July 27, 2023

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Argonne National Laboratory

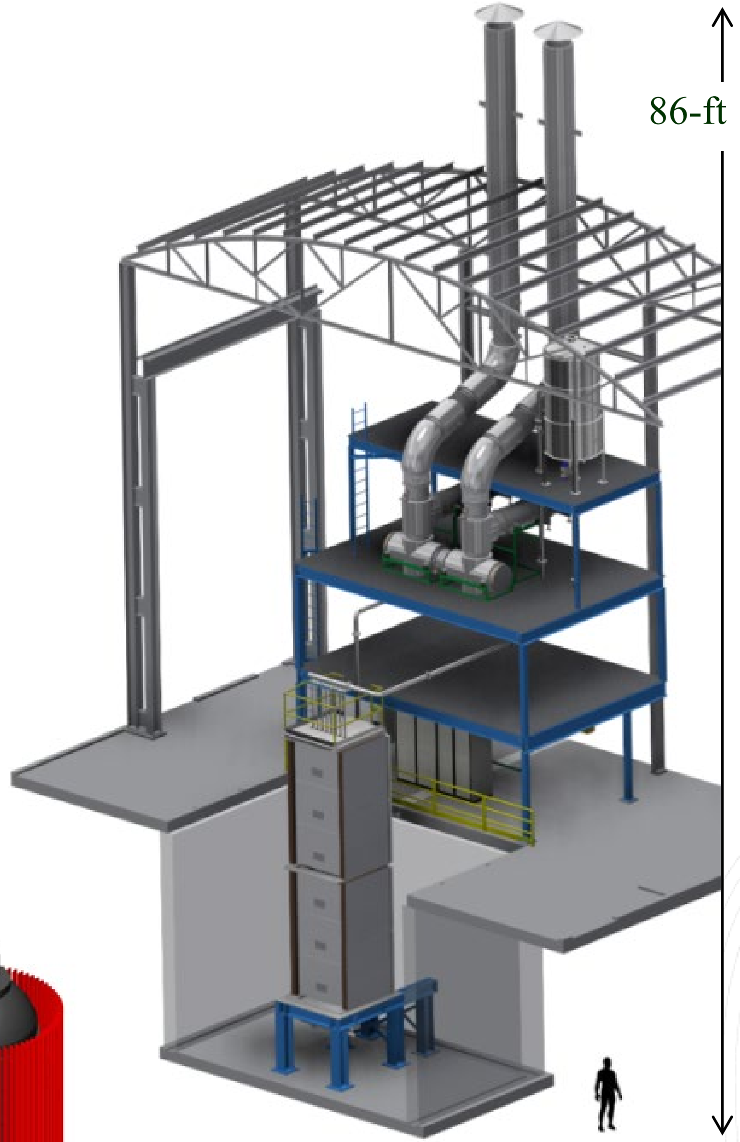
Water-Cooled Natural Convection Shutdown Heat Removal Test Facility (NSTF) Status and Recent Data Results

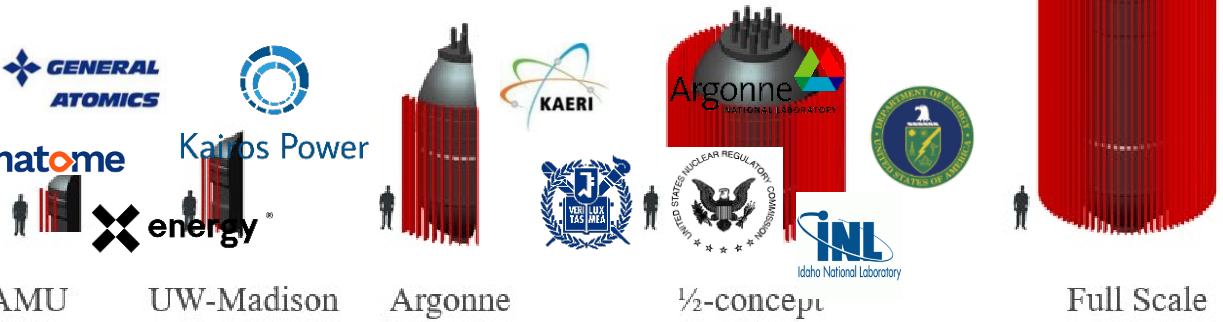
DOE ART Gas-Cooled Reactor (GCR) Review Meeting
Virtual Meeting
July 25 – 27, 2023

ART
Advanced Reactor Technologies

Introduction: NSTF at Argonne

- 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





FY23 Work Packages & Deliverables

Work Package	Activity	Months	Funding
AT-22AN060201	Program Administration & NQA-1	12	$100K
RD-22AN050201	Experimental Testing & Computational Analysis	12	$880K

- Funding from Gas-Cooled Reactor Campaigns in ART and ARRD
  - Separate packages for program management and testing/analysis
  - Reduction from previous years, currently funded at minimum level to cover staff / overhead
- Computational analysis, partially unfunded in previous years, returned to FY23
  - Limited to only RELAP5 two-phase development (no CFD)
- Completion of year-end deliverables is on schedule

Level	Work Package / Deliverable	Due Date	Status
L3	**M3RD-23AN0502014** Progress report on RELAP5 modeling of NSTF two-phase	09/08/2023	*On Schedule*
L2	**M2RD-23AN0502013** Test report detailing experimental results from FY23 parametric	09/08/2023	*On Schedule*

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, 04/25 – 28/2022	☑ **MA** ☐ Internal ☐ External	Roberta Riel (ANL)
Spring 2023, 02/21 – 23/2023	☐ MA ☐ Internal ☑ **External**	Michelle Sharp (INL)
Spring 2023, 05/30 – 31/2023	☑ **MA** ☐ Internal ☐ External	Roberta Riel (ANL)

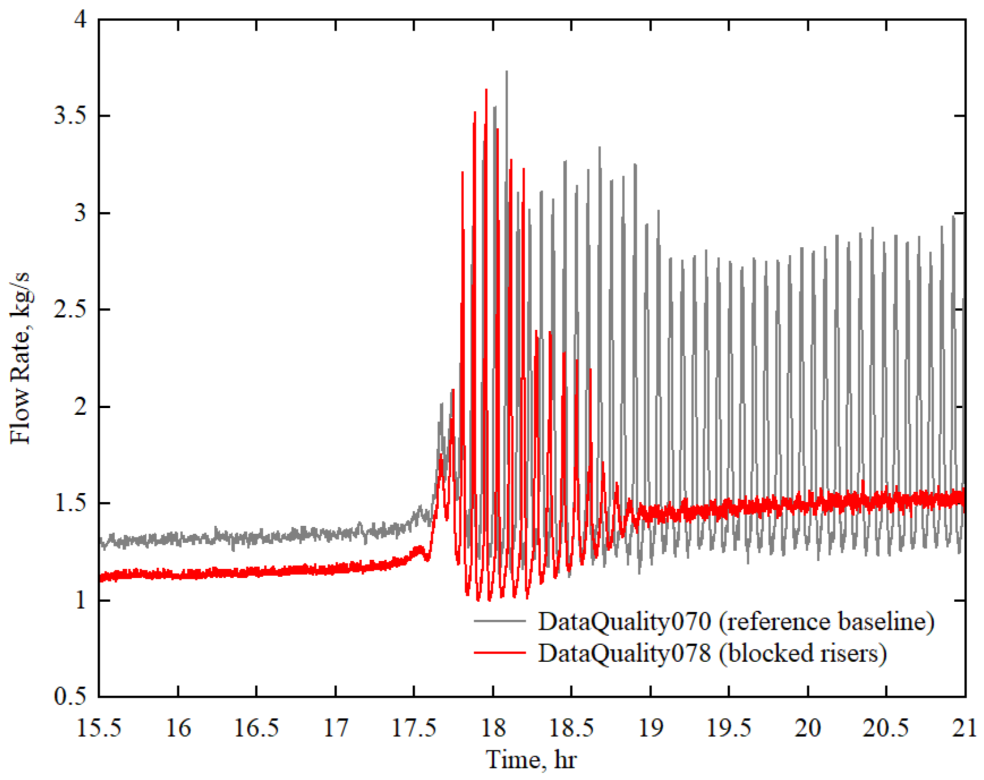
Summary of FY23 Accomplishments To-Date

- Hosted program review meeting, December 2022
  - Held every 1 – 2 years since 2010 with the purpose to gather feedback from external groups on progress, direction, and accomplishments of the NSTF program
  - This years meeting included participation from Federal (DOE, INL, NRC), Industry (Framatome, Kairos, X-Energy), US Univ. (TAMU, UW-Madison)
- Formal external audit for NQA-1 compliance, February 2023 (✓*compliant*)
- Continuation of two-phase matrix testing
  - Off-normal test conditions with expansion of blocked riser conditions; Expansion of depleted inventory condition with focus on refill methods
  - Introduced flow restriction at tank inlet for parametric loss testing
- Data packaging and exchange with active US vendors
  - Comprehensive packaging of previously collected data including both air & water cases dating to 2013
  - Exchanged with multiple US companies in recent months
- Regular use of RELAP5 for predictive capability; supporting tests

FY23 Testing Results

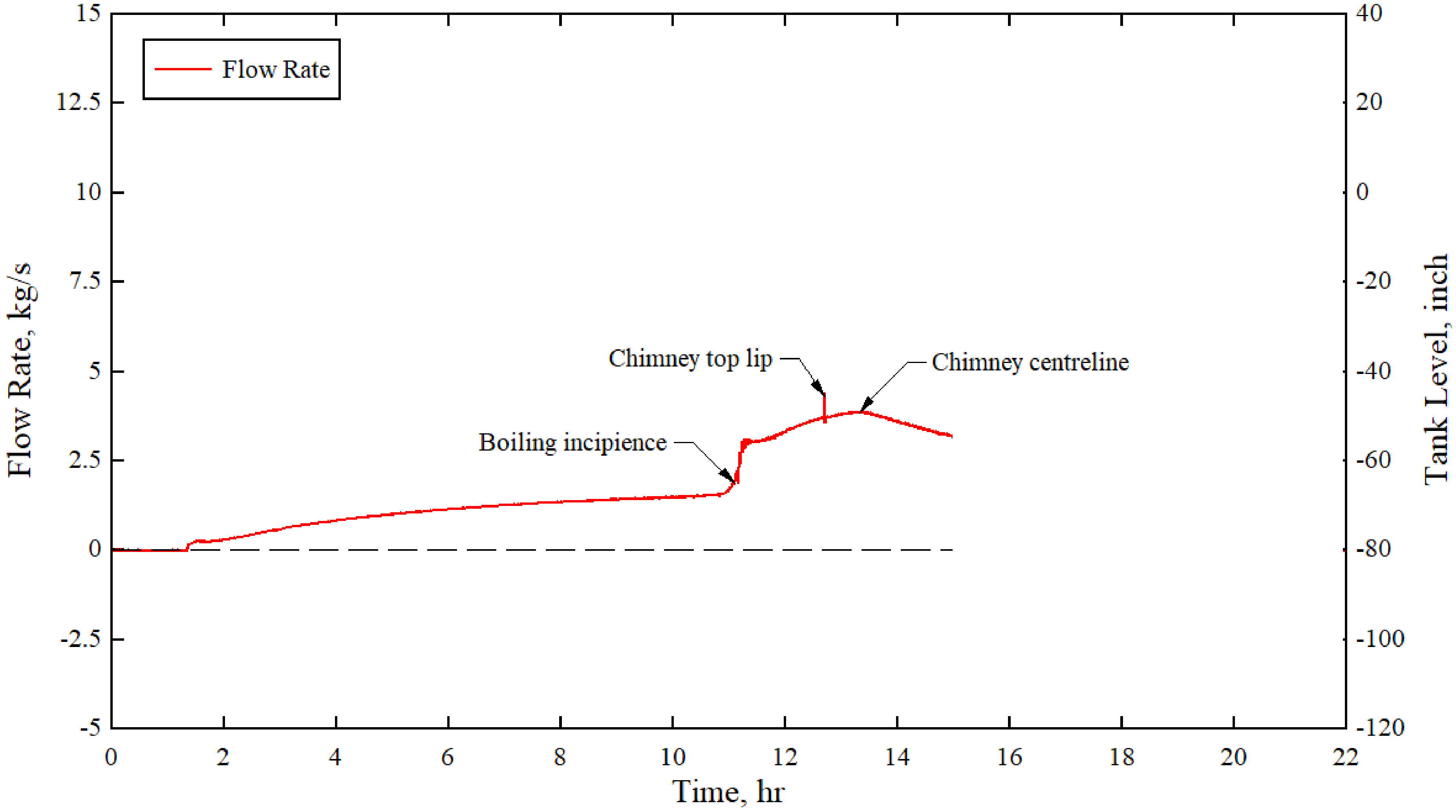
Blocked riser channels (#3 & 6)

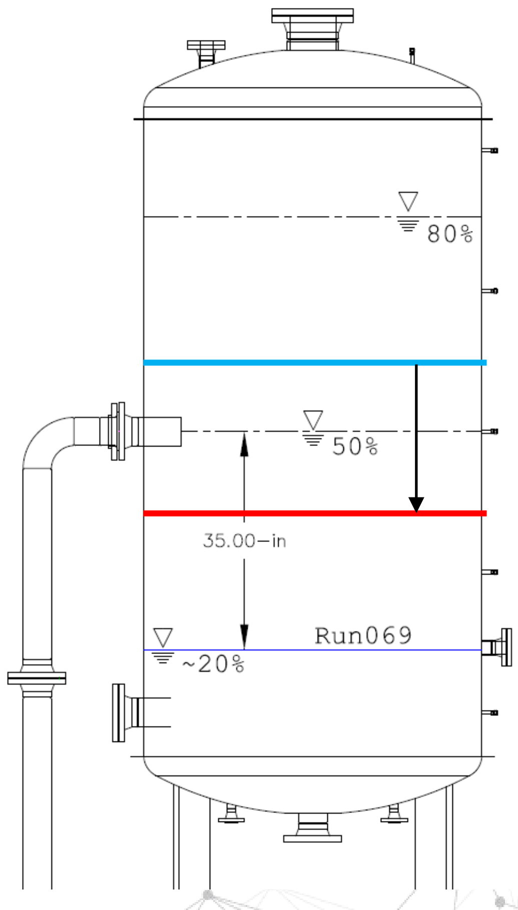
- Two-phase baseline test was repeated with riser channels #3 & 6 full blocked
  - Blockage was initiated ~2-hr prior to onset of boiling
  - Tubes were vented to prevent pressure build-up and allow liquid boil-off
- Dry-out conditions reached 1.6-hr after starting of boiling



	Baseline	**Blocked**	*diff*
Primary flow rate, kg/s	1.79	1.51	*-15.5%*
Riser flow rate, kg/s	0.227	0.258	*13.4%*
Heated section ΔT, °C	3.83	4.22	*10.1%*
Water tube, hot side °C	112.6	214.9	***91.0%***
Water tube, cold side °C	106.4	201.34	***89.3%***
Panel fins, hot side °C	133.5	177.1	*32.6%*
Panel fins, cold side °C	133.2	175.9	*32.1%*
Heated plate surface °C	340.16	343.69	*1.0%*
Side walls °C	181.7	179.1	*-1.4%*
Cold wall °C	105.8	108.8	*2.8%*

Depleted inventory scenario





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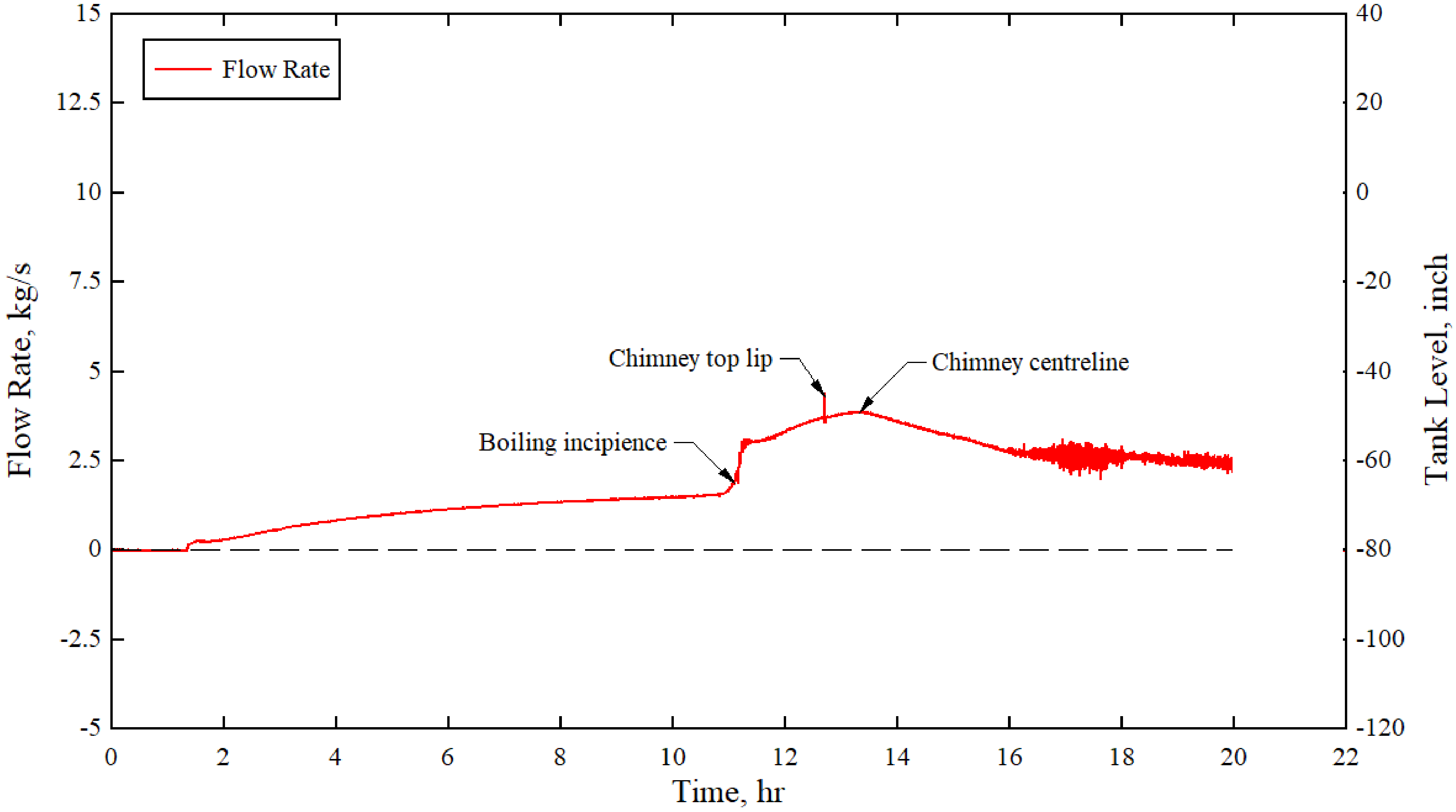

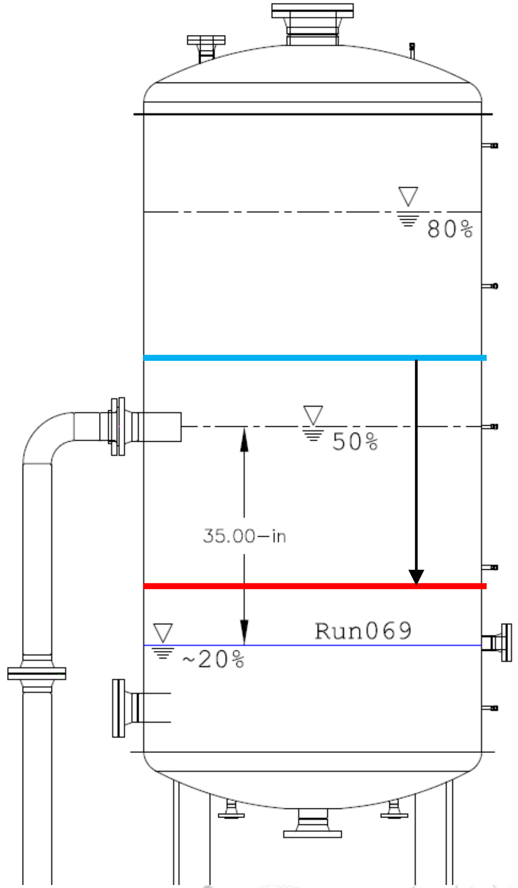

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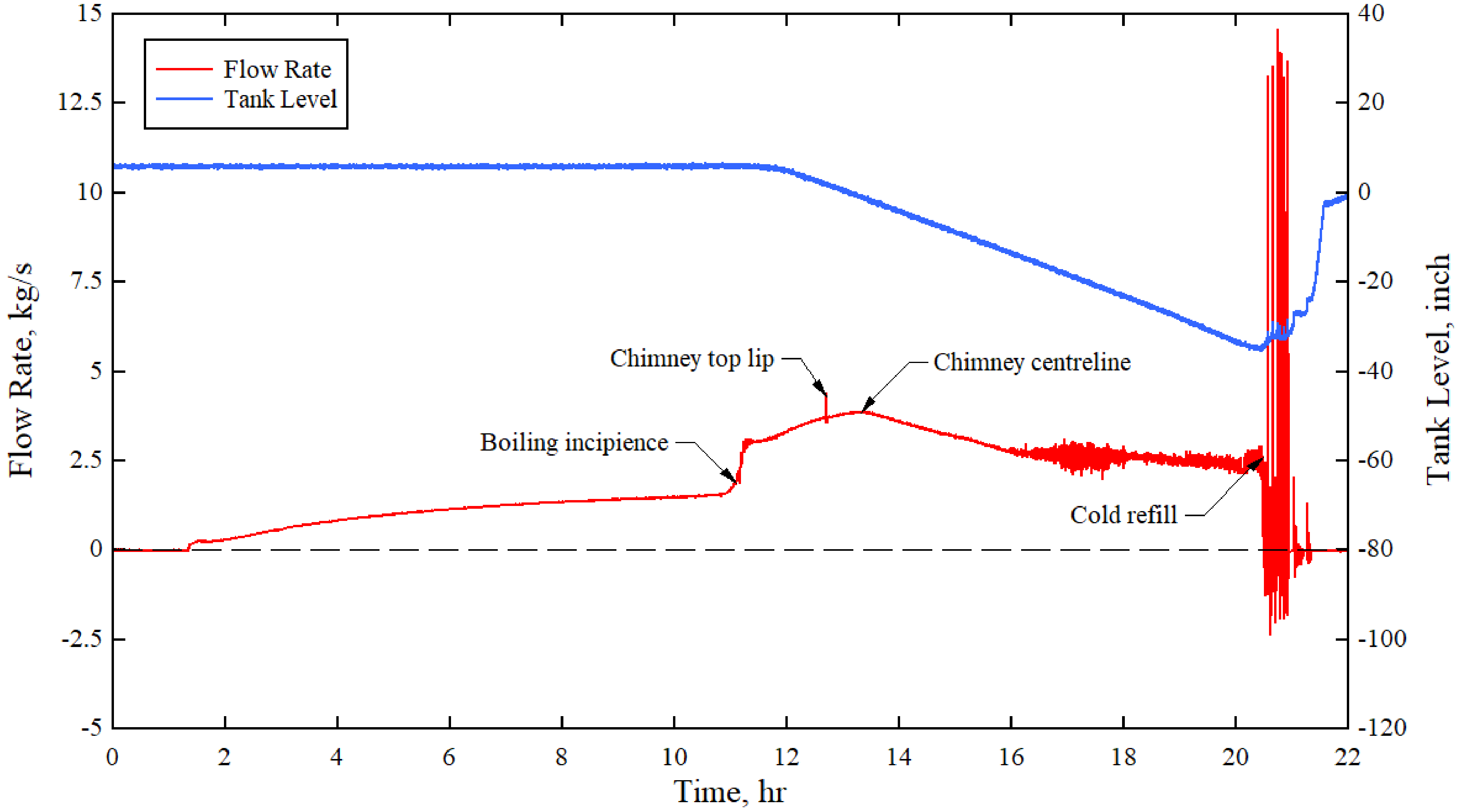

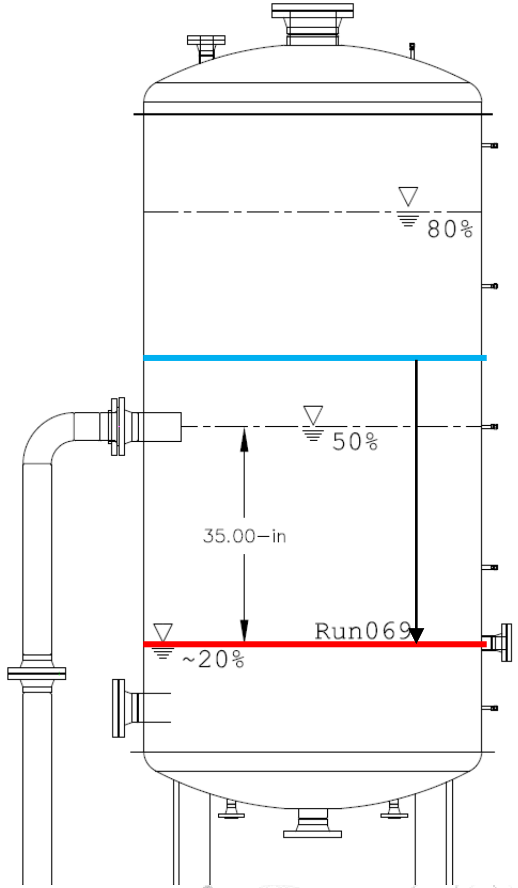

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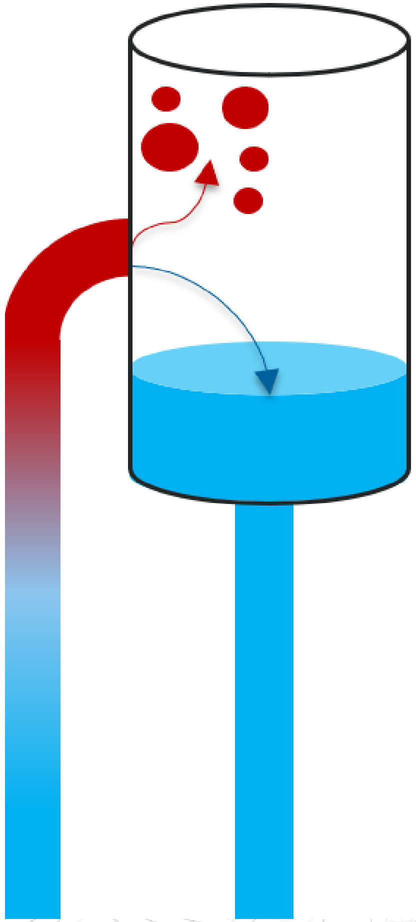

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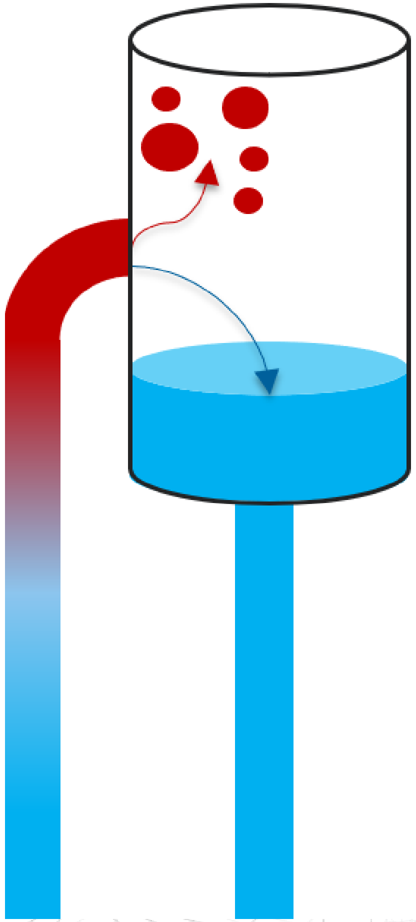
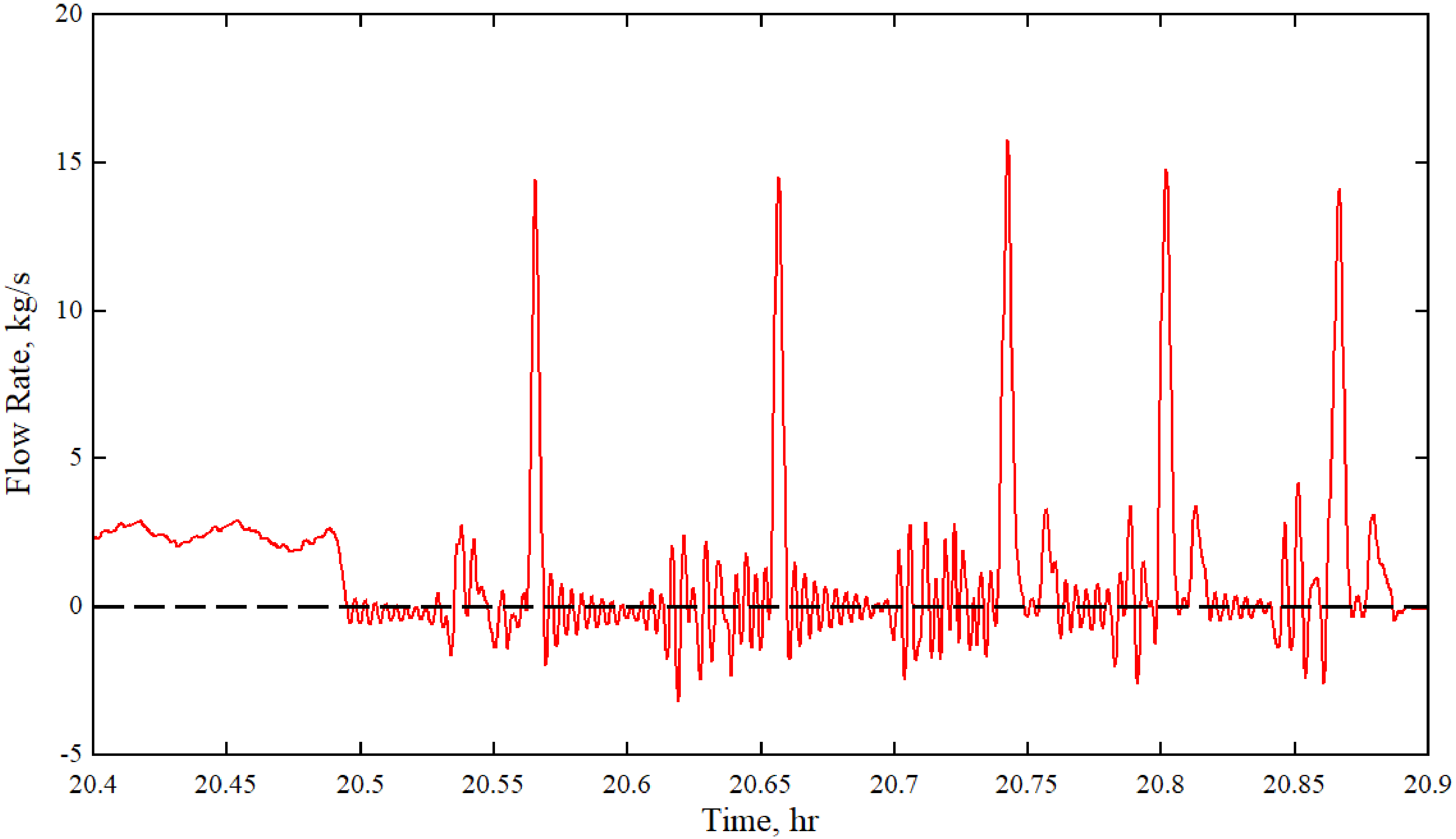
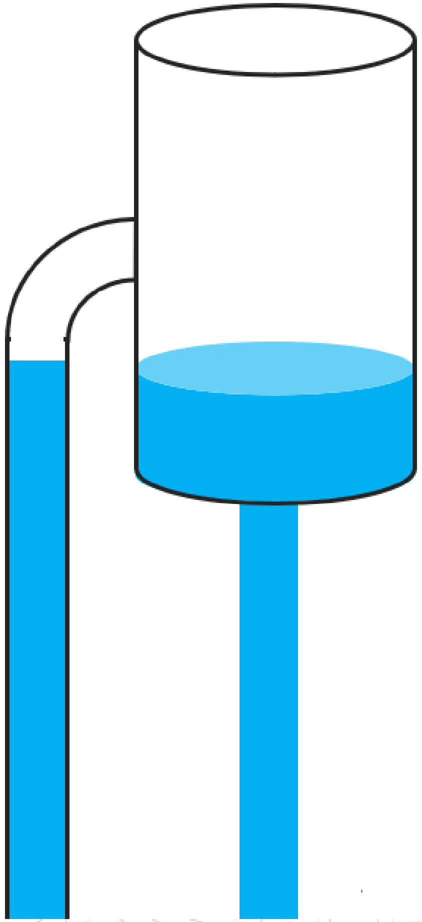


Stagnation & instability

Stagnation of loop flow → Quiescent fluid in risers → Geysering





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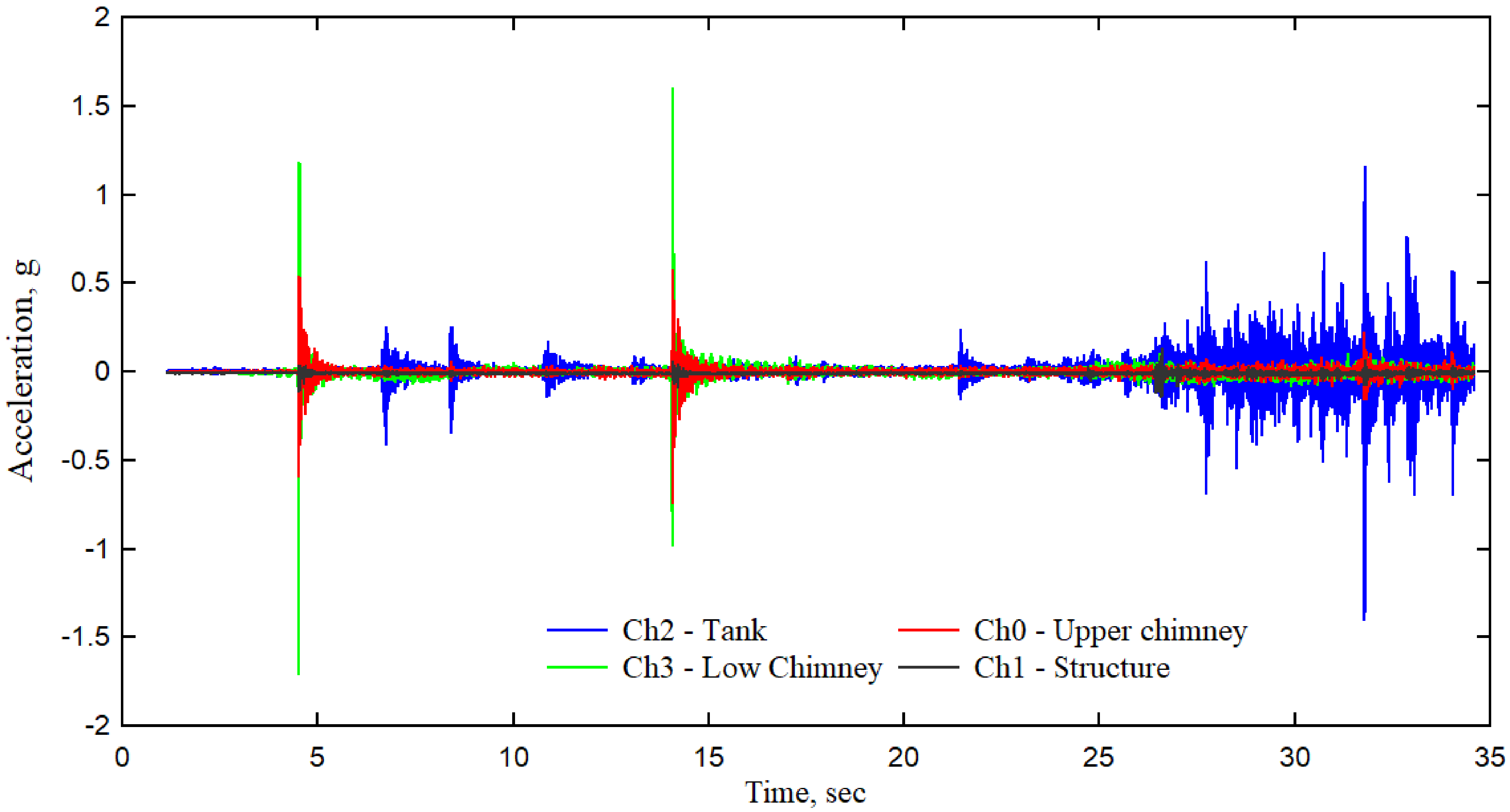
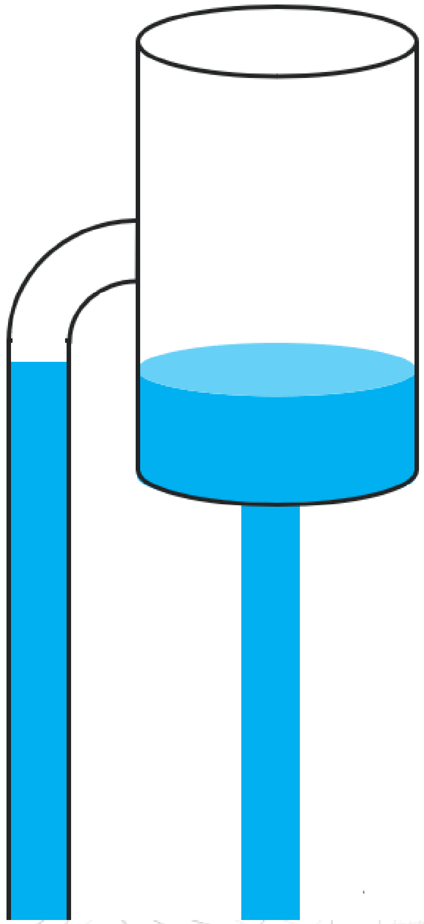
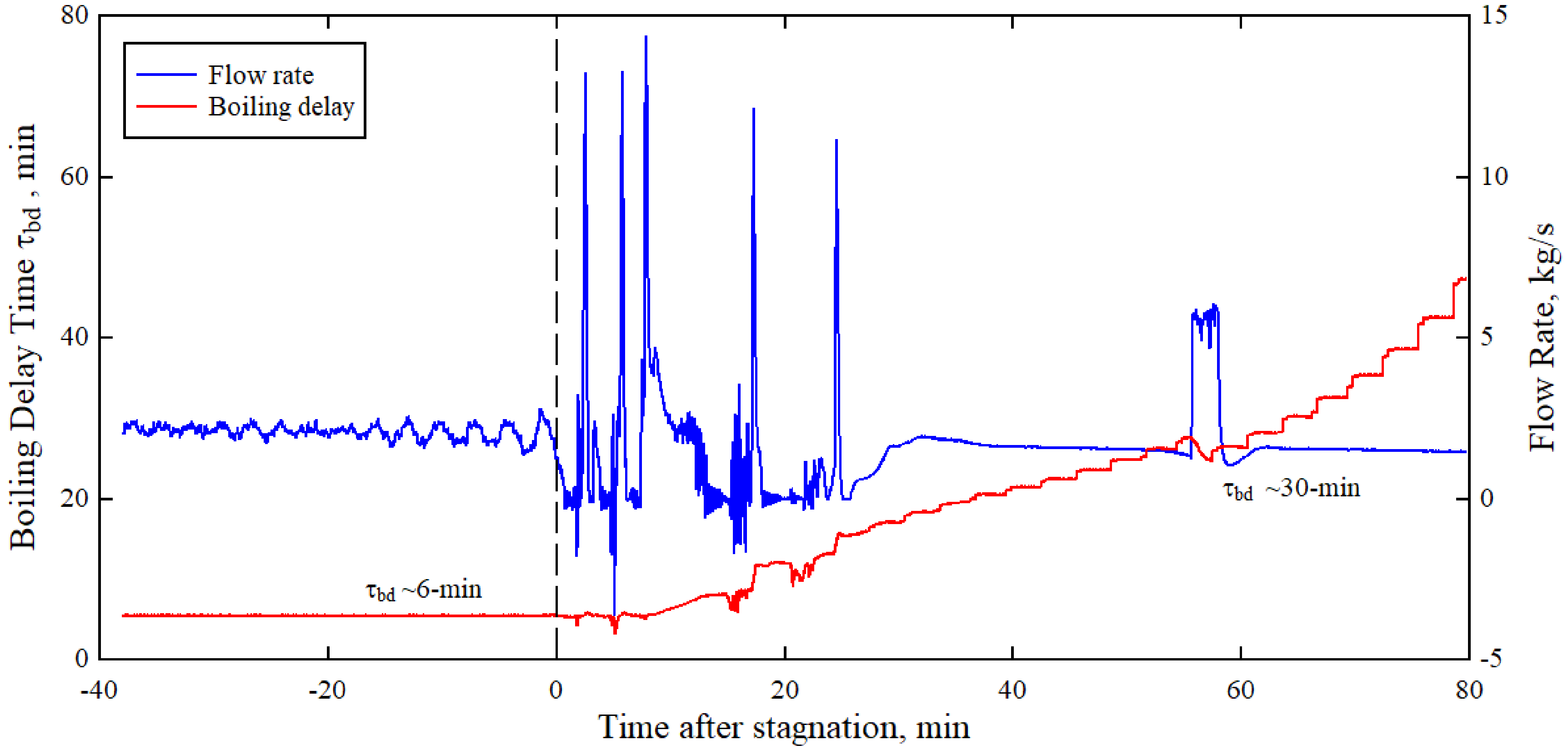
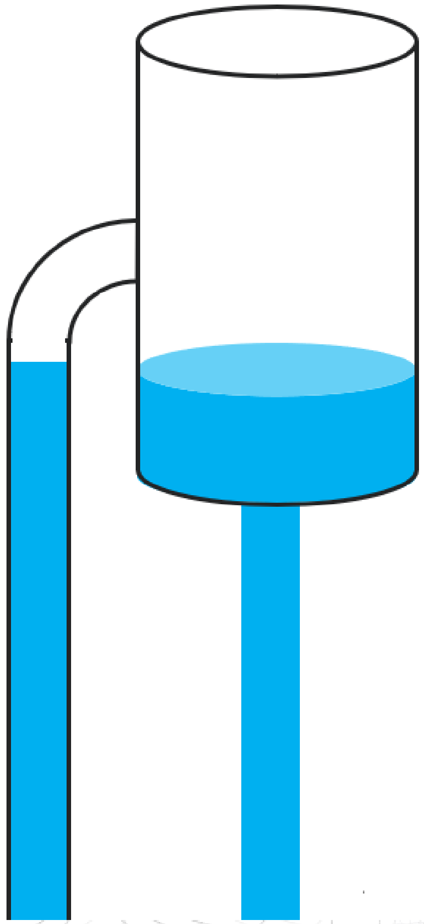




Boiling delay time for geysering





Test No.	Refill Location	Refill Rate	Time to re-establish natural circulation	No. geysering events
DataQuality069	Inlet header	1.5 GPM	160 min	8+
DataQuality074	Primary tank	3.2 GPM	90 min	~6
DataQuality081	Primary tank	14.8 GPM	28 min	2-3

RELAP5 Modeling

Computational Modeling

- "Symbiotic" relationship between experimental and computational work
  - **Mutually beneficial** to both campaigns
  - Good communication between both teams
- Experimental data helps to benchmark computational modeling approaches
  - System-level measurements (e.g. mass flow rate) beneficial for RELAP5
  - Fine-grained measurements (e.g. numerous thermocouples) beneficial for CFD
  - Provides more confidence in using analysis tools for future work
- Computational studies help elucidate some physical mechanisms
  - Also provide a "sanity check" for the experimental data

Component-level CFD analysis

- Detailed cavity air flow simulations
- Header design on flow distribution
- Mixing behavior in tank
- Porosity of insulation in heated region

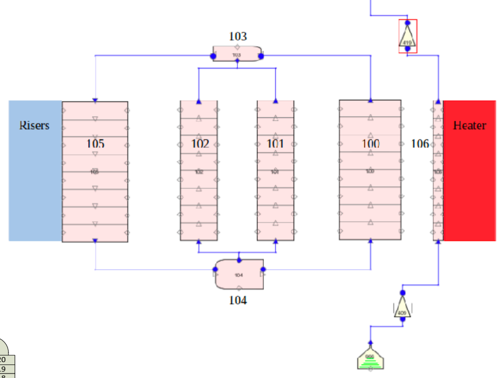
Integral System RELAP5 model

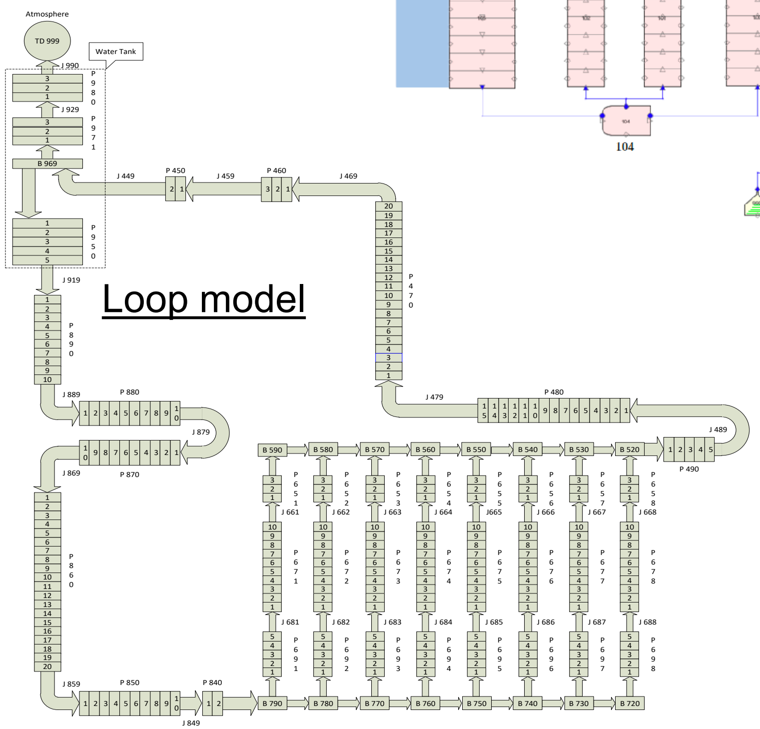
- Loop benchmarking
- Full length transient scenarios
- Instability analysis
- Predictive capability for test guidance

RELAP5 - Model Development

- RELAP5-3D v4.3.4
- Primary loop model:
  - Consists of pipes, branches, junction components
  - Simplified tank model
  - No secondary cooling: steam is vented to the environment
- Cavity model:
  - Natural convection modeled by pipes and branches
  - Fluid flow in the cavity is coupled to heat structures
  - 'Enclosure' system to model thermal radiation

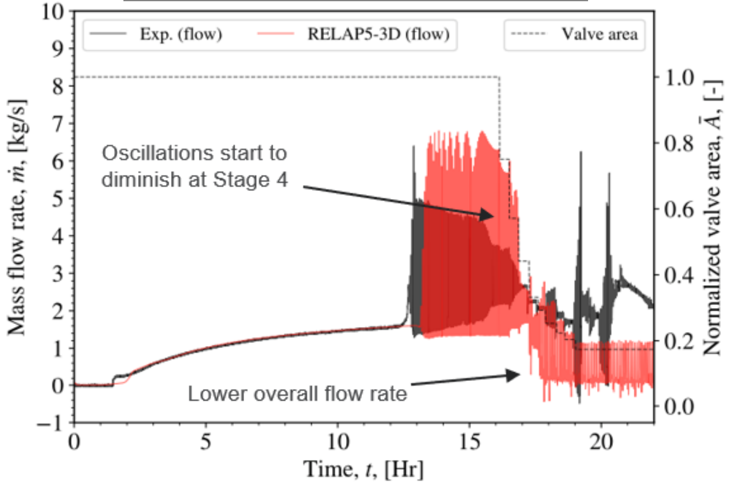
Cavity model



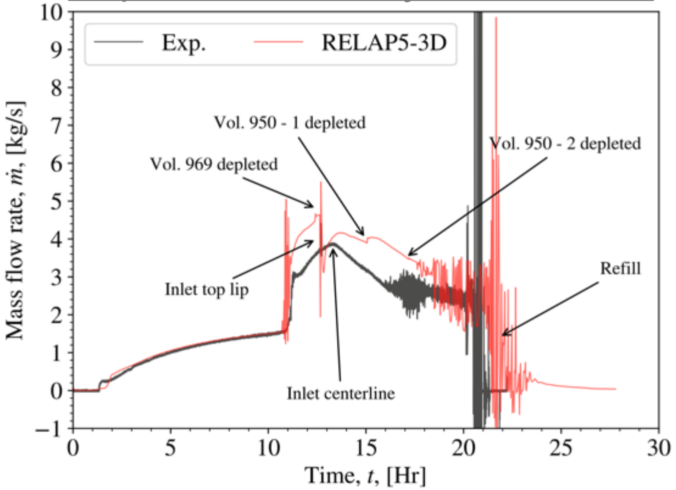


Loop model

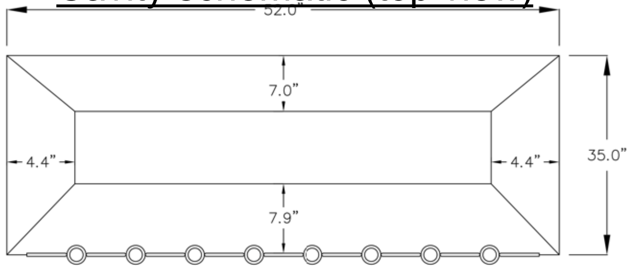
Inlet Throttle Benchmark



Depleted Inventory Benchmark



Cavity schematic (top view)



Test Summary & Path Forward

Completed Matrix Test Case

	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, 80a%	☐ 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
	DataQuality052	01/16 - 17/2019	029h4m	Single-phase, 2.1 MW_t baseline, 80%	☑ **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
	DataQuality055	6/13 – 14/2019	026h01m	Single-phase, 2.8 MW_t baseline, 80%; 42kW_t addt'l	☑ **Accepted**	☐ Trending	☐ failed	☐ n/a
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
	DataQuality061	09/23 – 24/2020	016h55m	Two-phase 2.1 MW_t baseline; 60% inventory	☑ **Accepted**	☐ Trending	☐ failed	☐ n/a
FY21	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, 70% ARPA-E fault #1,2,&3	☑ **Accepted**	☐ Trending	☐ failed	☐ n/a
	DataQuality073	03/16 - 17/2022	021h02m	Two-phase 2.1 MW_t baseline 70% tank; Refill; Riser throttle	☑ **Accepted**	☐ Trending	☐ failed	☐ n/a
	DataQuality074	04/18 - 21/2022	071h45m	Framatome accident scenario, V.2 scaled x5.2, 80% initial tank	☑ **Accepted**	☐ Trending	☐ failed	☐ n/a
	DataQuality075	07/13 - 14/2022	019h04m	Two-phase 2.8 MW_t high power, 70% tank, Transient	☑ **Accepted**	☐ Trending	☐ failed	☐ n/a
	DataQuality076	07/28/2022	025h47m	Static boiling, 36kWe, refill up	☐ Accepted	☐ Trending	☑ **failed**	☐ n/a
	DataQuality077	08/10/2022	014h53m	Static boiling, 36kWe, drain down	☐ Accepted	☑ **Trending**	☐ failed	☐ n/a
	DataQuality078	09/08 - 09/2022	023h58m	Two-phase 1.4 MW_t, 70%; tank, Transient, Blocked #3&#6	☑ **Accepted**	☐ Trending	☐ failed	☐ n/a
FY23	DataQuality079	10/04 - 05/2022	021h23m	Two-phase 1.75 MW_t medium power, 70%; tank, Transient	☐ Accepted	☑ **Trending**	☐ failed	☐ n/a
	DataQuality080	11/02 - 03/2022	021h08m	Two-phase 1.75 MW_t medium power, 70%; tank, Transient	☑ **Accepted**	☐ Trending	☐ failed	☐ n/a
	DataQuality081	11/30 – 12/01/22	019h37m	Two -phase 2.1 MW_t, 50% invent.; Depletion; High flow refill	☑ **Accepted**	☐ Trending	☐ failed	☐ n/a
	DataQuality082	01/19/2023	011h25m	Static boiling, 48kWe, drain down	☑ **Accepted**	☐ Trending	☐ failed	☐ n/a
	DataQuality083	03/08 – 09/2023	025h53m	Low power throttle test	☑ **Accepted**	☐ Trending	☐ failed	☐ n/a
	DataQuality084	04/05 – 06/2023	021h55m	High power throttle test	☑ **Accepted**	☐ Trending	☐ failed	☐ n/a
	DataQuality085	06/27 – 28/2023	019h57m	70% baseline repeatability; tank valve scoping trials	☑ **Accepted**	☐ Trending	☐ failed	☐ n/a
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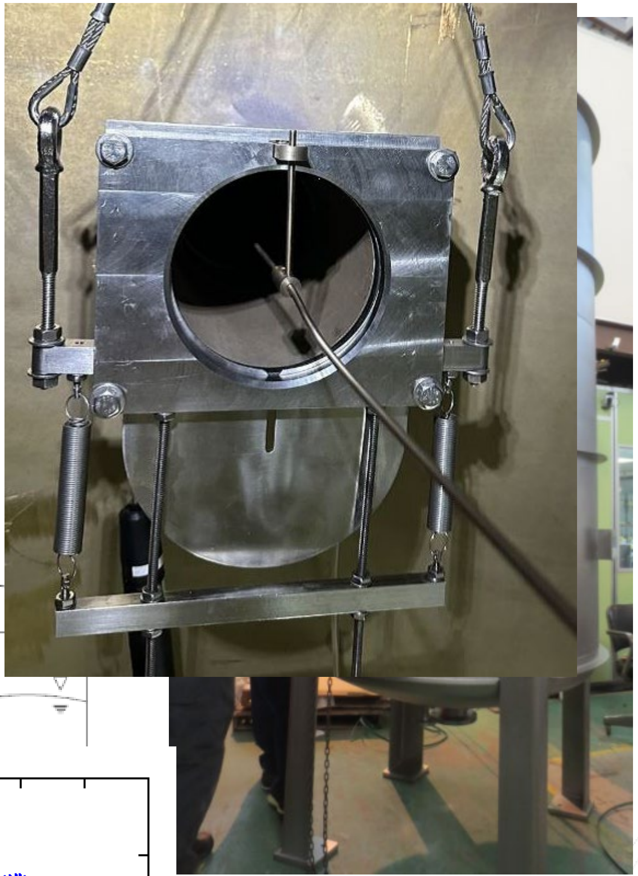
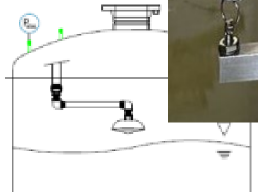
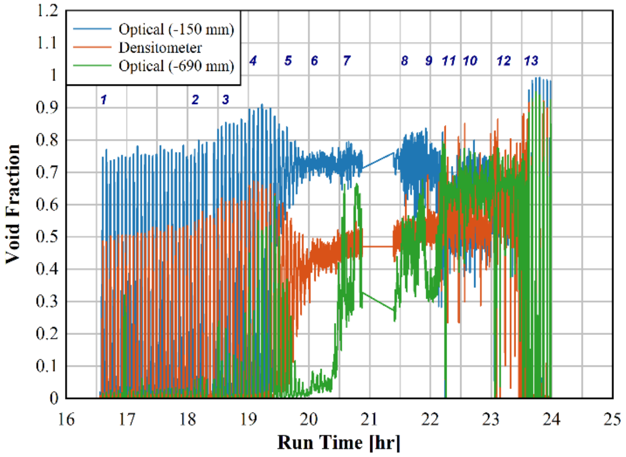
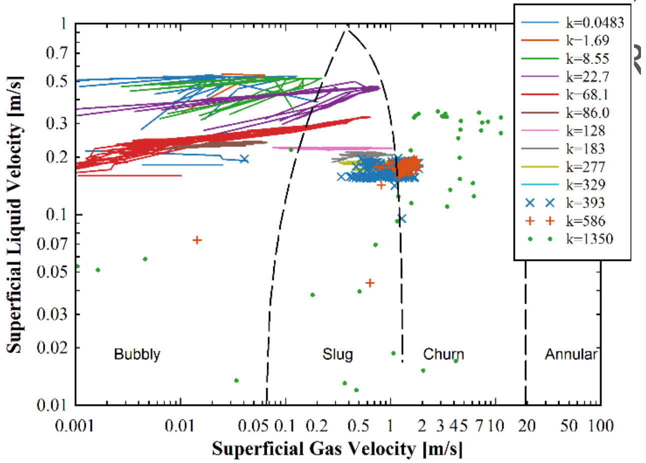
Activities Remaining & FY24

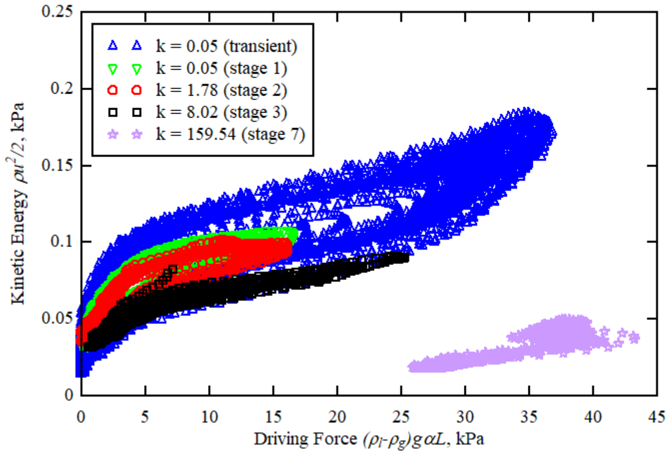
- Continuation for remainder of FY23
  - Continuation of loss coefficient / blockages for off-normal scenarios
    - Recently added throttle valve at chimney (two-phase) outlet
  - Ramp-up analysis of performance and stability
    - Deep dive into two-phase phenomena and system parameters at tested conditions
    - Global identification of stable and unstable operating windows
    - Continued development of this computational modeling tools
- Data packaging and exchange with active US vendors
  - Comprehensive packaging of new and previously collected data

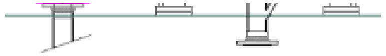












- Create short-circuit with high vapor carry over

Current & Future Role of NSTF

Outreach Effort – Industry Needs & Future of NSTF

- Because of continued support from the DOE, the NSTF program has been able to provided relevant and timely support to US vendors for development of their passive decay heat removal systems
- There is a strong interest in maximizing the DOE investment to allow continuation of this support for the evolving landscape of current and active industry technologies
- Led by the program federal manager, and in coordination with technical leads, a white paper was released in early 2023:
  - summarizes past, ongoing, and future work
  - evaluates industry gaps and inputs, identifies risks
  - considerations, options, risks, and recommendations related to disposition of the NSTF
  - recommendations for continued future use of the facility

Outreach Effort – Industry Needs & Future of NSTF

- An outreach campaign was initiated to identify future roles, purpose, and needs of the NSTF program at Argonne
  - 19 US companies were contacted requested information on their gaps and needs for passive decay heat removal in the design and development of their advanced reactor(s)
  - We received detailed communication and/or written responses from 15 companies
  - Identified strong interest in specific technologies pertaining to RCCS and RVACS
- Based on the feedback, we identified the following:
  - All reactor vendors are including *some* form of passive decay heat removal in their designs
  - Majority utilize existing technologies in a traditional form; some have incorporated hybrid concepts
    - RVACS (traditional & hybrid)
    - RCCS (air & water)
    - DRACS
  - There was curiosity in use of heat pipes for large scale heat removal, but feasibility is yet to be determined
- At the current time, the traditional RVACS and water-cooled RCCS stand out as main contenders

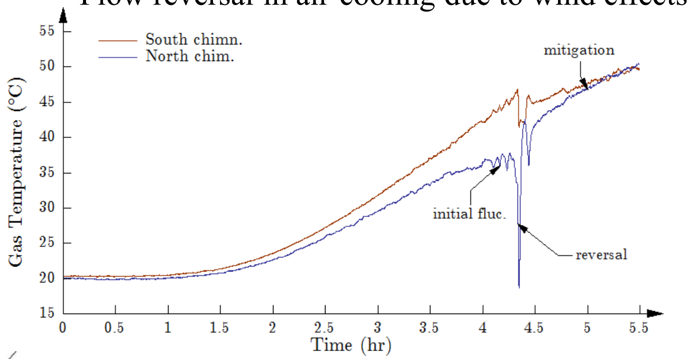
Vendor	Reference Reactor	Passive Heat Removal System	
		Concept Design	*Working Fluid*
ARC Clean Technology	ARC-100	[redacted]	
Boston Atomics	HC-HTGR		
BWX Technologies	BANR		
BWX Technologies	PELE		
Framatome	SC-HTGR		
GE - Hitachi	PRISM		
GE - Hitachi	BWRX-300		
General Atomics	FMR		
General Atomics	EM^2		
Holtec Intl.	SMR-160		
Kairos Power	KP-FHR		
NNSA	*Generic*		
Oklo	Aurora		
Southern Co.	MCFR		
TerraPower	Natrium		
Terrestrial Energy	ISMR		
Ultra Safe Nuclear	MMR		
US NRC	*Generic*		
Westinghouse	LFR		
Westinghouse	eVinci		
X-Energy	Xe-100		

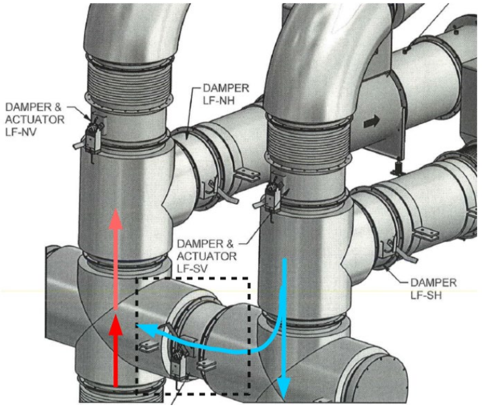
Breadth & Impact of NSTF Program

- Facility infrastructure reflects a generic containment and reactor vessel, able to generate decay heat load representative of nearly *any* reactor design by US vendors (LWR, SFR, GFR, MSR, SMR, etc.)
  - 6.7 m (22 ft.) heated section
  - 23 kW/m^2 / 500°C peak RPV power
- Overall program has been on-going since 2013
  - Industry collaboration with Kairos, Framatome, Boston Atomics and Westinghouse
  - Provided JAEA and US vendors with validation data
- Testing matrix covers broad range of expected, design-basis accident, and off-normal scenarios

	Water	**Air**
Duration	61-month	33-month
Active Hours	1,288-hr	2,250-hr
Data-Quality	32	27
Accepted	*26*	*16*
Trending	*8*	*7*
Failed	*3*	*4*
Total Runs	54	40

Flow reversal in air-cooling due to wind effects

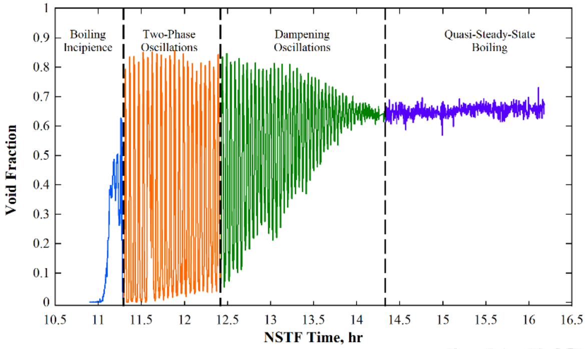




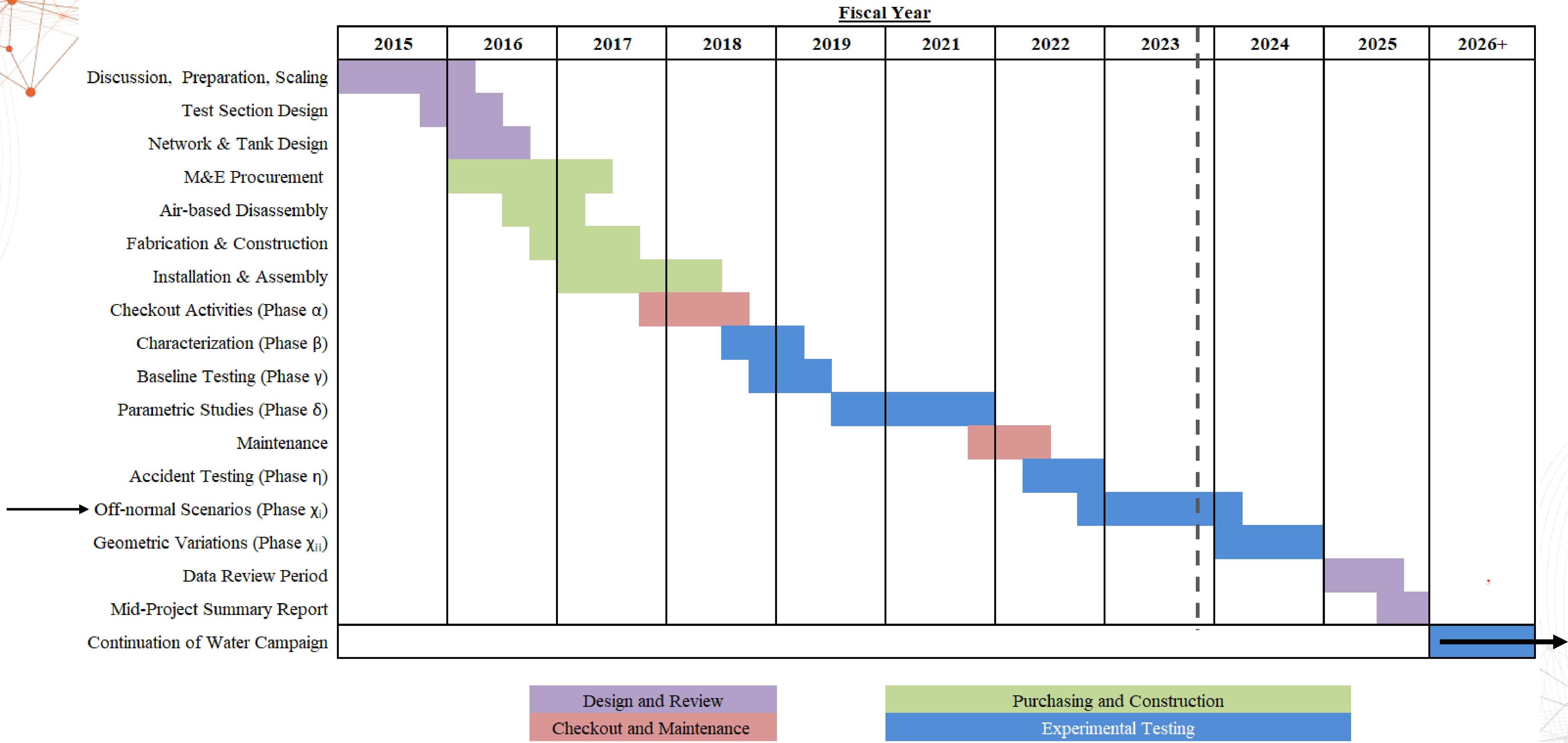
Short circuit air by-pass scenario

Chugging during inventory depletion scenario

Stabilization of two-phase oscillations



Program Timeline



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THANK YOU