GEN IV International Forum℠

PASSIVE DECAY HEAT REMOVAL SYSTEMS

Dr. Mitchell Farmer
Argonne National Laboratory, USA

October 23, 2019

Meet the presenter

Dr. Mitchell Farmer is a Senior Nuclear Engineer in the Nuclear Science and Engineering (NSE) Division at Argonne National Laboratory. He has over twenty-five years of experience in various R&D areas related to reactor development, design, and safety. A principal career focus area has been light water reactor (LWR) severe accident analysis and experiments.

More recently, he has also been involved in the analysis, design, and conduct of experiments related to operations and safety of Generation IV reactor concepts including sodium fast reactors, as well as high-temperature gas cooled reactors. He has over 200 publications in the above-mentioned technical areas. Dr. Farmer also manages the LWR Programs within Argonne's NSE Division in which these and other programs are carried out.

Dr. Farmer earned his Bachelor's degree in Nuclear Engineering from Purdue University, his Master's degree in Mechanical Engineering from the University of Nebraska, and his Ph.D. in Nuclear Engineering from the University of Illinois

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Motivation

- The reactor accidents at Fukushima Daiichi reinforced the need for fully passive safety systems that will ensure safe shutdown of a nuclear reactor
    - BWR Mark I’s are a first-vintage (1960’s) design with heavy reliance on active cooling and safety systems

- Best attempts are made to account for all possible accident scenarios, but the design philosophy should not require specific considerations
    - Fully passive – NO reliance on active power, AC or DC
    - Always on – no human intervention required to active
    - ‘Walk away’ safety

Backup diesel generator at Fukushima engulfed in water due to Tsunami
Courtesy of TEPCO

Passive Safety Needs for GenIV

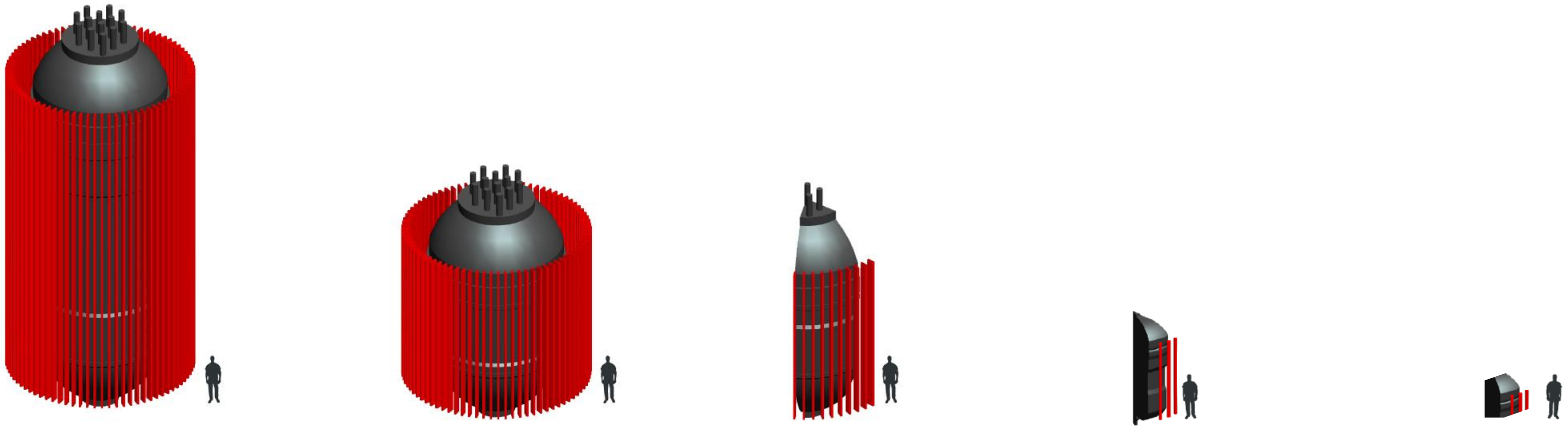
- GenIV initiative defines 8 technological goals, of which 3 are safety related:
  - “S&R 1 – System operations will excel in safety and reliability”
  - “S&R 2 – Very low likelihood and degree of reactor core damage”
  - “S&R 3 – Eliminate the need for offsite emergency response”

- The reactor cavity cooling system (RCCS) has emerged as a leading concept for meeting these goals
  - Possibility to provide inherently safe and fully passive means of decay heat removal
  - Offers a high level of performance with relative simplicity in design
  - Has been under consideration since 1950’s

- Though the RCCS is our focus, our ultimate objective is to support the continued development of safe and reliable nuclear power
  - Multi-institutional effort has brought together federal, industry, national laboratories, and universities

Project Scope and Reach

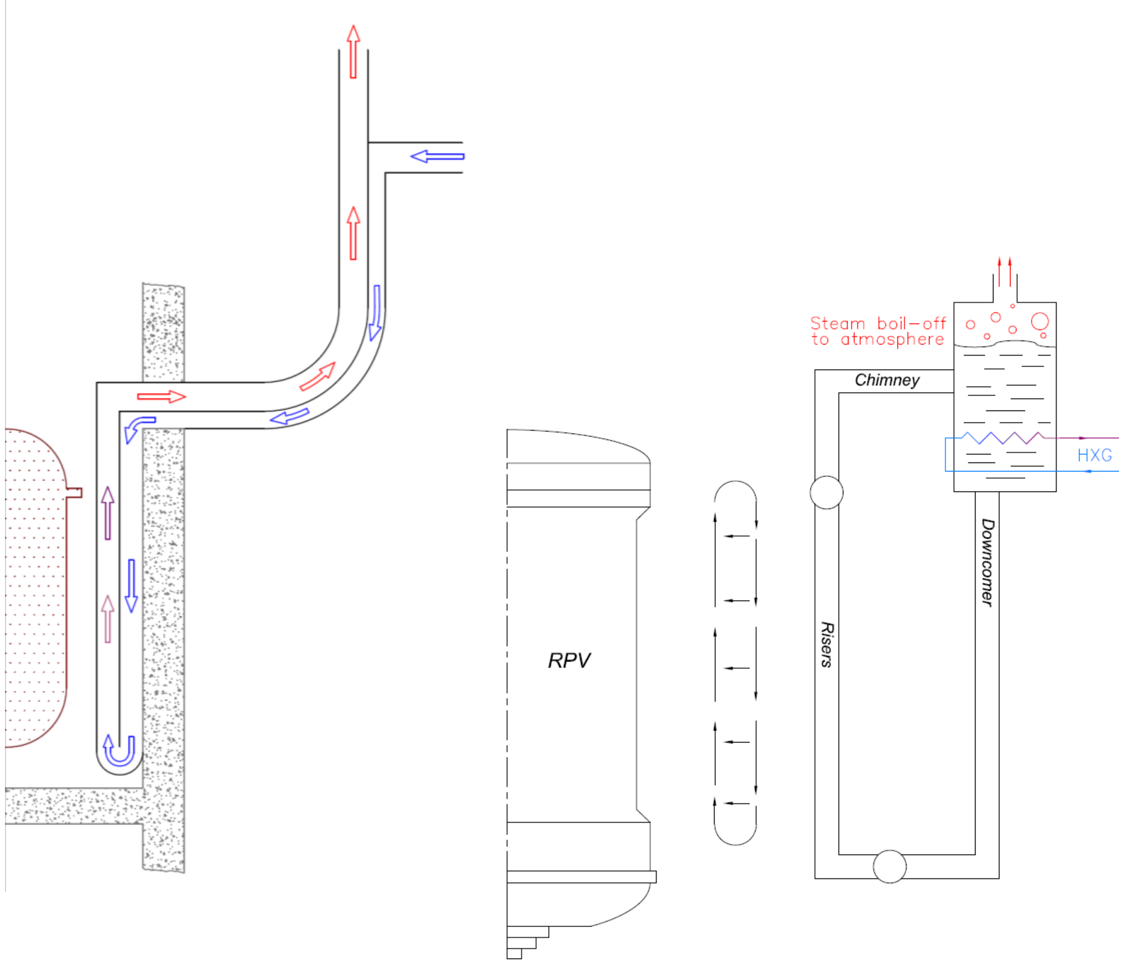
- Goal of inherent safety & fully passive decay heat removal
  - Simplistic, ex-vessel design provides cross-cutting opportunities
  - Heat flux alone off RPV serves as the mode of heat transfer
- Concurrent with a broader purpose including multiple US universities, industry, CFD modeling, and 1D analysis
  - Experimental efforts at multiple scales, using both air & water



RCCS Overview

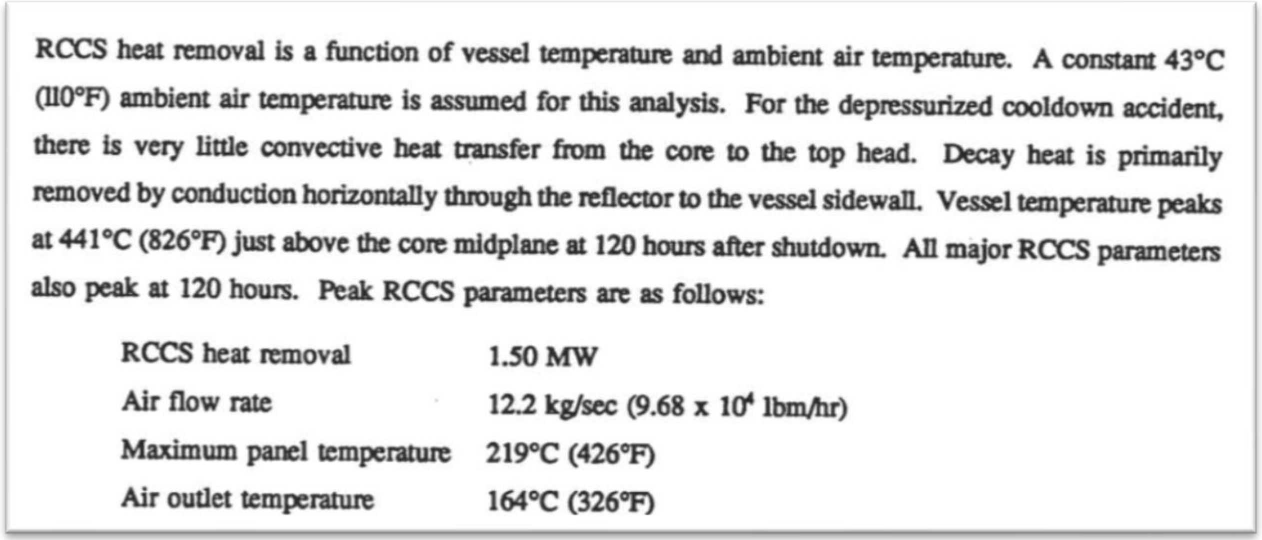
- Unique to recent generation of HTGR
  - Natural circulation in laminar and turbulent flow
  - Radiative (primary) and convective heat transfer
- Air and water under consideration
- Considered for both active cooling duration normal operation, and with other designs operating solely as a passive safety system during an accident transient
- Several designs, each unique in geometry, but sharing a common concept, are under design

Reactor	RCCS Coolant	Cooling Mode	Country	Power
HTR-10	Water	Natural	China	10 MW_t
VGM	Water	Natural	Russia	20 MW_t
HTTR	Water	Forced	Japan	30 MW_t
PBMR	Water	Natural	South Africa	400 MW_t
SC-HTGR	Water	Natural	USA	625 MW_t
HTR-PM	Water / Air	Natural	China	250 MW_t
GA-MHTGR	Air	Natural	USA	450 MW_t
GT-MHR	Air	Natural	Russia	600 MW_t



Decay heat load requirements

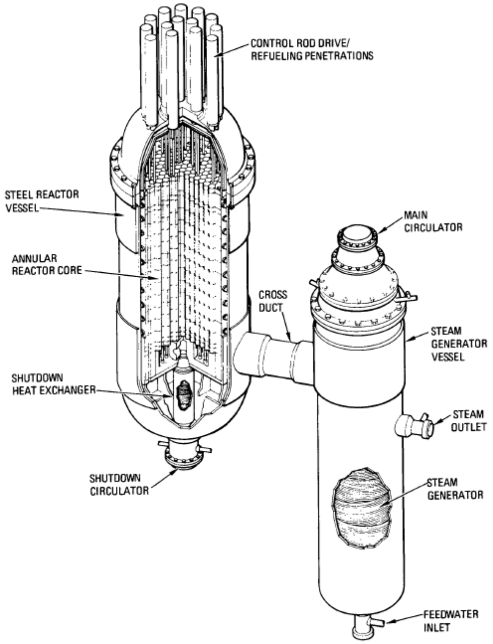
Parameter	GA RCCS	½ scale	Scaling Ratio
Height Scaling	1:1	2:1	ℓ_R
Total RCCS Height	55.2 m	26 m	ℓ_R
Heated Riser Section	13.86 m	6.82 m	ℓ_R
Riser Duct Count	*x*227	*x*12	-
Decay Heat	1.5 MW_t	56.07 kW_t	$\sqrt{\ell_R}$
Decay Heat Flux	4.82 kW/m^2	6.82 kW/m^2	$\ell_R^{-0.5}$
System Flow Rate	12.2 kg/s	0.456 kg/s	$\sqrt{\ell_R}$
Heated ΔT	121 ° C	121 ° C	1



RCCS heat removal is a function of vessel temperature and ambient air temperature. A constant 43°C (110°F) ambient air temperature is assumed for this analysis. For the depressurized cooldown accident, there is very little convective heat transfer from the core to the top head. Decay heat is primarily removed by conduction horizontally through the reflector to the vessel sidewall. Vessel temperature peaks at 441°C (826°F) just above the core midplane at 120 hours after shutdown. All major RCCS parameters also peak at 120 hours. Peak RCCS parameters are as follows:

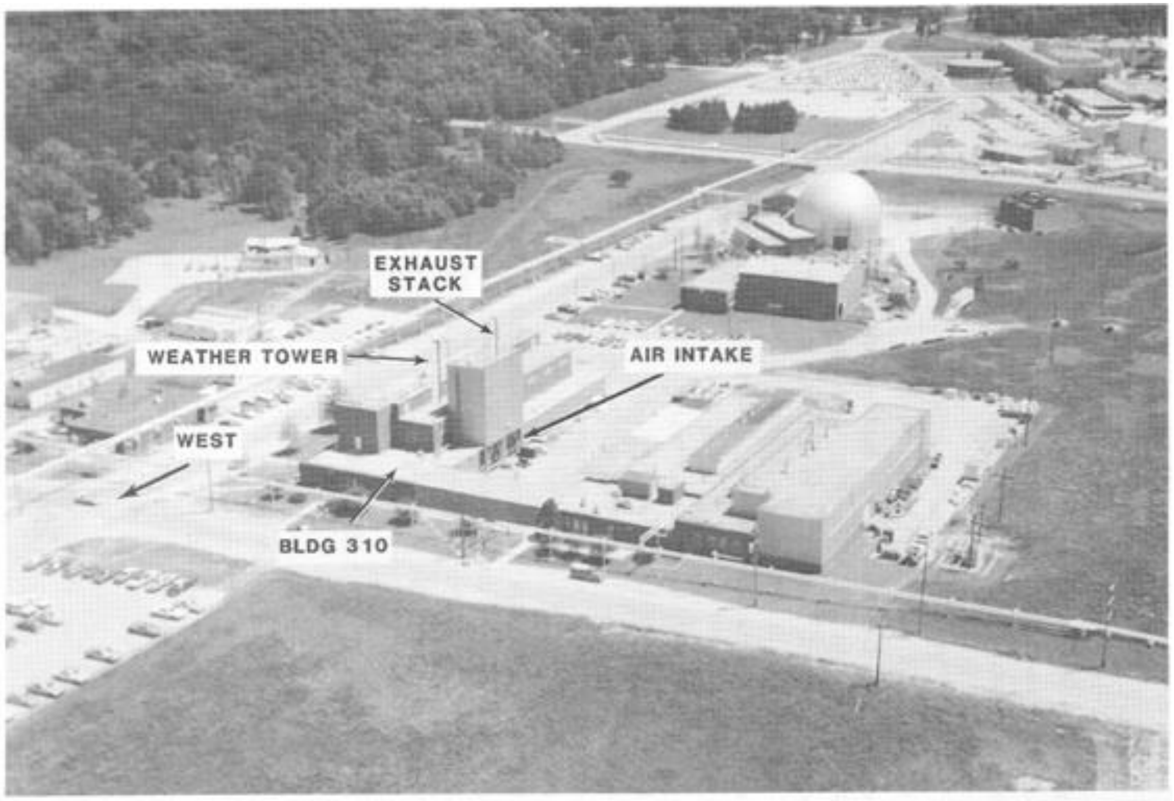
RCCS heat removal	1.50 MW
Air flow rate	12.2 kg/sec (9.68 x 10^4 lbm/hr)
Maximum panel temperature	219°C (426°F)
Air outlet temperature	164°C (326°F)

”Preliminary Safety Information Document for the Standard MHTGR,”
HTGR-86-024, Vol. 1, Amendment 13, U.S. Department of Energy, (1992)



NSTF at Argonne (legacy)

- Original NSTF built to provide confirmatory data for the GE PRISM RVACS design
- Successfully operated through the late 1980’s



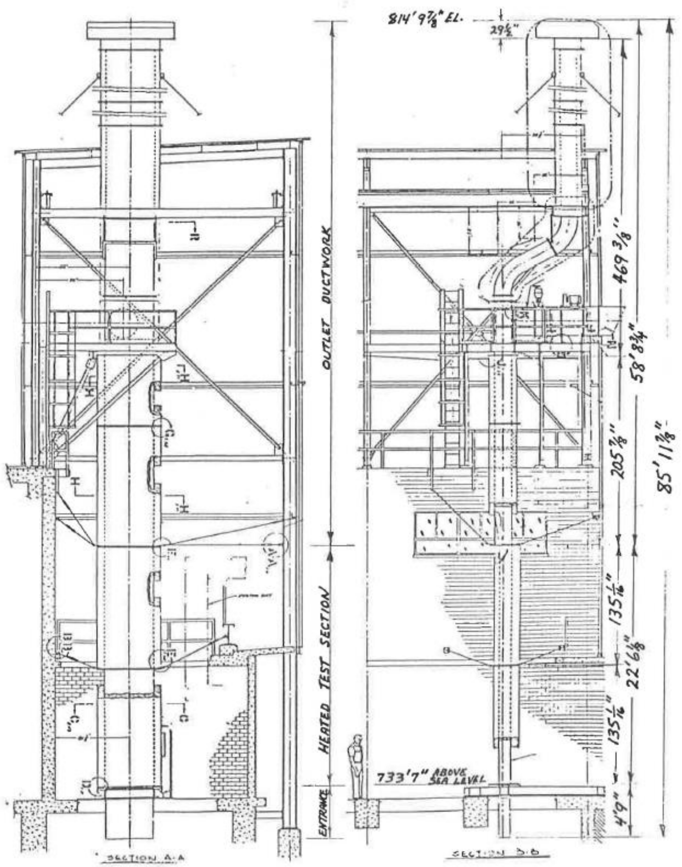


Figure 3-1. ANL Shutdown Heat Removal Test Assembly (Reduction of ANL Dwg. No. R0408-0004-DE, Sheet 1 of 4).

NSTF at Argonne (legacy)

- Beginning in 2010, the aging facility was revisited
- Several design aspects were re-used, however focus shifted to include features of newer high temperature gas-cooled reactors
- Many components were updated to latest technologies…

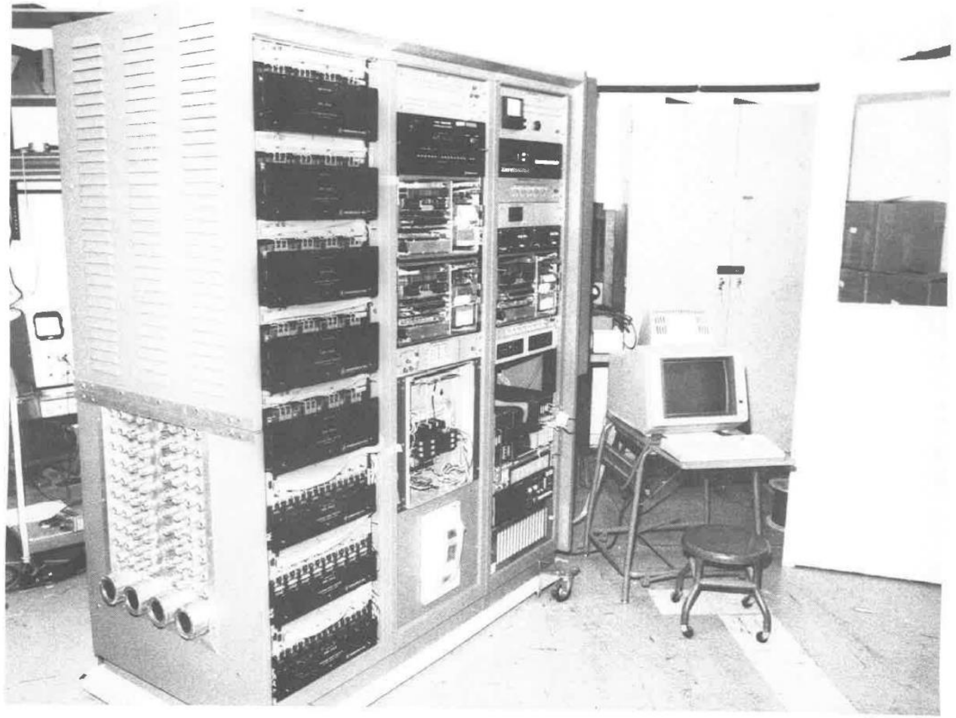
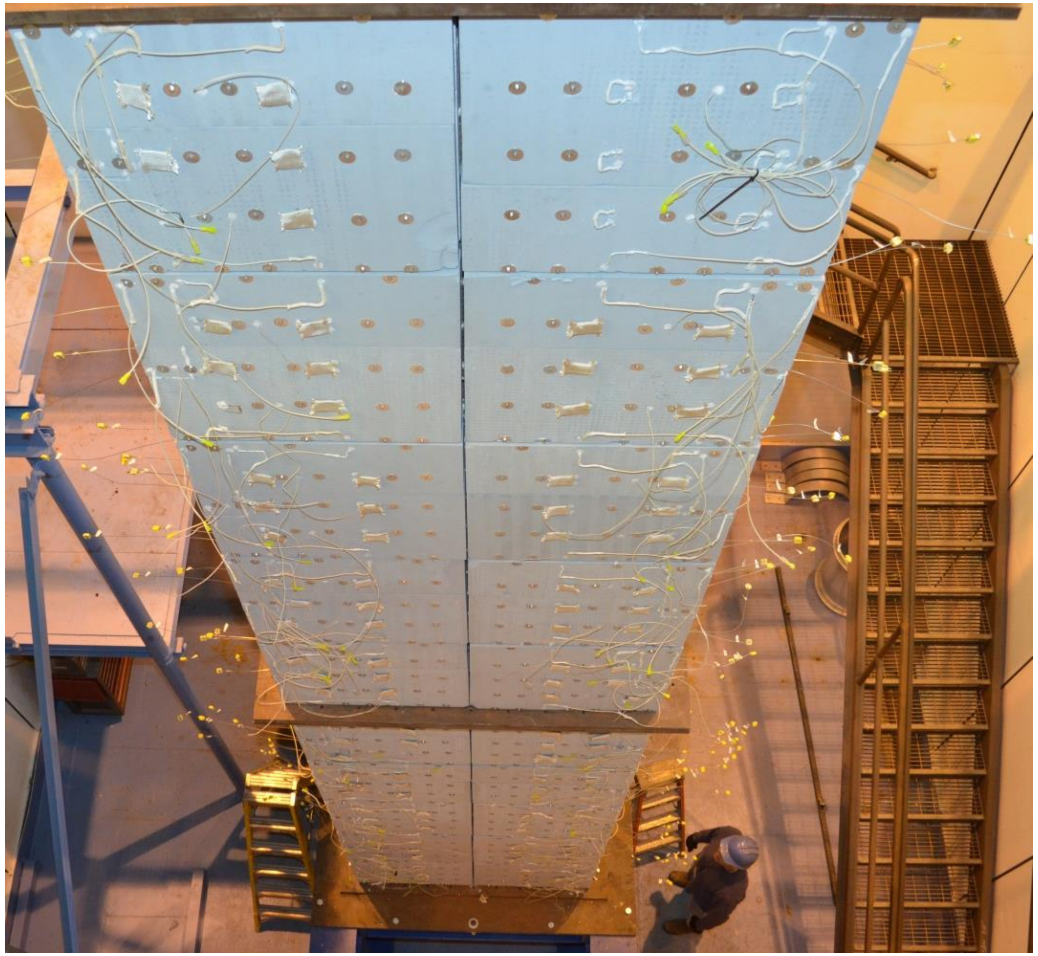


Figure 3-17. Computer Control and Data Acquisition Console.

NSTF at Argonne (present)

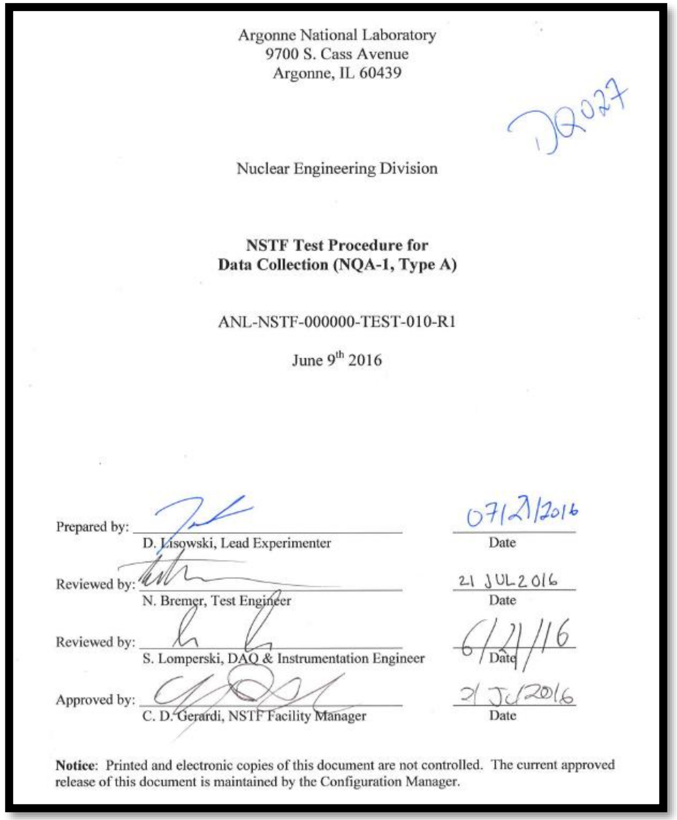
- The Natural Convection Shutdown Heat Removal Test Facility (NSTF) was initiated in FY2010 in support of DOE programs NGNP, SMR, and now ART
  - Program operates according to Nuclear Quality Assurance (NQA)-1 standards
- The top-level objectives of the NSTF program are:
  1. examine passive safety for future nuclear reactors
  2. provide a user facility to explore alternative concepts
  3. generate benchmark data for code V&V
- Concurrent collaborations for a broader scope
  - Experimental facilities at multiple scales (½, ¼, etc.) for both air and water designs
  - Complimenting CFD modeling and 1D systems level analysis
  - Collaborating towards the development of a central data bank for the RCCS concept



Quality Assurance

- Experimental data generated by the NSTF program is suitable for licensing initiatives by US vendors
  - The program meets requirements of ASME NQA-1 2008 w/ 2009 addendum
  - Regular audits maintain compliance to NQA-1
  - Small team of dedicated individuals with strong management support

Date	**Audit Type**		
Spring 2014	☐ MA	☐ Internal	☑ **External**
Winter 2014	☑ **MA**	☐ Internal	☐ External
Summer 2015	☐ MA	☑ **Internal**	☐ External
Fall 2015	☐ MA	☐ Internal	☑ **External**
Winter 2016	☑ **MA**	☐ Internal	☐ External
Summer 2016	☐ MA	☑ **Internal**	☐ External
Fall 2016	☑ **MA**	☐ Internal	☐ External
Fall 2017	☐ MA	☑ **Internal**	☐ External
Spring 2018	☐ MA	☐ Internal	☑ **External**
Summer 2018	☑ **MA**	☐ Internal	☐ External
Winter 2019	☐ MA	☑ **Internal**	☐ External



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DQ027

Nuclear Engineering Division

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

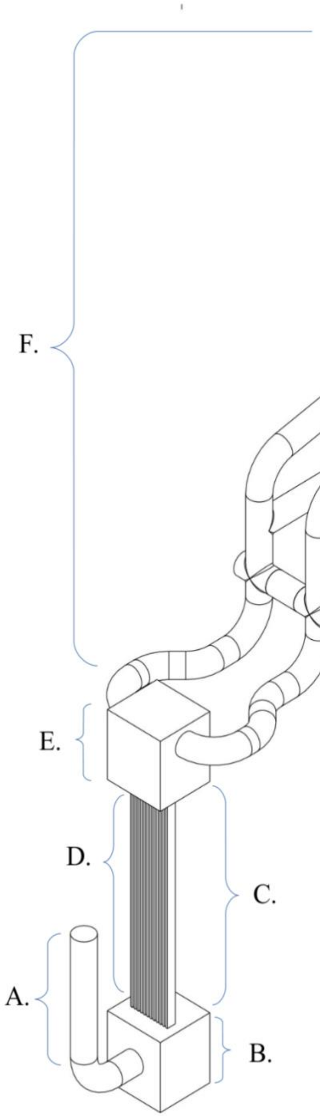
ANL-NSTF-000000-TEST-010-R1

June 9th 2016

Prepared by: D. Lisowski, Lead Experimenter — Date: 07/21/2016
Reviewed by: N. Bremer, Test Engineer — Date: 21 JUL 2016
Reviewed by: S. Lomperski, DAQ & Instrumentation Engineer — Date: 6/21/16
Approved by: C. D. Gerardi, NSTF Facility Manager — Date: 21 Jul 2016

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

Facility Overview



F. Chimney ductwork

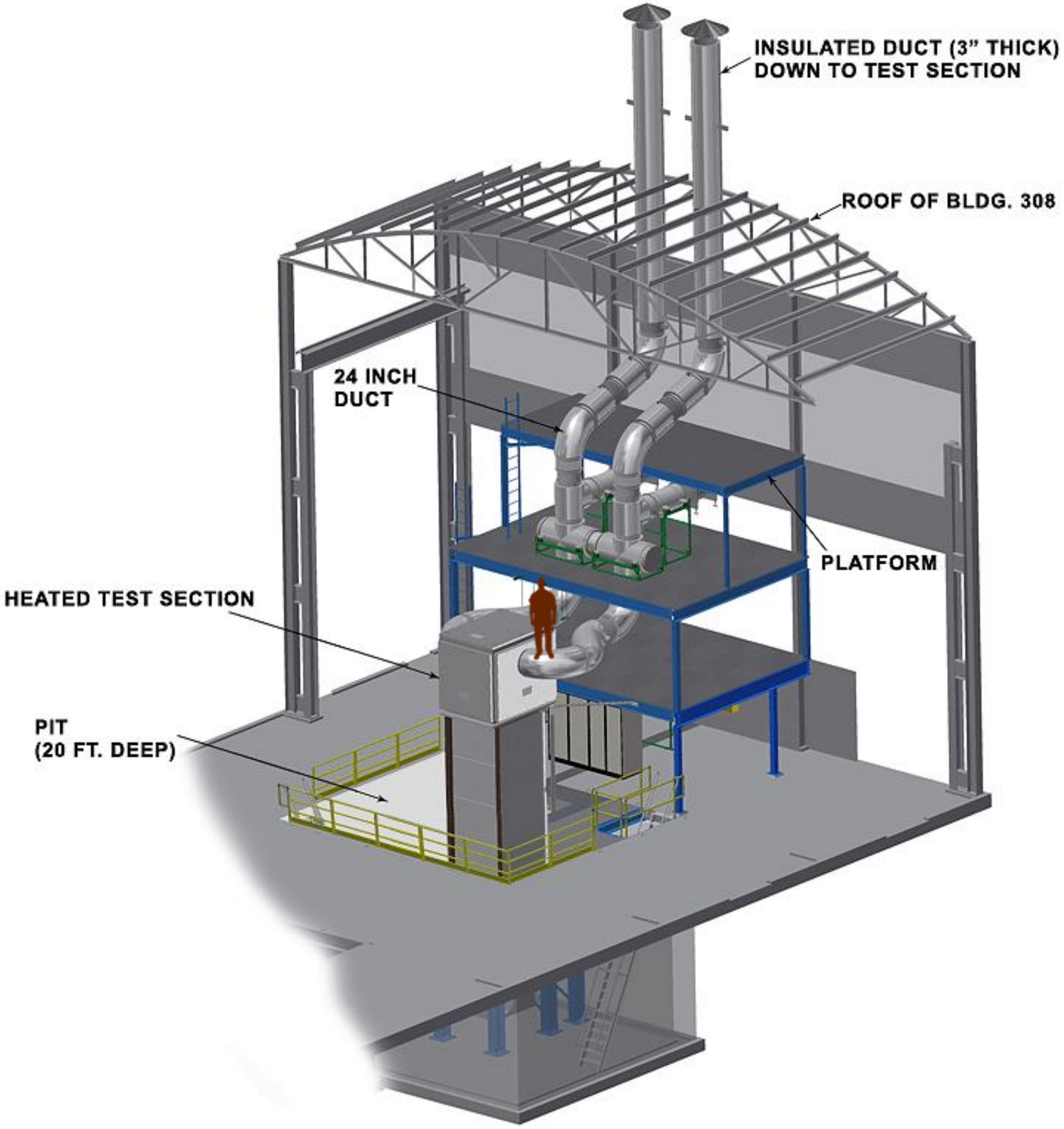
E. Outlet plenum

D. Riser ducts (7.5-m)

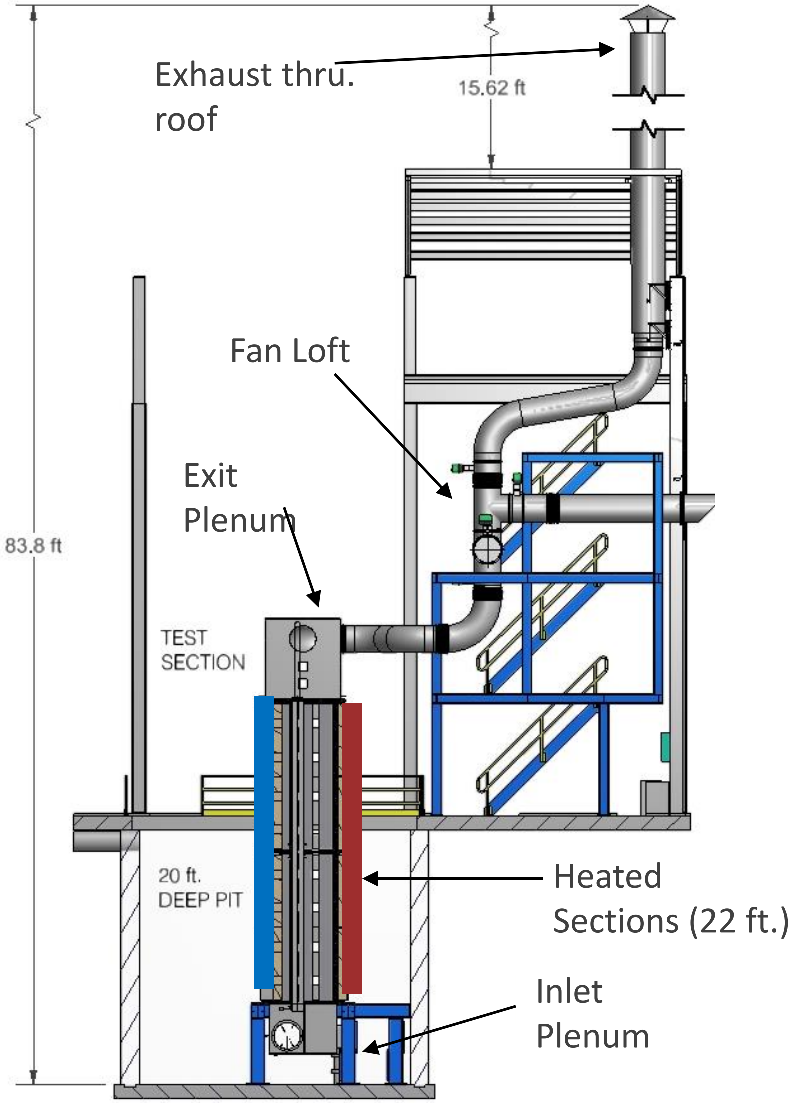
C. Heated cavity

B. Inlet plenum

A. Inlet downcomer

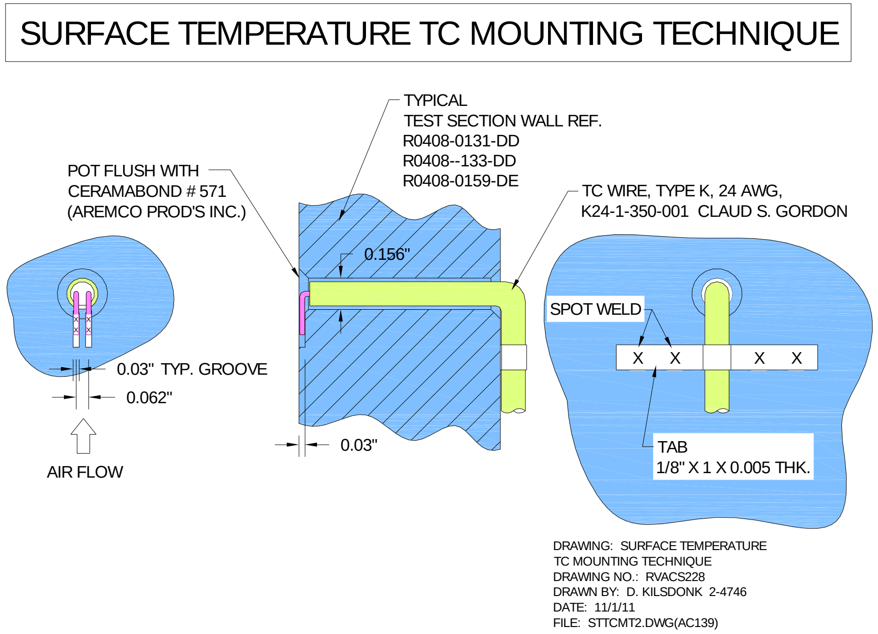


Facility Overview

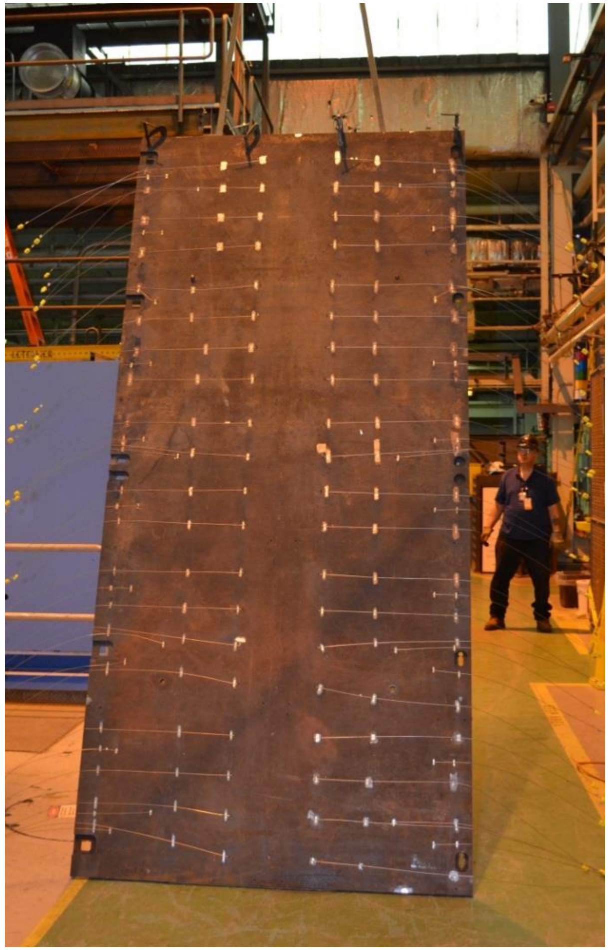


Accurate Boundary Conditions

- Two plates provide a physical representation of the RPV surface for heat transfer
  - Mill scale, surface ε between 0.7 and 0.9 (verified)
  - 2.5 cm thick, SAE 1020 low carbon steel



Heater plate TC mounting method

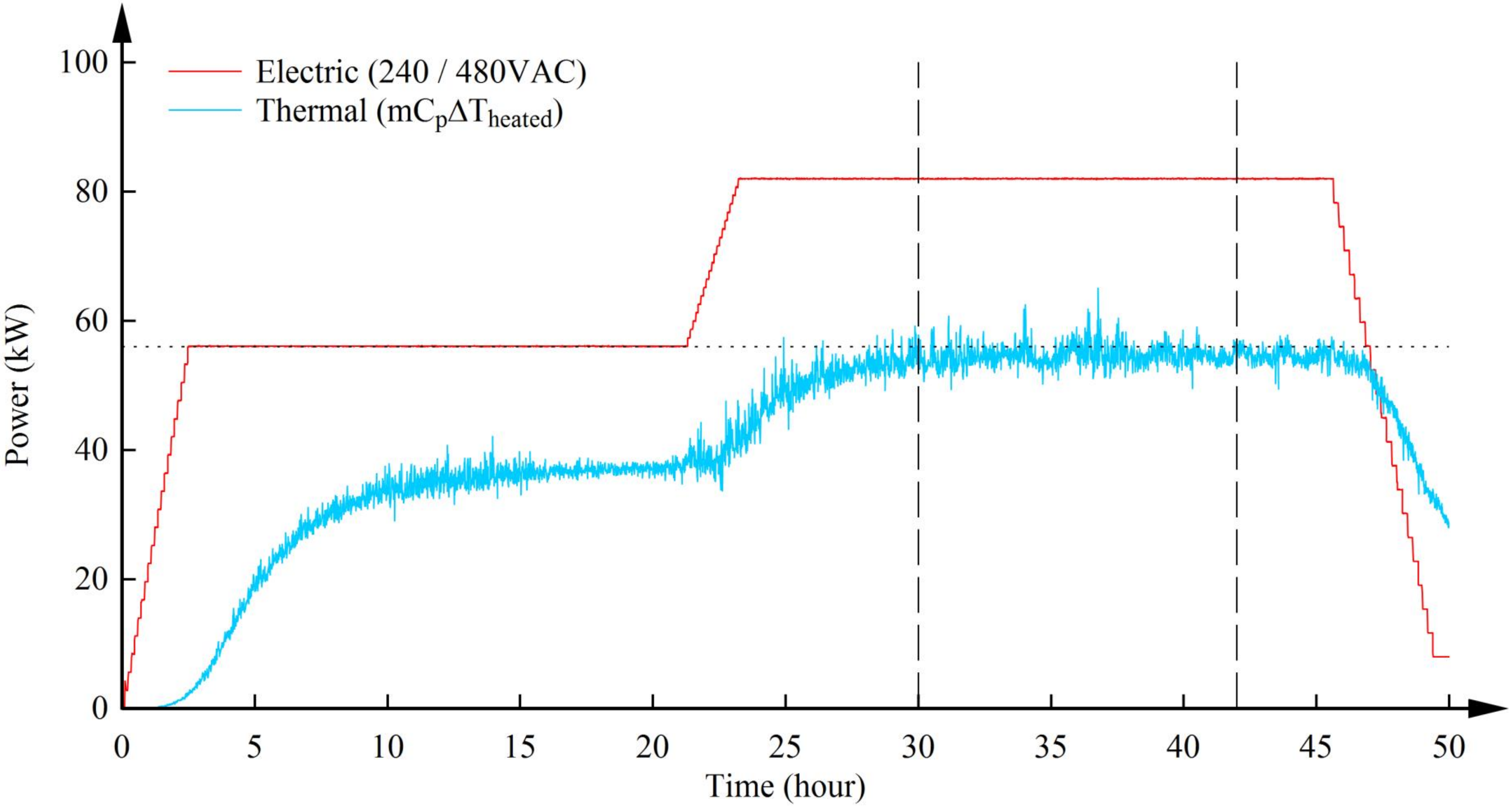


One half of RPV plate (long dimension is 3.4 m)

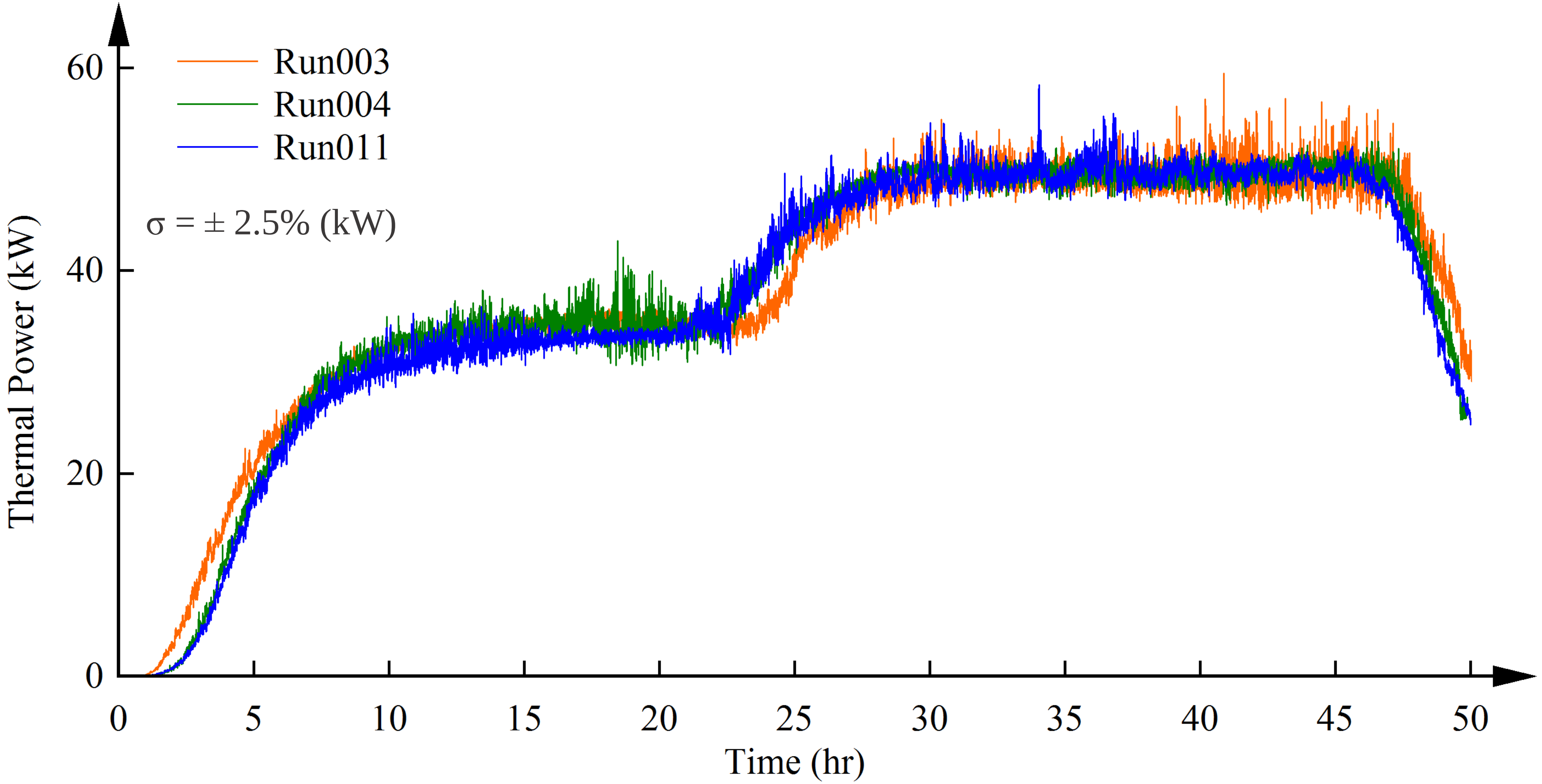
Test Matrix

- Shakedown/Calibration/Isothermal Characterization
- Baseline testing (QR = 1, ΔT = 1)
- Scaling verification
  - Integral power variation
  - Reduced physical scale
- Heated profile shaping
- GA-MHTGR accident scenario
  - Full time history of decay power profile
- Performance testing
  - Single chimney configuration
  - Forced flow operation
  - Blocked riser channels (incrementally block up to 6 out of 12 ducts)
  - Adjacent chimney roles (N. vertical stack inlet, S. vertical stack outlet)
- Repeatability / Weather
  - Repeat tests performed at baseline, GA-MHTGR accident scenario
  - Repeat tests performed in unfavorable or varied weather conditions
  - Regular repeats of baseline case

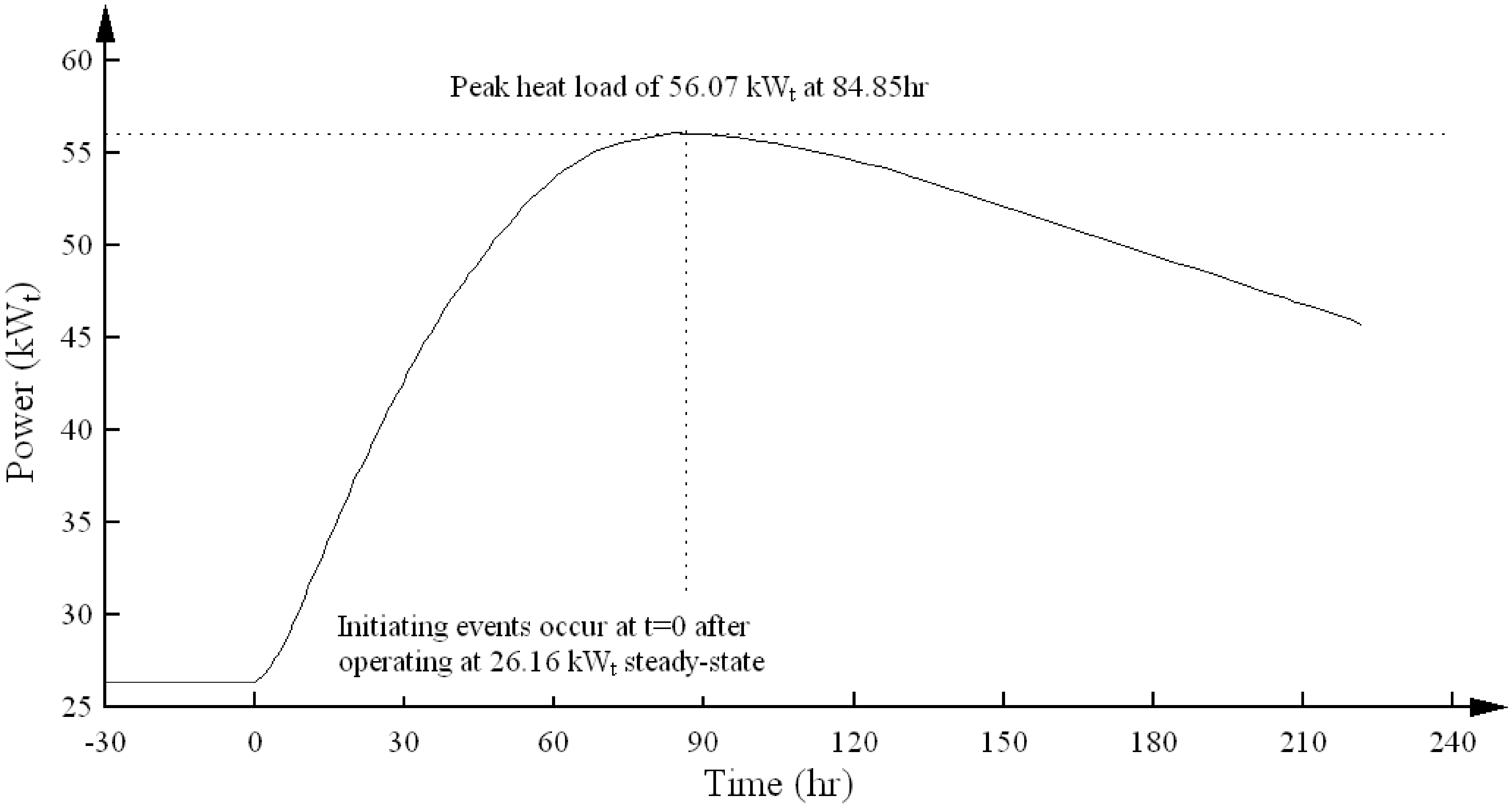
Baseline Testing Conditions



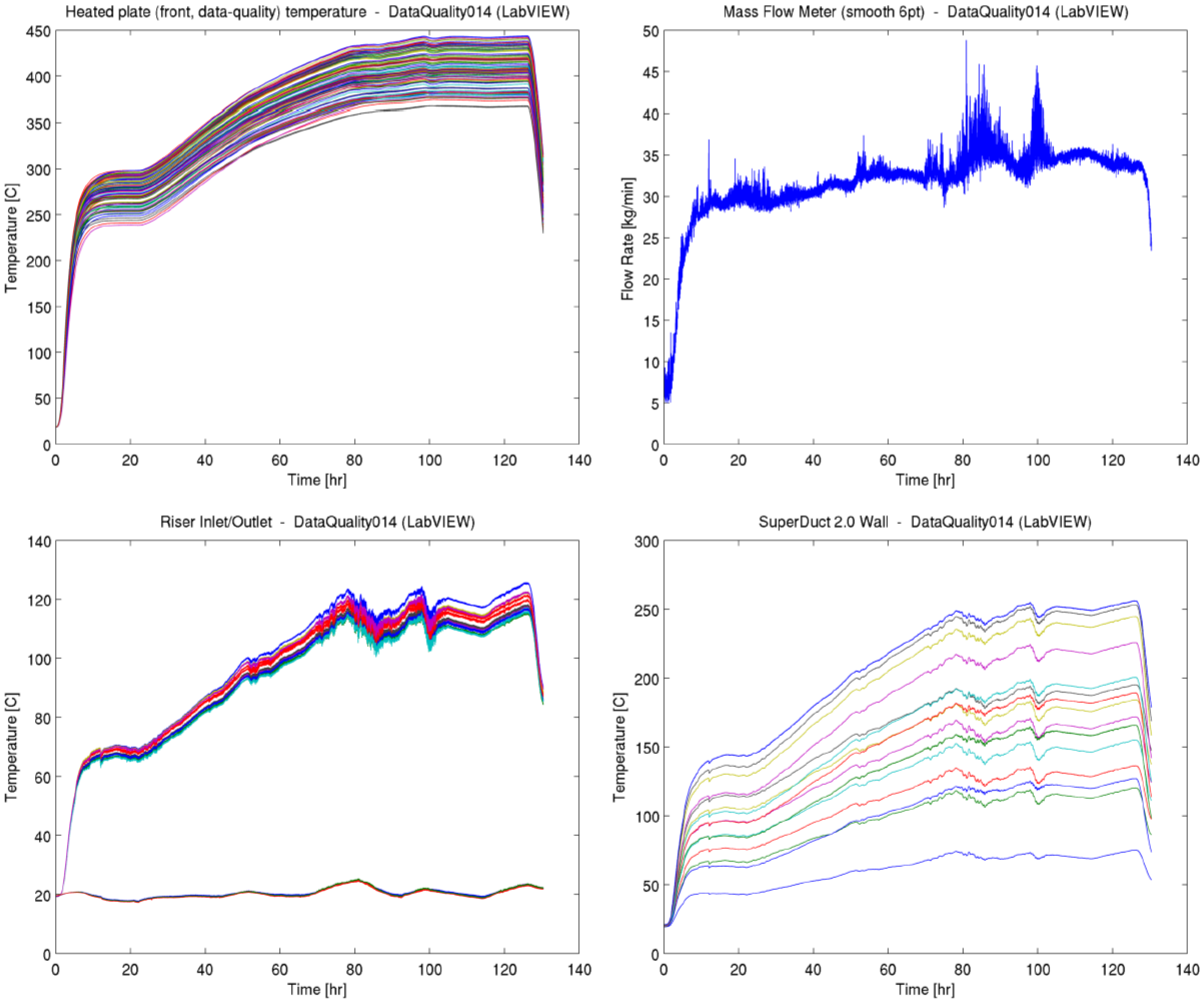
Repeatability



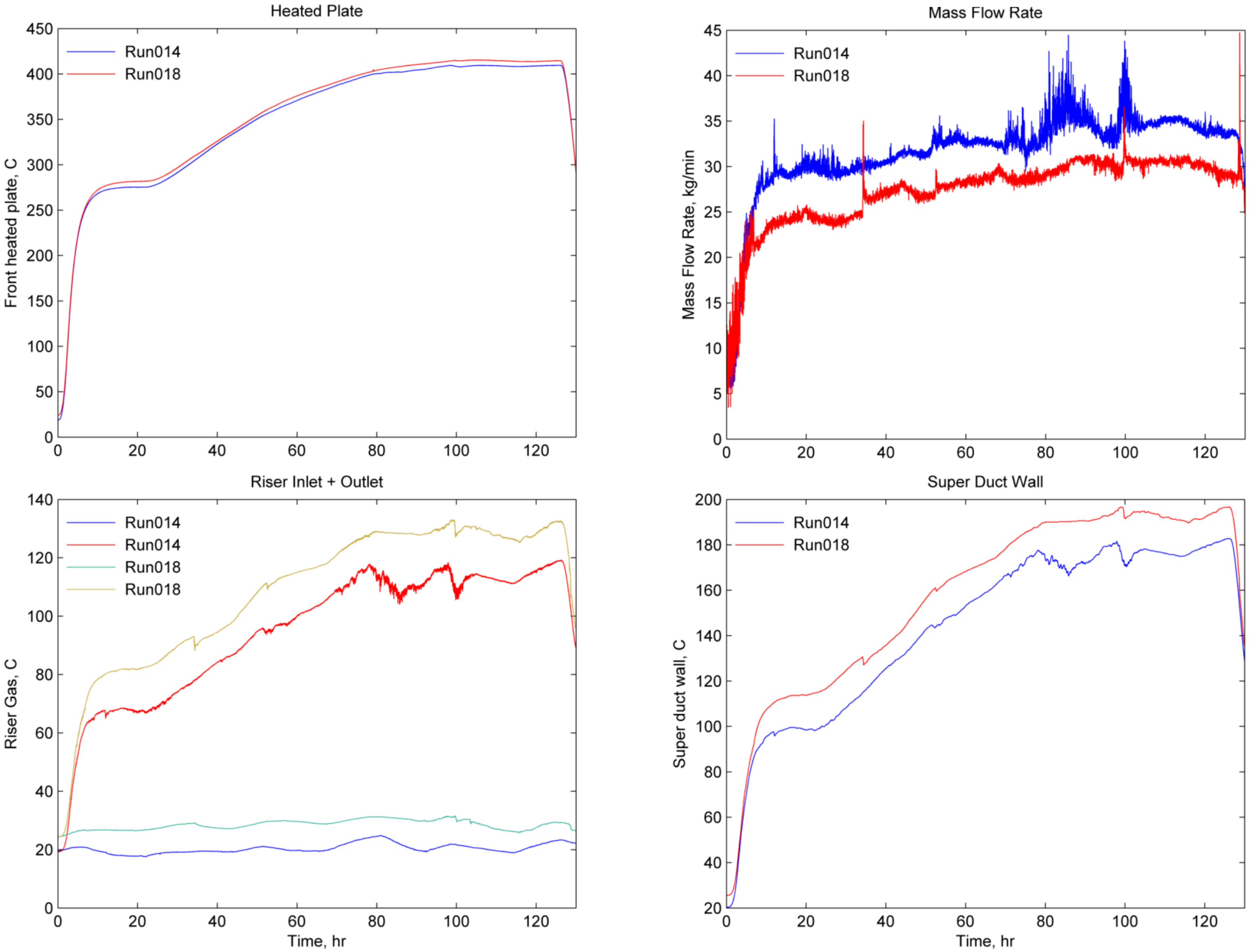
GA-MHTGR Accident Scenario



GA-MHTGR Accident Scenario



GA-MHTGR Weather Influences



Adjacent Chimney Configuration

- The prototypic full scale design places the entire reactor core below grade
- Thus, both inlet and outlet ductwork run adjacent along a majority of their length
- The NSTF was modified to best represent this configuration

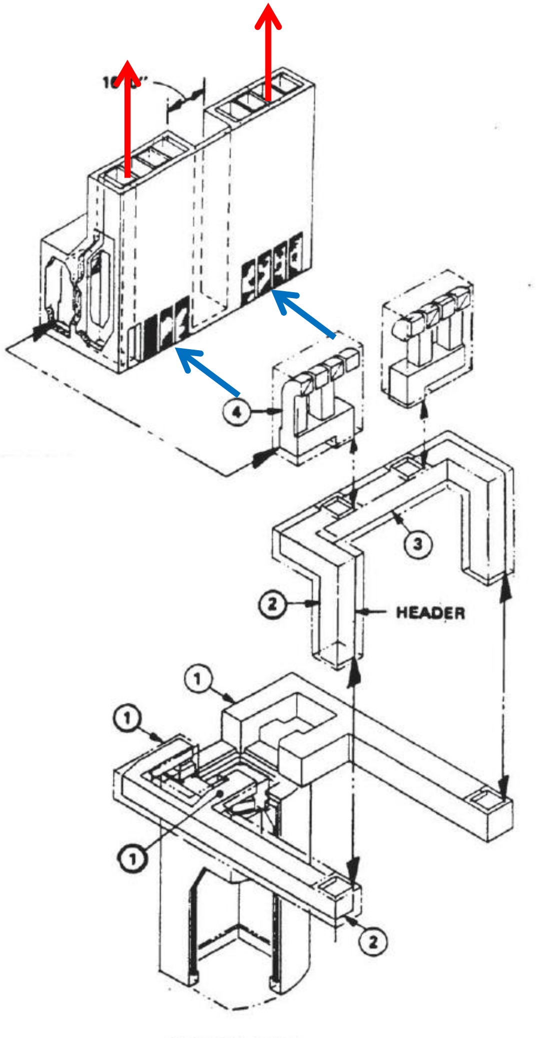
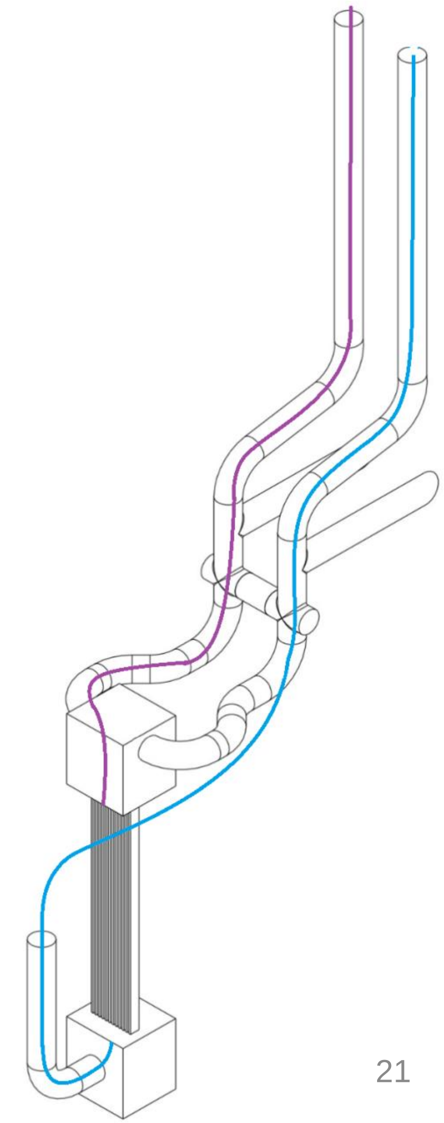
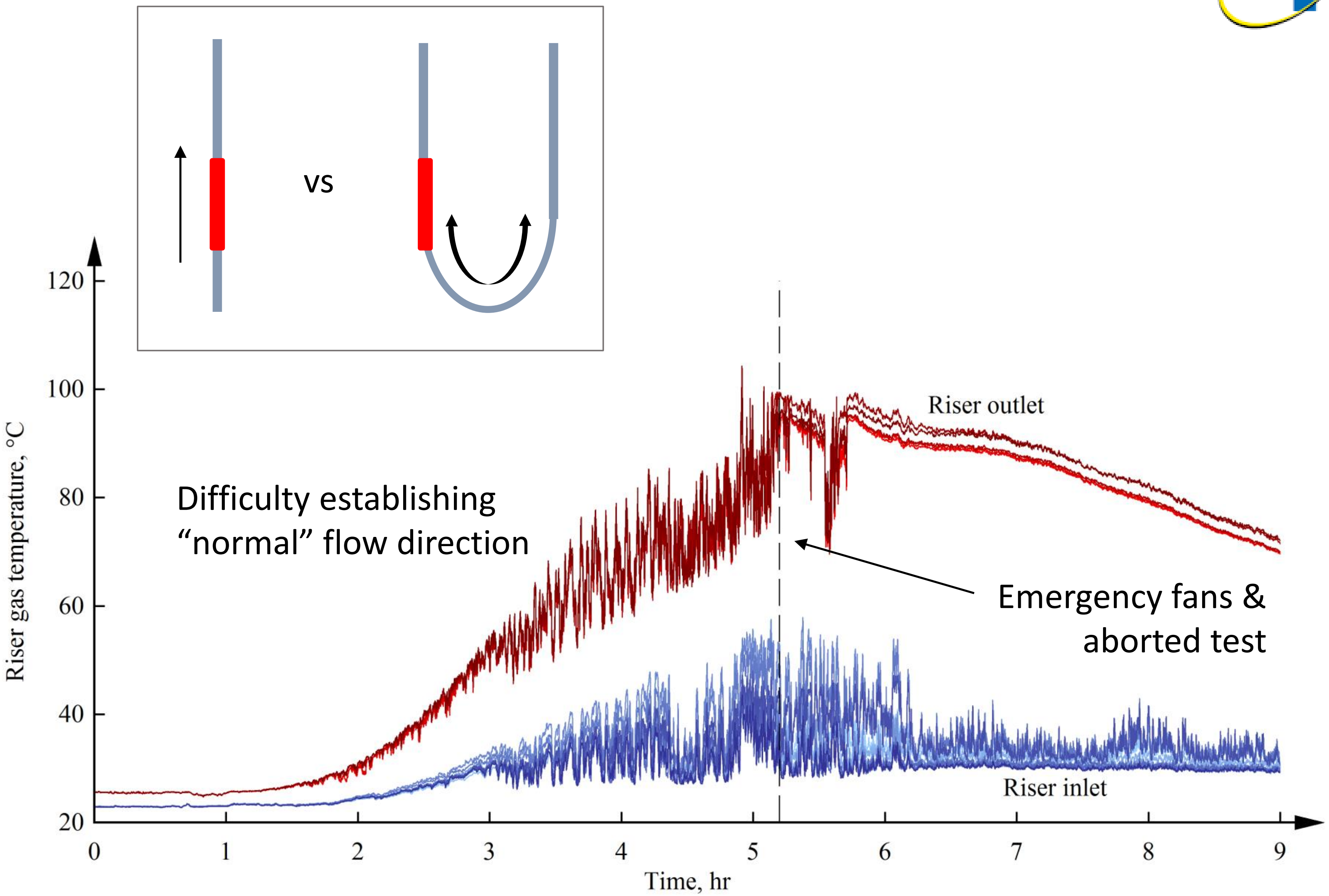


FIGURE 5.5-3
RCCS DUCTWORK
ISOMETRIC
HIGH TEMPERATURE GAS-COOLED REACTOR
PRELIMINARY SAFETY INFORMATION DOCUMENT
HTGR-86-024

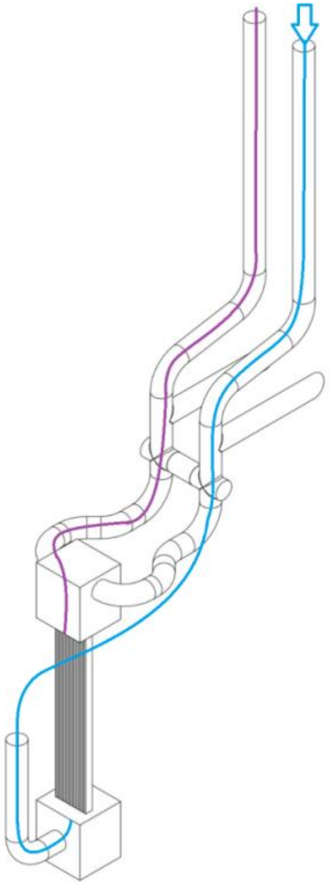


Adjacent Chimney Configuration



Difficulty establishing “normal” flow direction

Emergency fans & aborted test



Completion of Air Testing

- Air-based testing program officially concluded on July 5th 2016
  - Final modeling report documented in ANL-ART-46
  - Final project report documented in ANL-ART-47
  - Formal internal audit for all 18 elements of NQA-1 2008 June 29th 2016
- All program requirements were completed
  - High level program objectives drafted in 2005, prior to facility design and assembly
  - Experimental objectives drafted in 2013, prior to testing campaign
  - Items identified during early 2016 data review meeting, prior to testing conclusion
    - Attendees included the DOE, NRC, INL, AREVA, GA, and US Universities
- Program accomplishments
  - 33-month testing campaign duration
  - 2,250 active hours of heating
  - 27 conducted tests (16 accepted)
    - Multiple baseline repeats, GA-MHTGR accident scenario, blocked risers, power variations, azimuthal and cosine skew, adjacent chimney roles, meteorological variations, I-NERI test series
  - 24 publications since inception (numbered reports, journals, and conference)

Air-Testing Observations

- Ambient temperature
  - While heat removal performance remains largely unaffected, flow rates / absolute temperatures vary dramatically
- Meteorological perturbations
  - Systems exhibits sensitivity to such phenomena
  - Engineering controls (e.g. anti-draught cowls)
- Power Sensitivity & Low Power Start-up
  - At low powers, system may be unstable
  - Exhibits robust performance once flow is developed and system is operating at higher powers
- Blocked Riser Channels
  - Performance is relatively unaffected by blocked risers

Disassembly and Storage

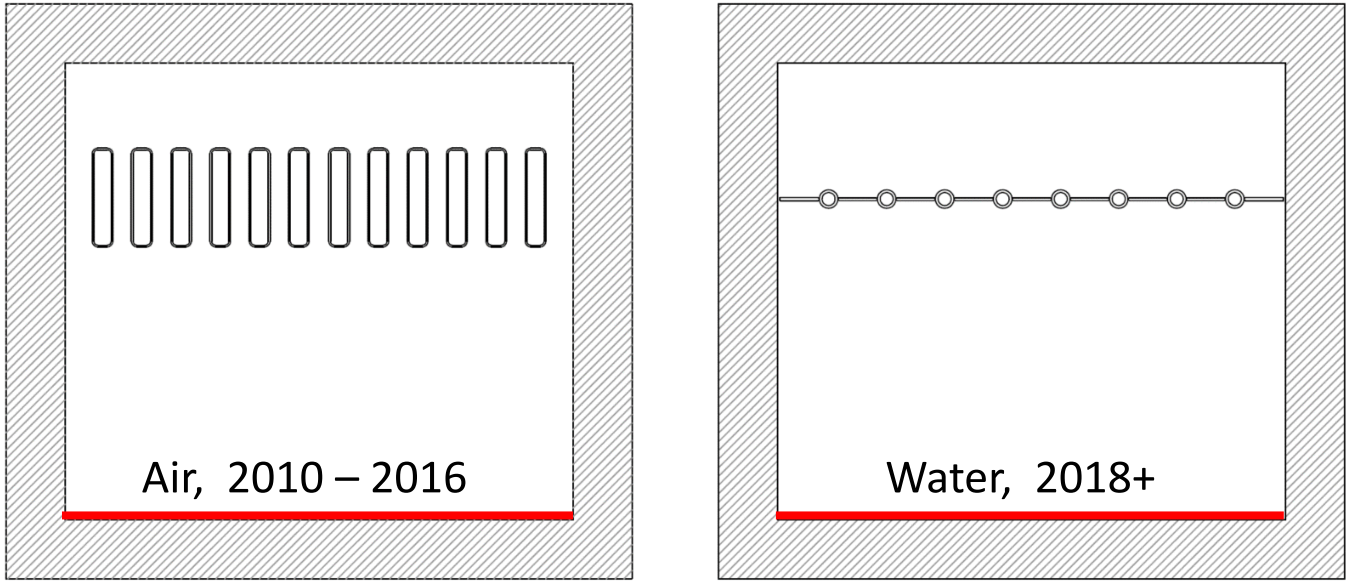
- Disassembly of the air facility commenced on July 5, 2016, after acceptance of final scheduled test
- Generated data backed up, stored within locked storage cabinets at two separate buildings
- Process was performed according to a written procedure and in an archival style manner

Metal label plate indicating installed position secured to front face

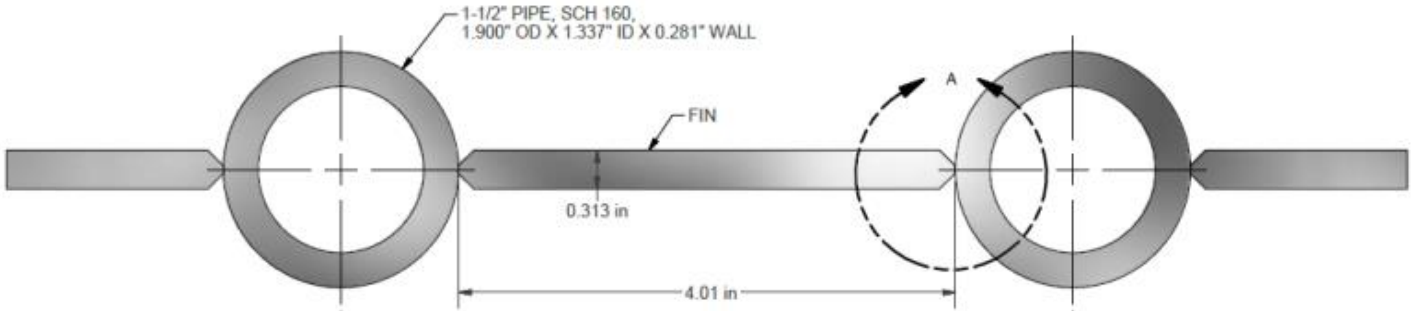
NSTF personnel hoisting riser duct #11 from heated cavity

Air to Water Conversion

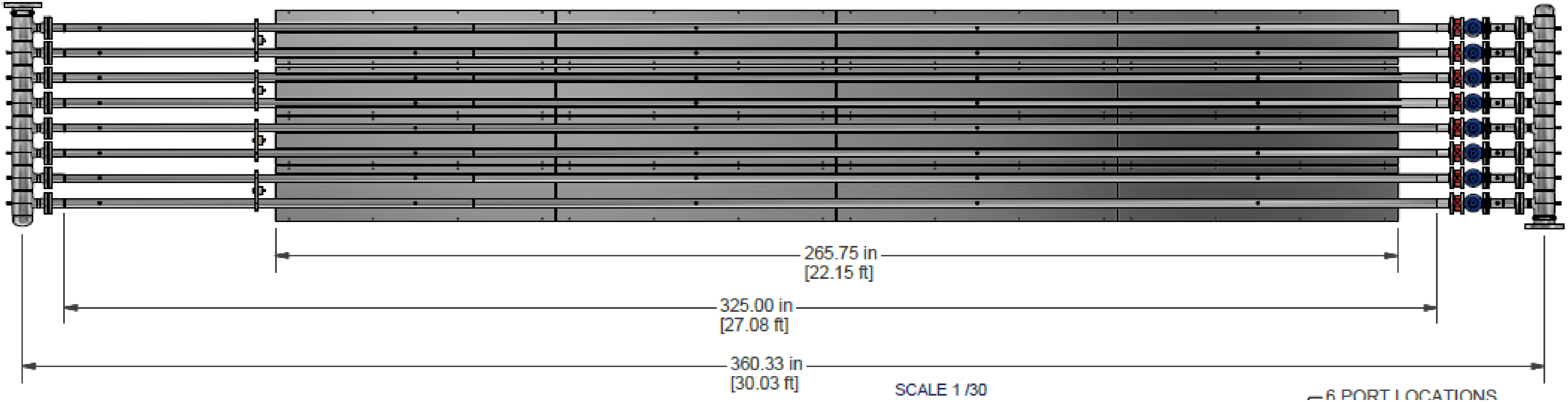
- With conclusion of air-based testing, program has shifted to a water-based operation of the existing test facility
- Water-cooled NSTF based on concept design for Framatome 625 MWt SC-HTGR (formally AREVA)
  - DOE sponsored HTGR Technology Economic/Business Analysis and Trade Studies Argonne performed scaling studies, geometric parameter simulations, thermal and stress calculations, tank depletion time estimates, steam quality/flow rate determinations, etc.



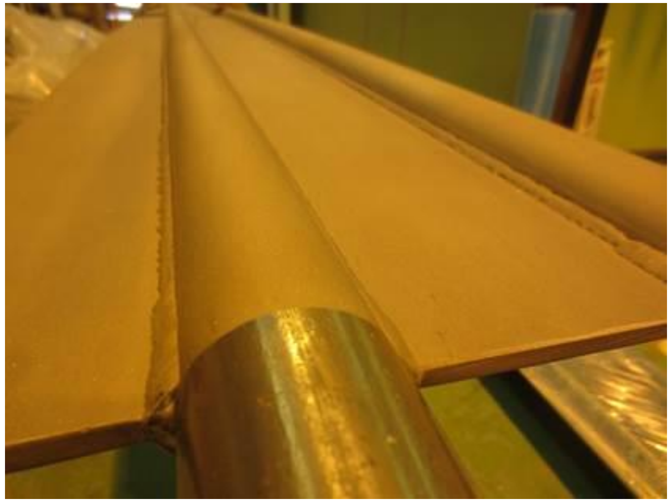
Water Test Section Design



	Material	k (W/m-K)	ε (-)
Fin	1018 carbon	51.9	> 0.8
Pipe	316L stainless	16.2	< 0.3



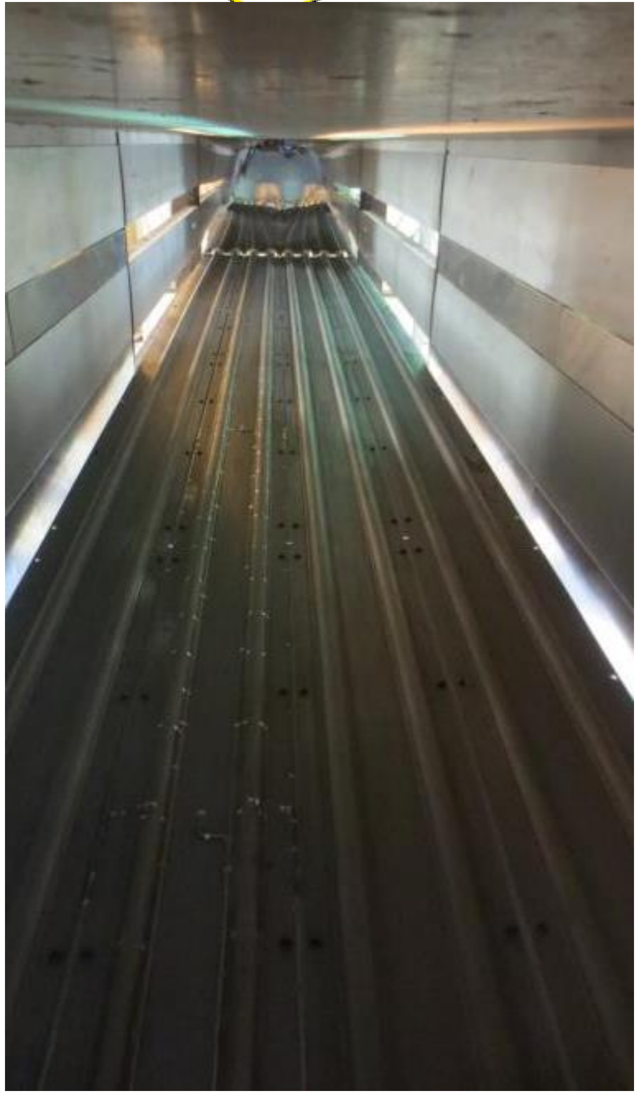
Water Cooling Panel Test Section



Bead blasted cooling panel surface

Assembled panel staged for 180° flip

Panel hoisted vertical prior to install



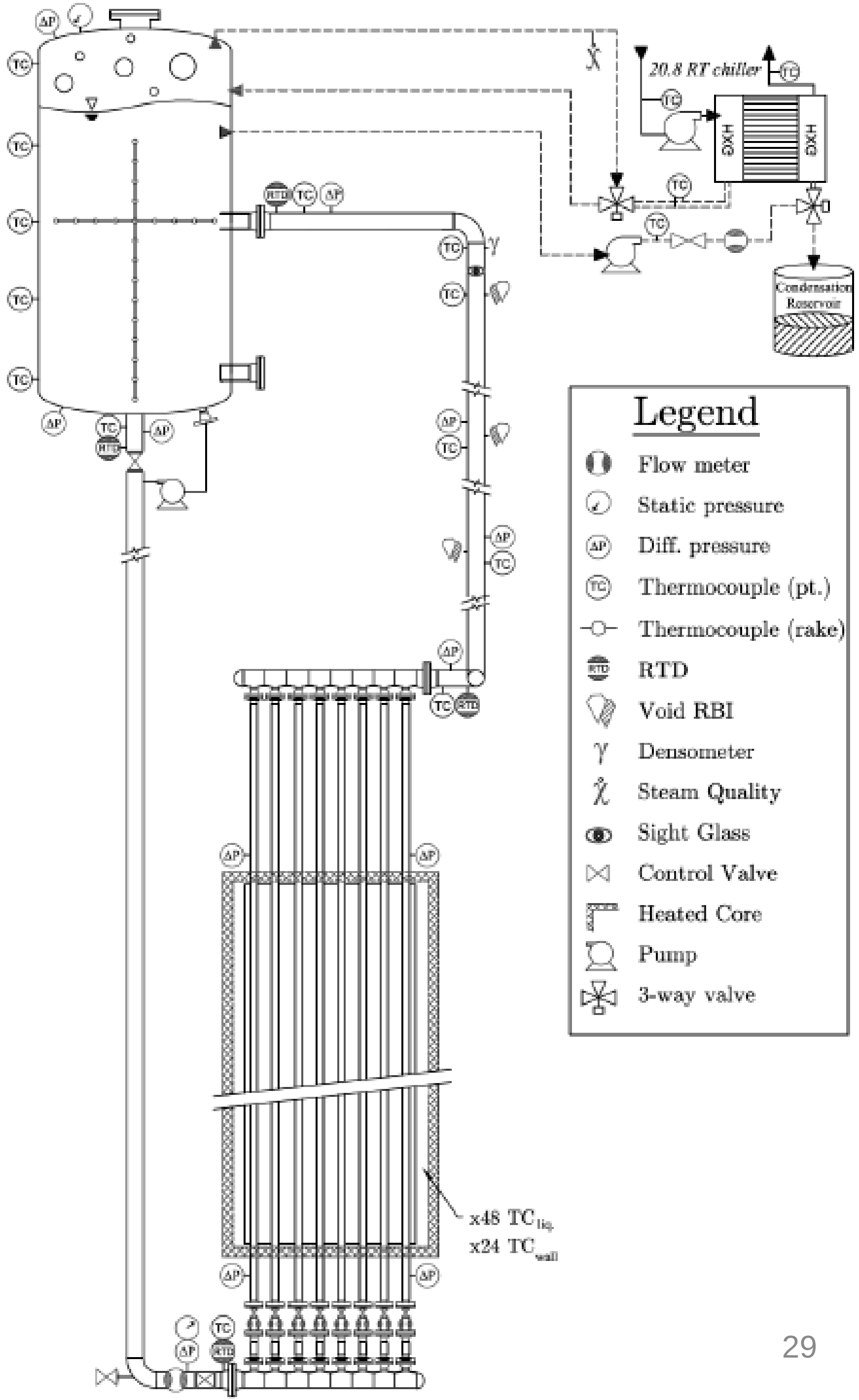
Installed test section, view in heated cavity

Water Instrumentation

Measurement	Sensor	Location	Qty.	Mfg.	Model	Range
Flowrate	Magnetic	Inlet header	x1	Krohne	Optiflux 4000	±5kg/s
Flowrate	Magnetic	Inlet riser	x8	Krohne	Optiflux 4000	±1kg/s
Static head	Strain	Inlet header	x1	Rosemount	3051S	0 - 10bar
Steam pressure	Strain	Gas space	x1	Rosemount	3051S	0 - 2bar$_{abs}$
ΔP	Strain	Chimney	x2	Rosemount	3051S	±6kPa
ΔP	Strain	Risers	x3	Rosemount	3051S	±62kPa
Liquid level	Strain	Tank	x1	Rosemount	3051S	0 - 3m
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	UP1/10DIN	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	Strain	x286	ARi	Silica20AWG	0 - 600°C
Temperature	DTS	Test section	x20	LUNA	ODiSI-A	0 - 300°C
Water pH	pH meter	Inlet header	x1	Emerson	RBI547	0 - 14pH
TrDO O_2	Amperometric	Inlet header	x1	Emerson	499A	0.1ppb-20ppm
Conductivity	Magnetic	Inlet header	x1	Krohne	Optiflux 4000	1 – 6000μS/cm

Electromagnetic flow meters

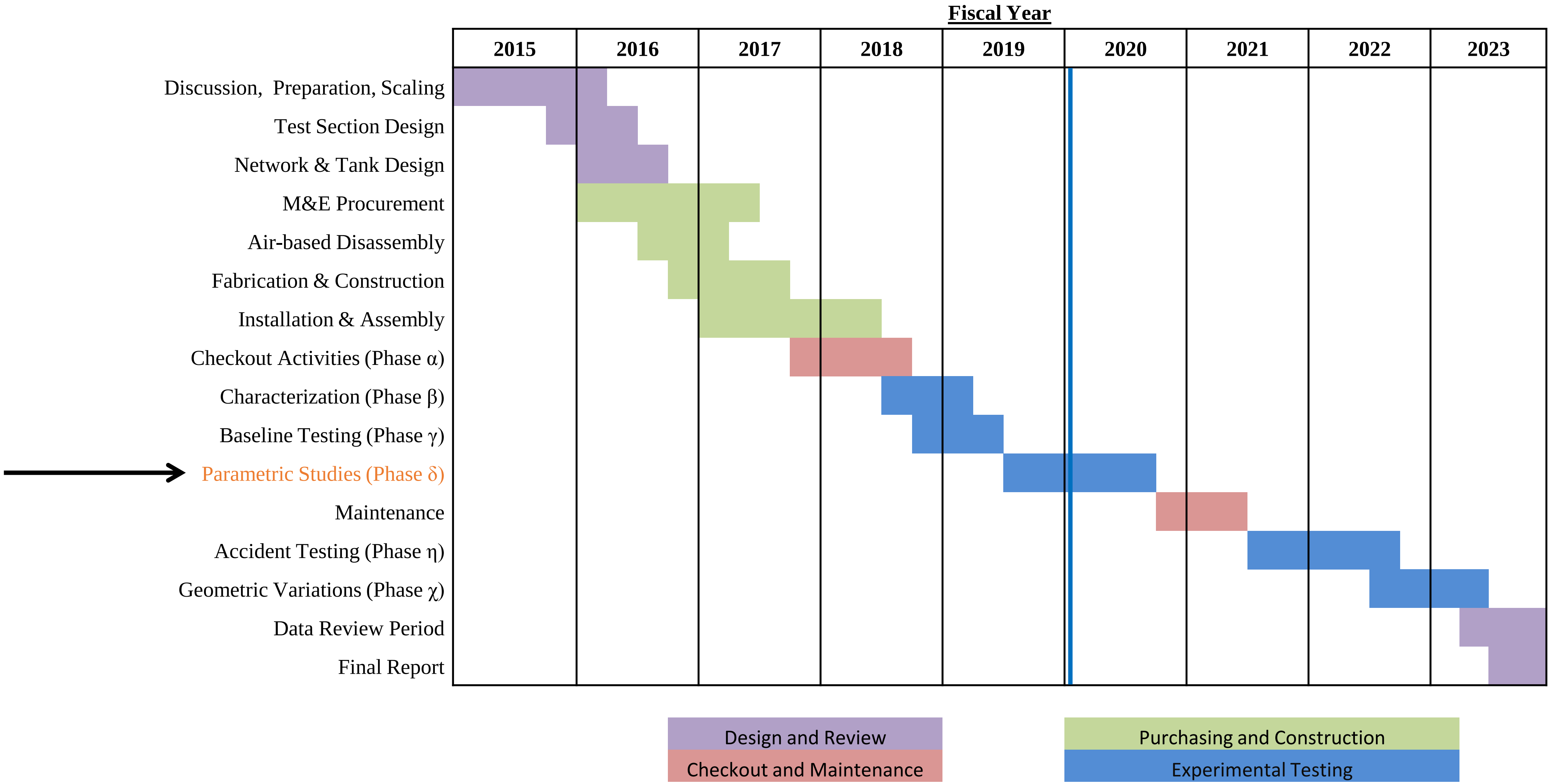
Gamma Densitometer



Water Accomplishments

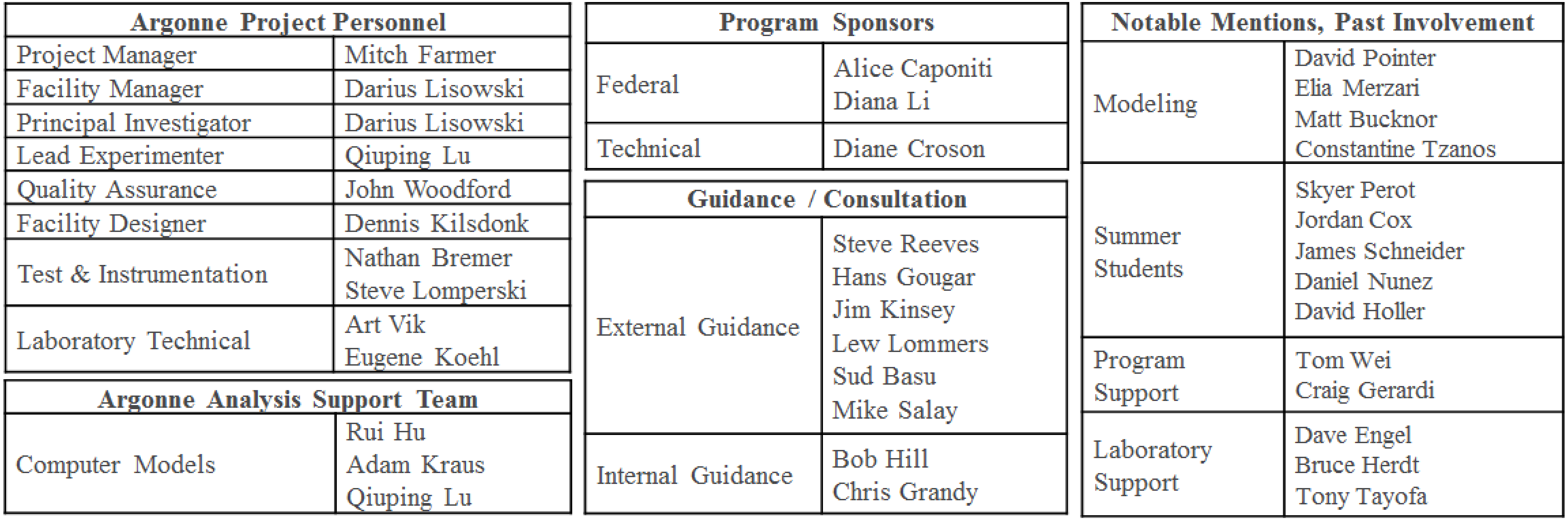
- May 2018 – Completed installation of test facility
  - Primary components: test section, water storage tank, and network piping
  - All sensors, hardware, control valves, etc.
- July 2018 – Shakedown and instrument verification
  - Signed verification sheets
- November 2018 – Single-phase demonstration test
  - Install and verify network piping sensors
  - Initial fill of test loop and system leak-test
- January 2019 – First accepted matrix test at single-phase conditions
  - Baseline ‘normal operation’; steady-state with 30°C inlet temperature
- August 2019 – Completion of single-phase parametric series

Water NSTF Timeline



Acknowledgements

This work was supported by the U.S. Department of Energy Office of Nuclear Energy, Office of Advanced Reactor Concepts under contract number DE-AC02-06CH11357



Argonne Project Personnel	
Project Manager	Mitch Farmer
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Principal Investigator	Darius Lisowski
Lead Experimenter	Qiuping Lu
Quality Assurance	John Woodford
Facility Designer	Dennis Kilsdonk
Test & Instrumentation	Nathan Bremer Steve Lomperski
Laboratory Technical	Art Vik Eugene Koehl

Argonne Analysis Support Team	
Computer Models	Rui Hu Adam Kraus Qiuping Lu

Program Sponsors	
Federal	Alice Caponiti Diana Li
Technical	Diane Croson

Guidance / Consultation	
External Guidance	Steve Reeves Hans Gougar Jim Kinsey Lew Lommers Sud Basu Mike Salay
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
Laboratory Support	Dave Engel Bruce Herdt Tony Tayofa

Upcoming Webinars

13 November 2019	Czech Experimental Program on MSR Technology Development	Dr. Jan Uhlir, Research Center Řež, Czech Republic
18 December 2019	TRISO Fuels	Dr. Madeline Feltus, DOE, USA
29 January 2020	Thermal Hydraulics in Liquid Metal Fast Reactors	Dr. Antoine Gerschenfeld, CEA, France