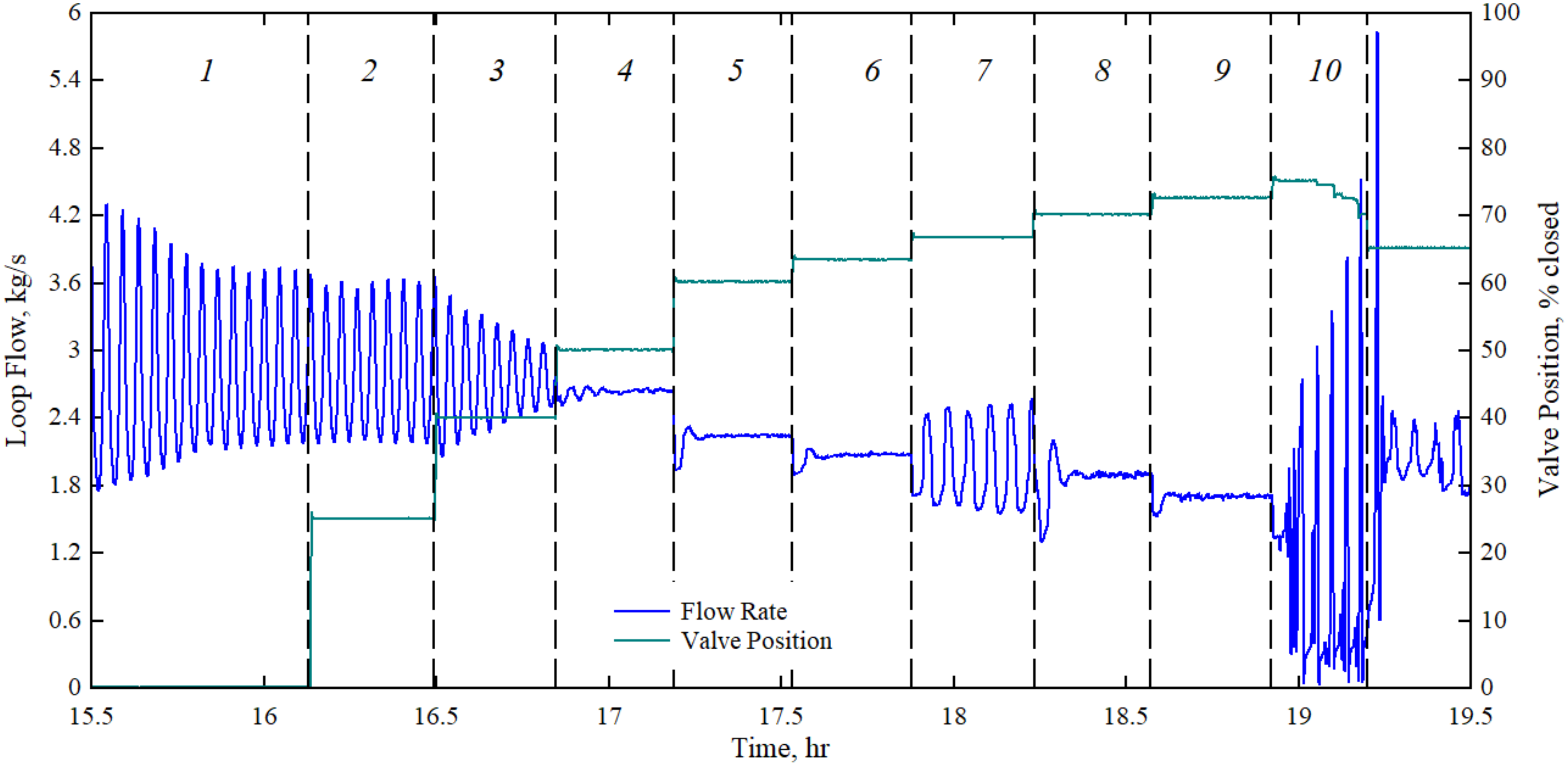
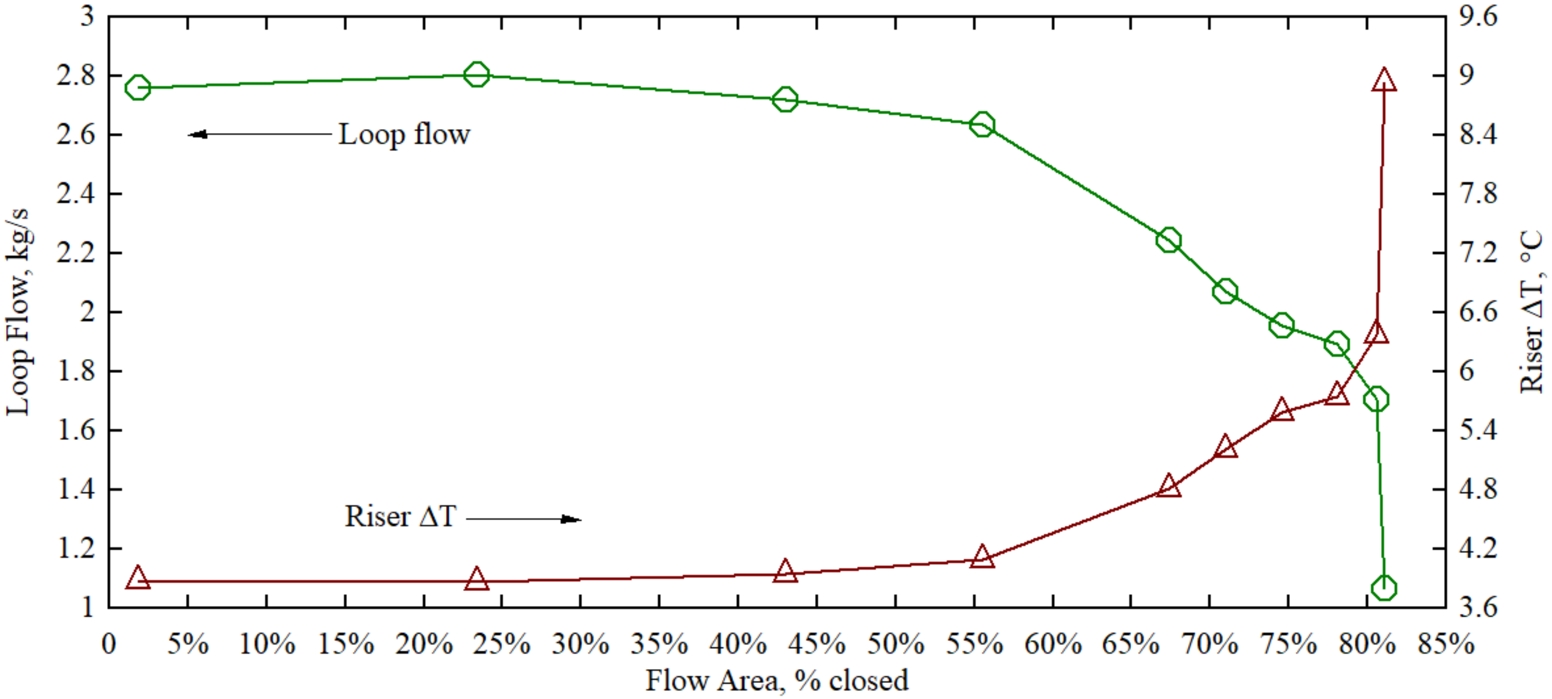


RESTRICTED FLUID INLET PARAMETRIC



IMPACT ON SYSTEM PERFORMANCE



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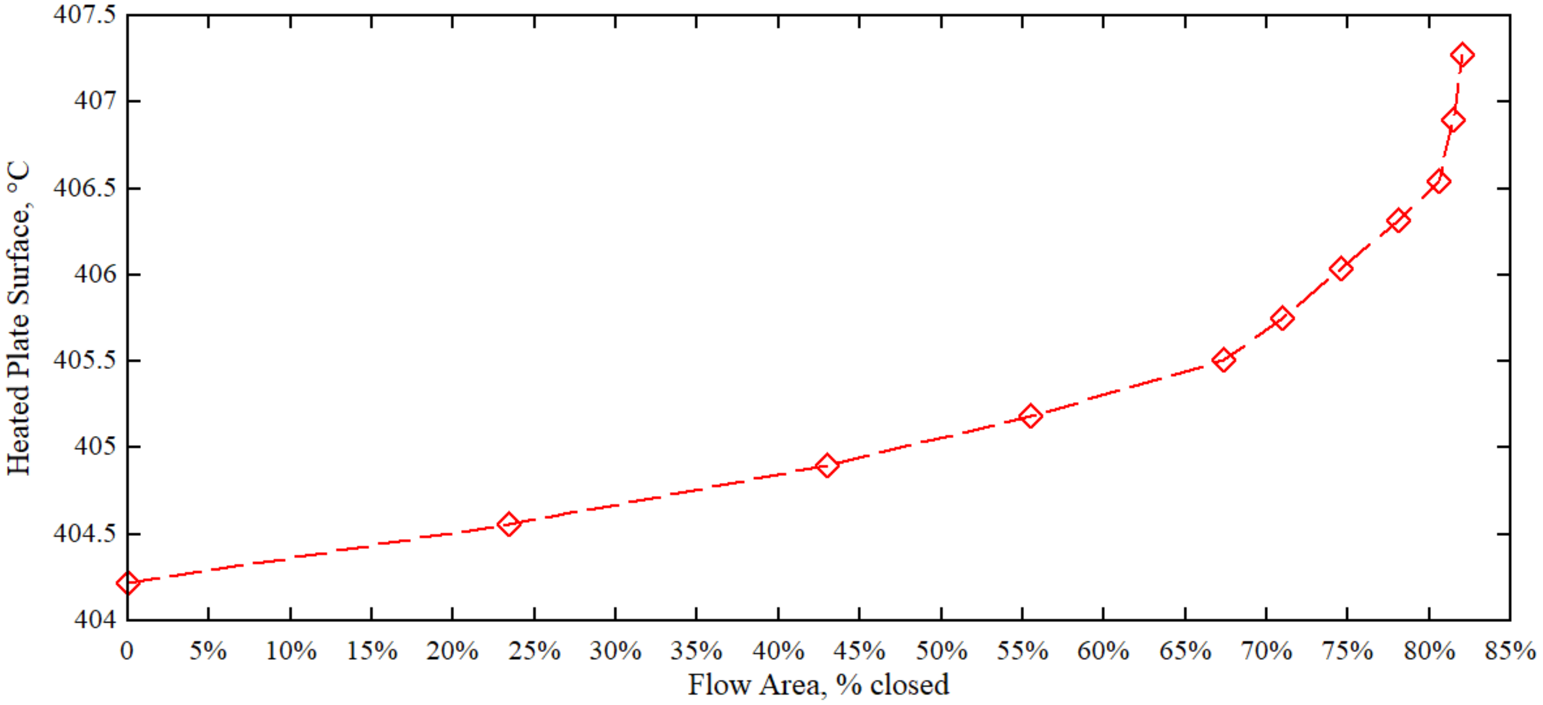
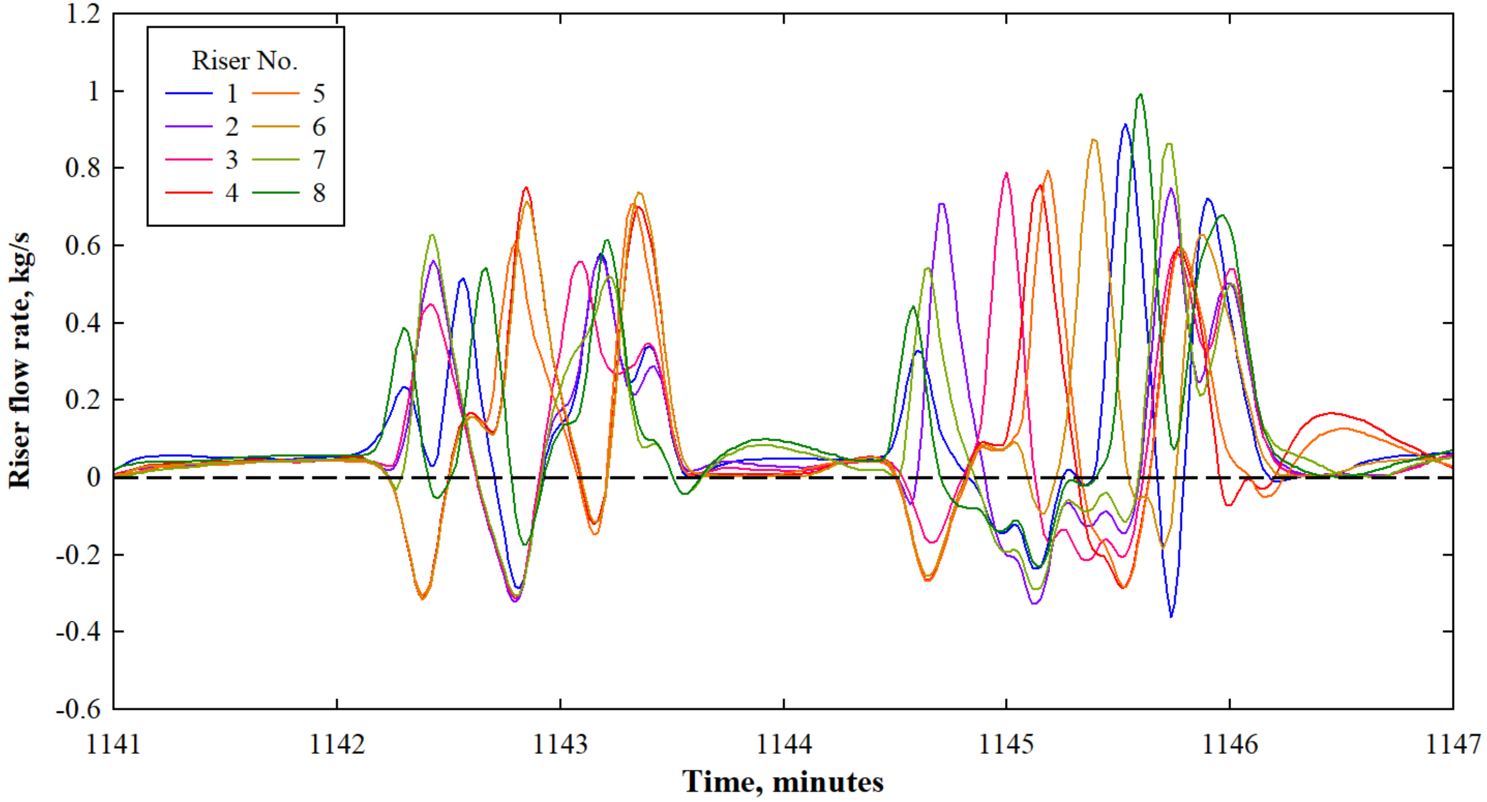
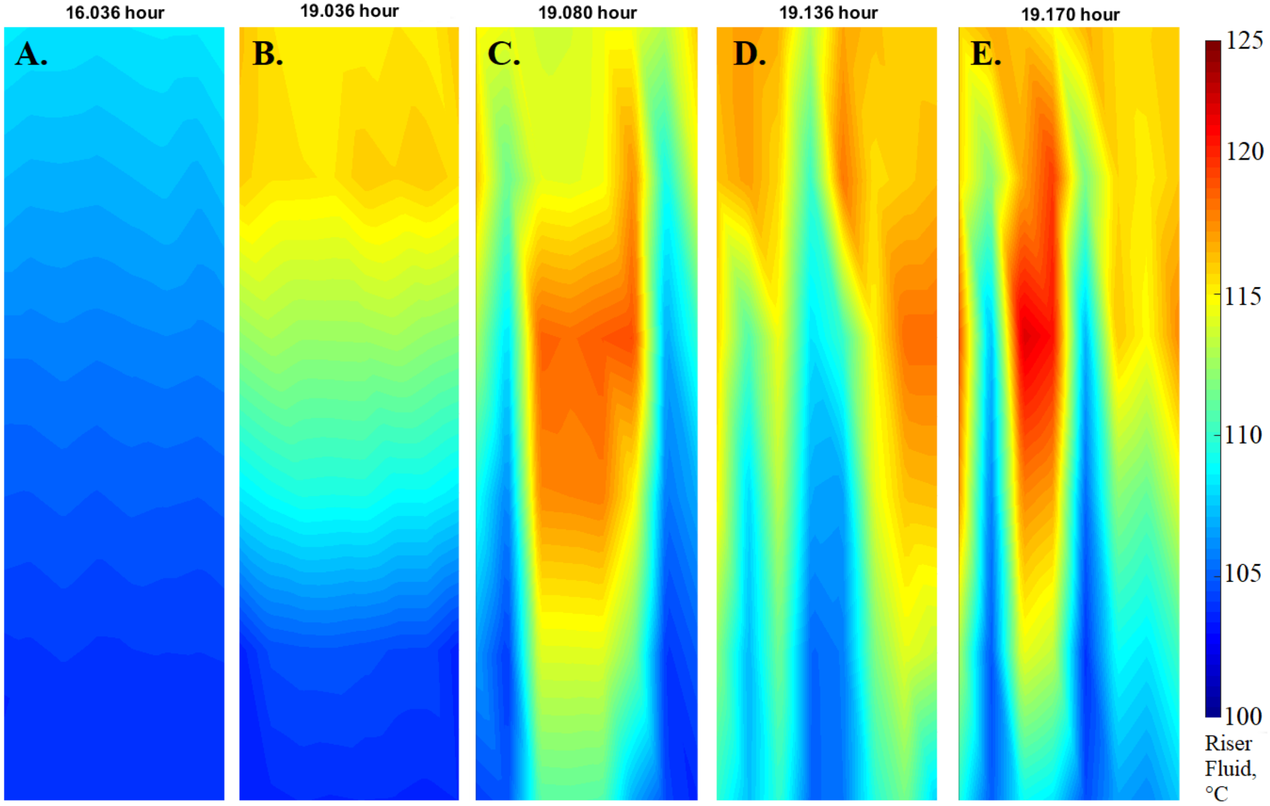


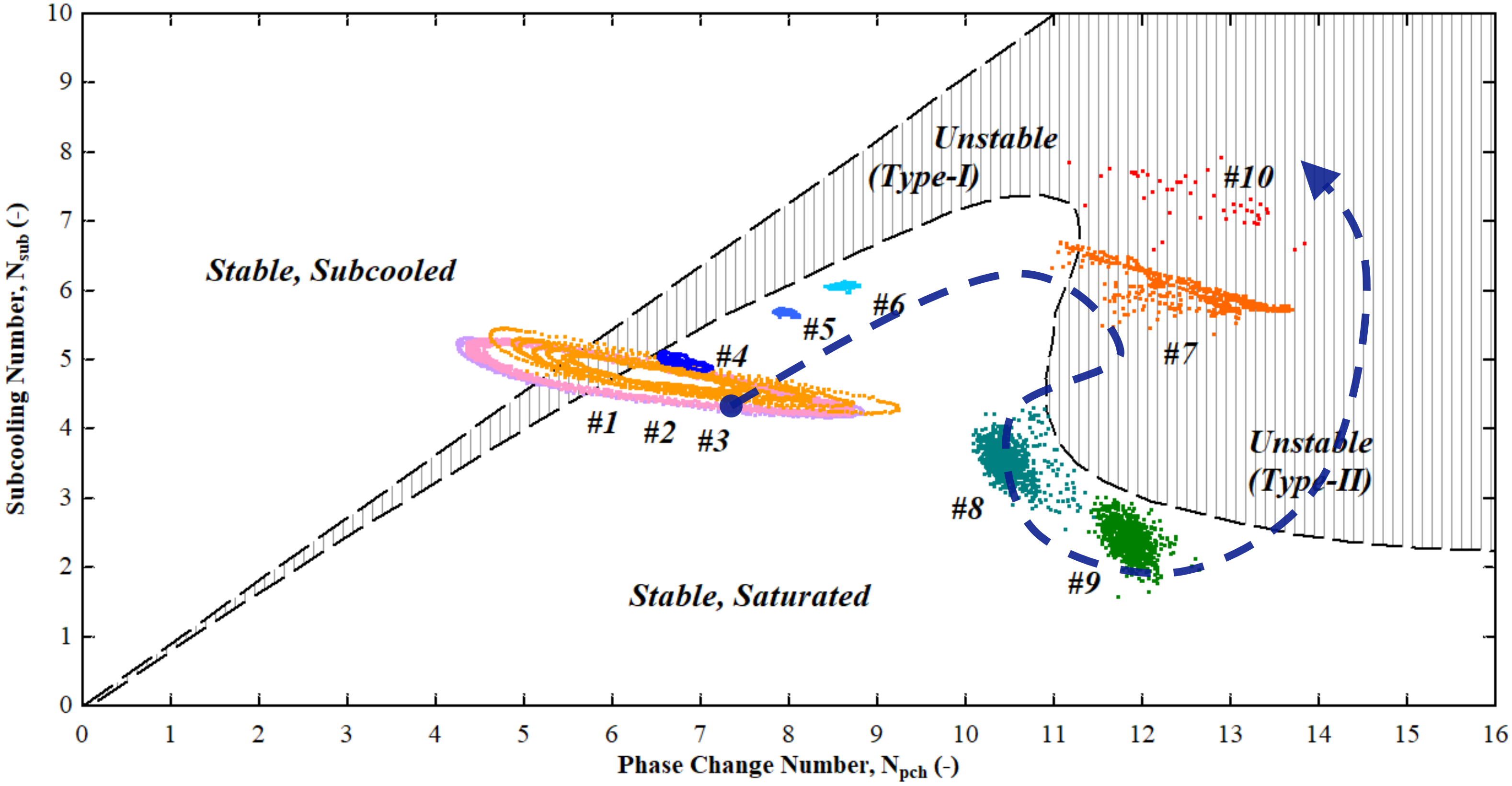
RISER FLOW BEHAVIOR, STAGE 10 (79.2% CLOSED)



PARALLEL CHANNEL INTERACTION IN RISERS



STABILITY PHASE MAPPING



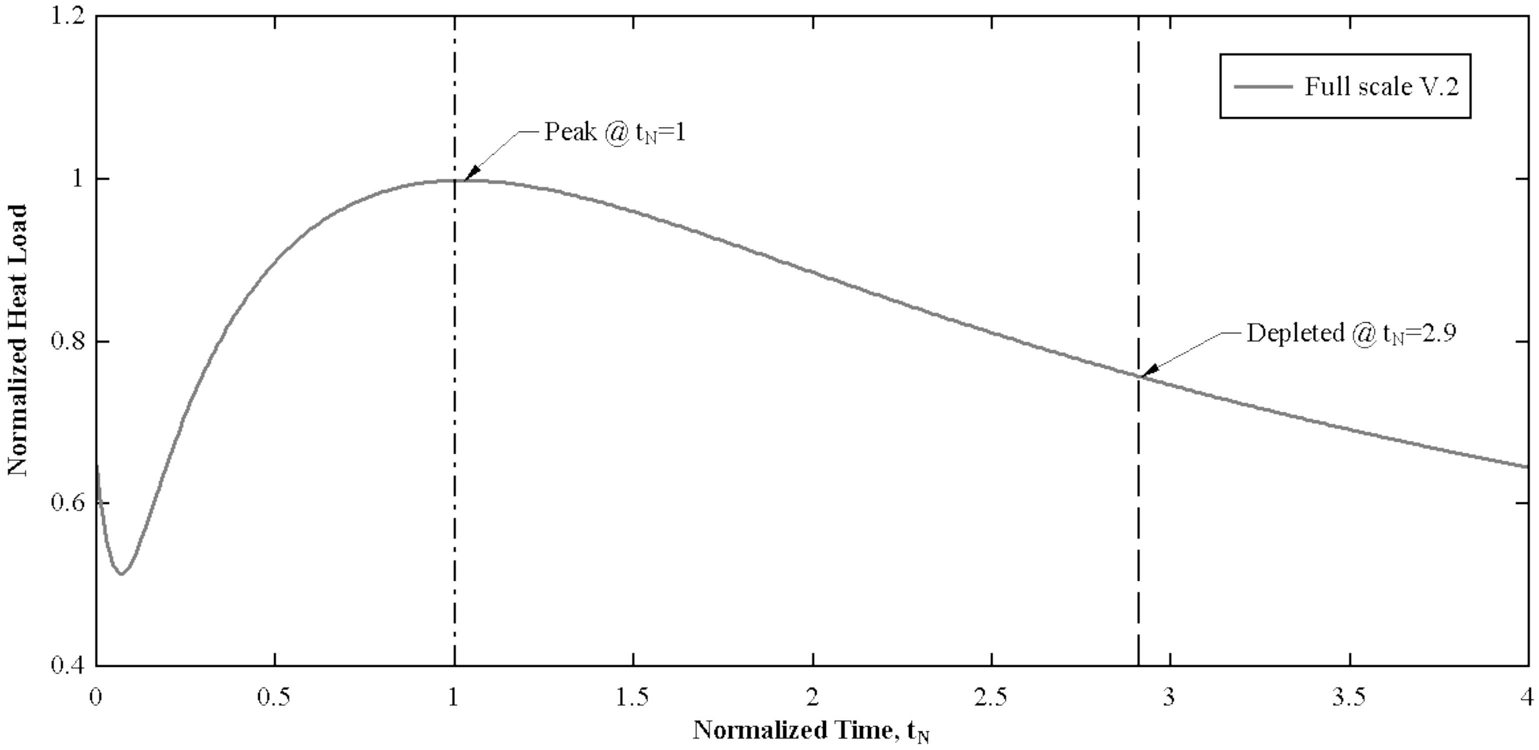
FY22 ACCIDENT SCENARIO

FY22 ACCIDENT SCENARIO TEST CASE

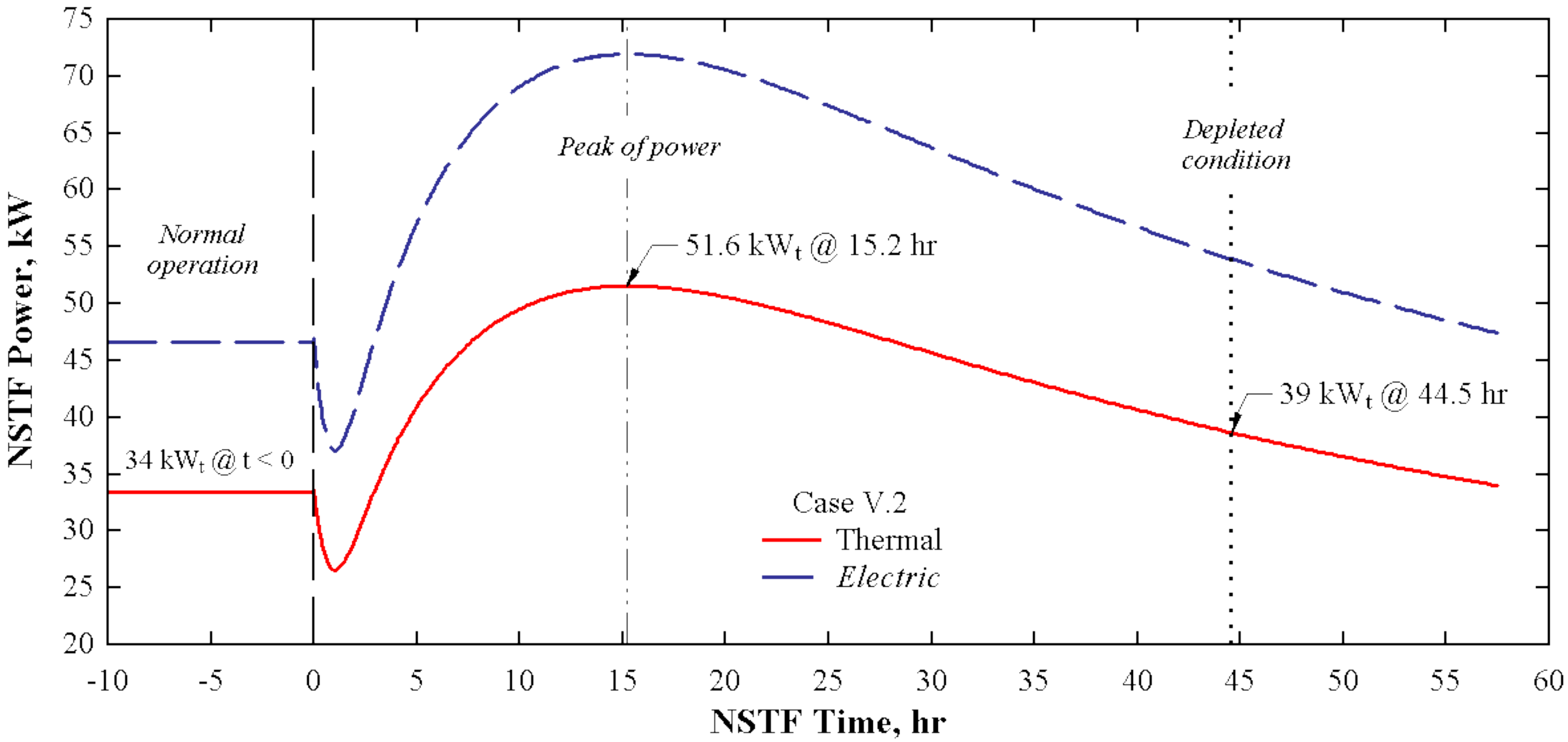
- 'Accident Scenario' test case, defined as the facility transitioning from….
  - Initial 'normal' single-phase steady-state operation with active cooling
  - Trip into 'accident' two-phase transient operation with inventory boil-off
  - Extended until depleted conditions and inventory refill
- Prototype heat load is based on Framatome's 625 MWt SC-HTGR, with 3 power-time curves transmitted to the Argonne team in April of 2022
- Case *V.2* represents the most conservative or limiting case for the RCCS heat load, and reflects
  - "*various uncertainties and performance variabilities embedded in the calculation were selected to provide a 95% confidence level for the vessel temperature which also corresponds to the maximum RCCS heat load case*"

Parameter	**Relationship**	Φ_R
Axial Length	l_R	0.5
Radial Length	1	1.0
Power	$\sqrt{l_R}$	0.707
Flow Rate	$\sqrt{l_R}$	0.707
Temperature	1	1.0
Time	$\sqrt{l_R}$	0.707

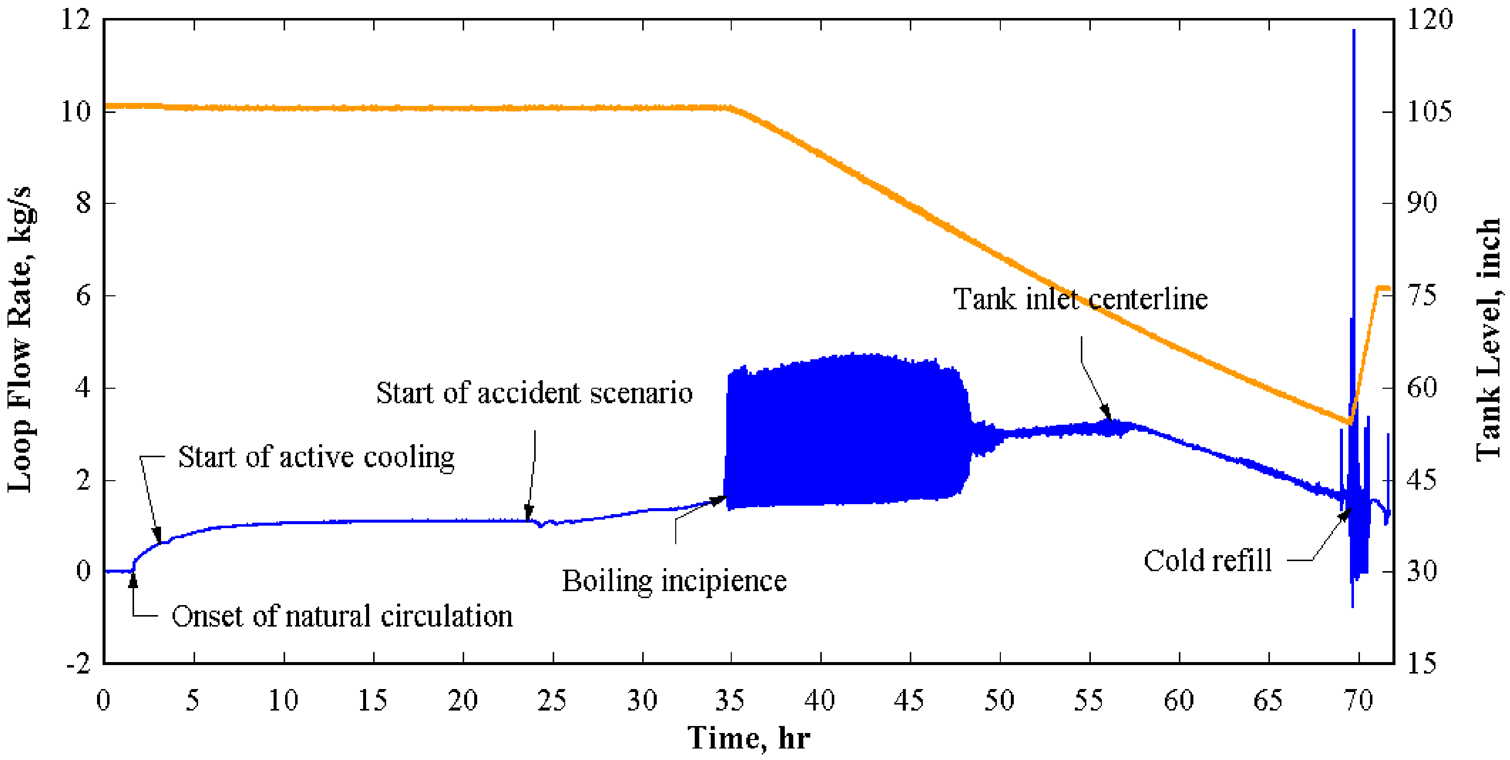
NORMALIZED ACCIDENT HEAT CURVE



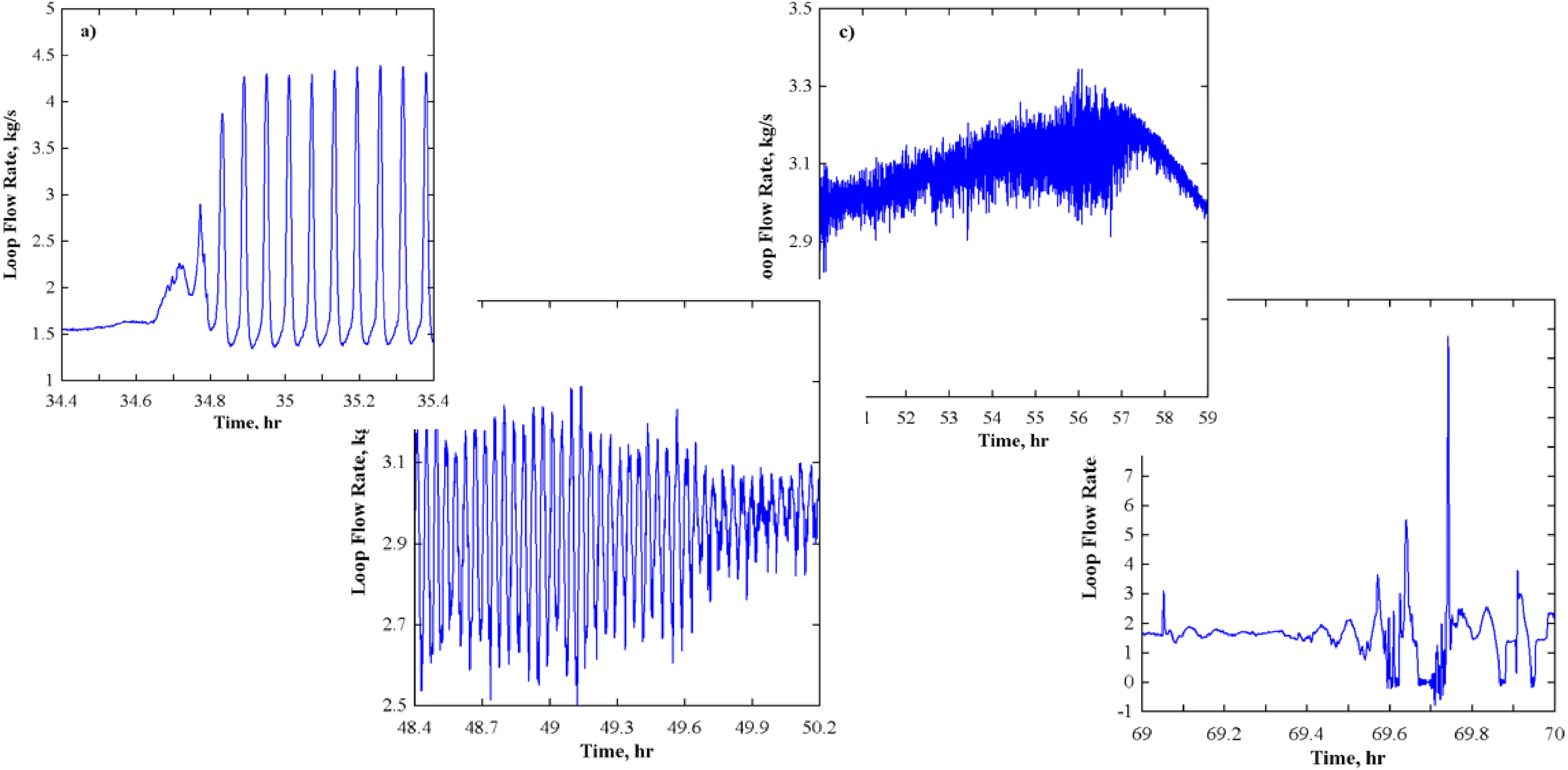
ACCIDENT SCENARIO HEAT INPUT CURVES



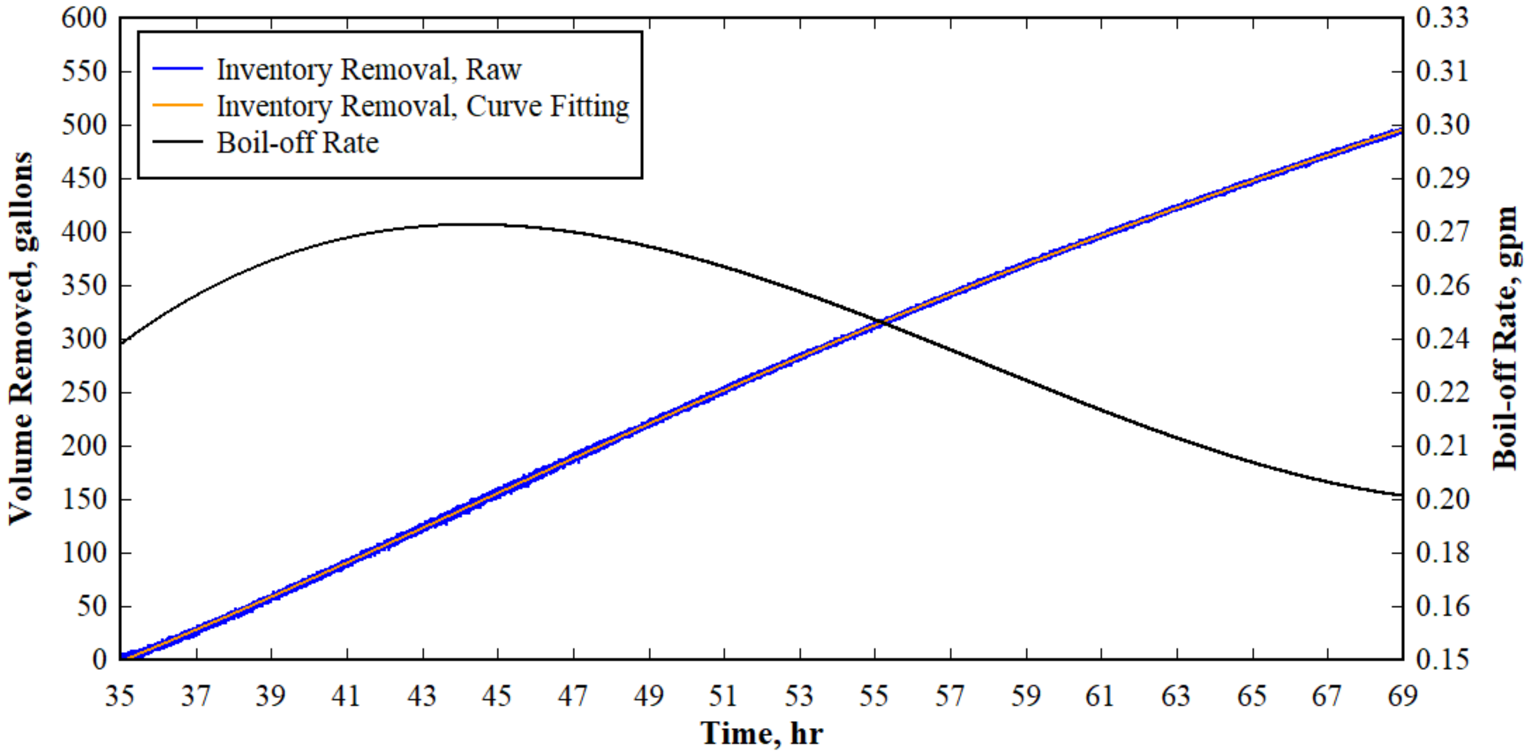
ACCIDENT SCENARIO FLOW & LEVEL



ACCIDENT FLOW, DETAILED



ACCIDENT BOIL-OFF RATE



PATH FORWARD

WHERE ARE WE GOING

Accident Scenario Testing

~~(a) Accident Scenario testing~~

~~i. Full time history of design basis power profile incorporated into test procedure, beginning from 'normal' single-phase steady-state at 1.4 MW_t until 'transient accident condition' with two-phase flow and boil-off at 2.1 MW_t.~~

~~(b) Storage tank inventory and refill~~

~~i. Full tank depletion and dry-out with refill~~

Off-normal Operating Conditions

(a) Network Blockages

i. ~~Riser tube throttling~~

ii. Riser full blockage

~~iii. Inlet throttling~~

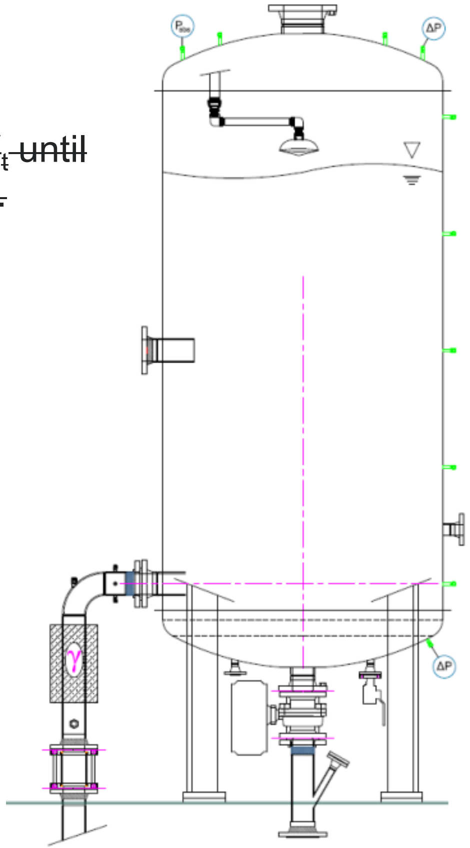
(b) Short circuiting discharge to return

Geometric Variations

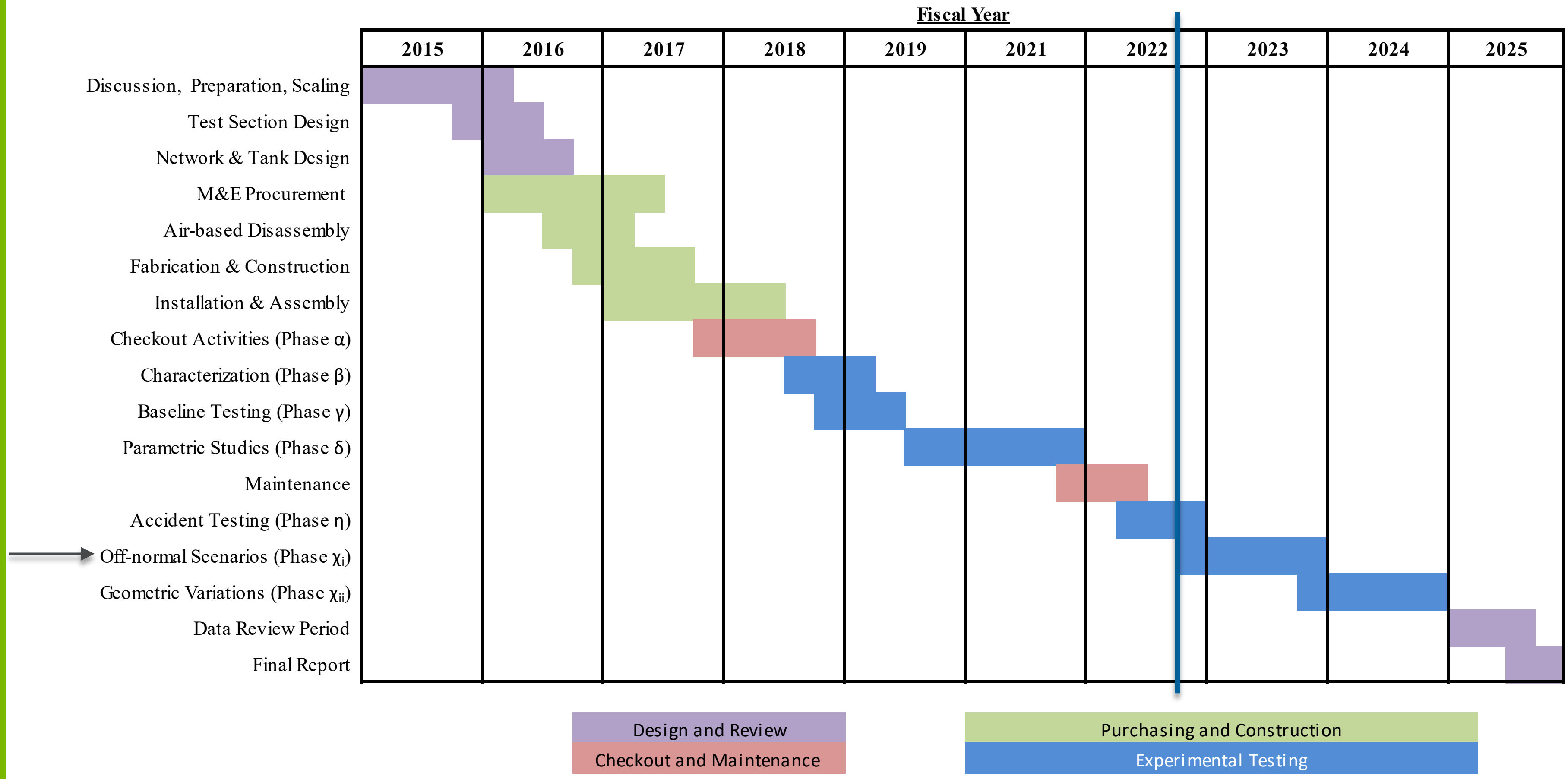
(a) Tank inlet baffle study

(b) Geometric Alterations (repeat baseline with varying geometry)

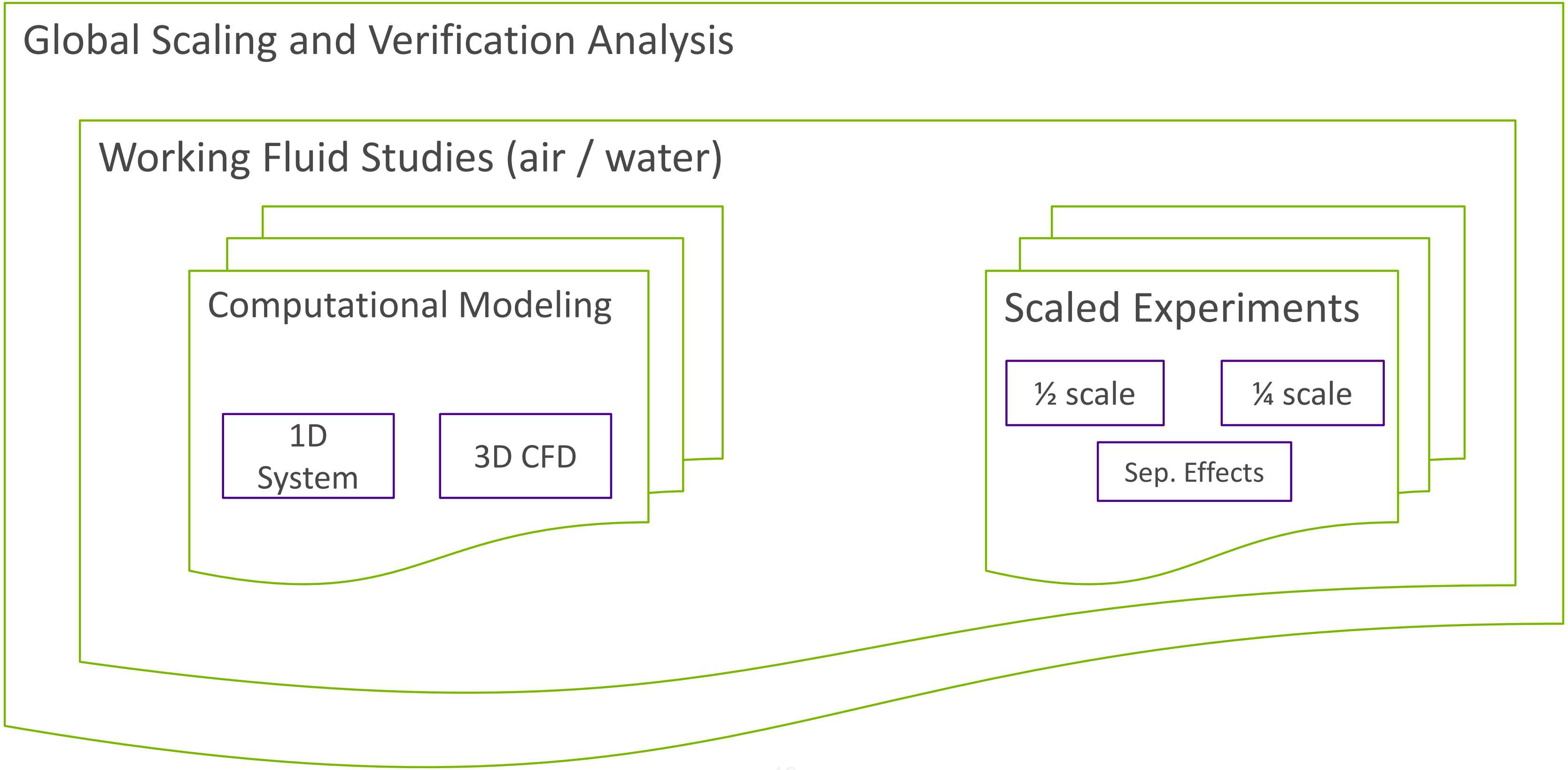
i. Lower tank inlet port



PROGRAM TIMELINE



FULL SCALE DEPLOYMENT OF THE RCCS



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Argonne Project Personnel	
Project Manager	Mitch Farmer
Principal Investigator	Darius Lisowski
Lead Experimenters	Qiuping Lv
Quality Assurance	John Woodford
Facility Designer	Dennis Kilsdonk
Test & Instrumentation	Matt Jasica Steve Lomperski
Laboratory Technical	Art Vik Eugene Koehl

Argonne Analysis Support Team	
Computer Models	Rui Hu Adam Kraus Zhiee Ooi

Program Sponsors	
Federal	Matthew Hahn Diana Li
Technical	Gerhard Strydom Mike Davenport

Guidance / Consultation	
External Guidance	Hans Gougar Jim Kinsey Lew Lommers Sud Basu Mike Salay Brian Woods
Internal Guidance	Bob Hill Chris Grandy

Notable Mentions, Past Involvement	
Modeling	David Pointer Elia Merzari Matt Bucknor Constantine Tzanos
Summer Students	Skyer Perot Jordan Cox James Schneider Daniel Nunez David Holler
Program Support	Tom Wei Craig Gerardi Diana Croson Steve Reeves
Laboratory Support	Bruce Herdt Tony Tayofa

WE START WITH YES.
AND END WITH THANK YOU.

DO YOU HAVE ANY BIG QUESTIONS?