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Presentations for July 26, 2018 Public Meeting
Regulatory Improvements for Advanced Reactors

In order of discussion, the meeting included the following topics and presentations

1) NRC Slides
    - Opening / Outline
    - Update on NRC Activities
    - Licensing Modernization (see #2 for industry slides)
    - Future Stakeholder Meetings

2) Licensing Modernization

3) Molten Salt Reactor Technology Working Group (FLIBE)

4) INL/Framatome/ANL Natural Convection Shutdown Heat Removal

Advanced Reactor Program

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Public Meeting on Possible Regulatory Process Improvements for Advanced Reactor Designs

July 26, 2018

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Telephone Bridge
(888) 793-9929
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Public Meeting

- Telephone Bridge

  (888) 793-9929

  Passcode: 7231346
- Opportunities for public comments and questions at designated times

Outline

- Introductions
- Update on NRC Activities
- Licensing Modernization Project
- Technology Working Groups - MSR

- Prioritization Considering O&M
- Natural Convection Shutdown Heat Removal
- Policy Issues, Future Meetings, Public Discussion

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Implementation Action Plans

Strategy 1 Knowledge, Skills and Capability
- ONRL Molten Salt Reactor Training
- Knowledge Management
- Competency Modeling

Strategy 2 Computer Codes & Review Tools
- Identification & Assessment of Available Codes

Strategy 3 Flexible Review Processes
- Regulatory Roadmap ✓
- Prototype Guidance ✓
- Non-LWR Design Criteria ✓
- Environmental Reviews
- Licensing Modernization Project

Strategy 4 Consensus Codes and Standards
- ASME BPVC Section III Division 5
- ANS Standards 20.1, 20.2 30.2, 54.1
- Non-LWR PRA Standard

Strategy 5 Policy and Key Technical Issues
- Siting near densely populated areas
- Insurance and Liability
- Consequence Based Security
- EP for SMRs and ONTs
- Functional Containment

Strategy 6 Communication
- NRC DOE Workshops ✓
- Periodic Stakeholder Meetings
- NRC DOE GAIN MOU
- International Coordination

- Potential First Movers
- Micro-Reactors

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Strategy 2 – RES Contracts

- Reactor Kinetics and Criticality
- Fuel Performance
- Thermal Hydraulics
- Severe Accident Phenomena
- Offsite Consequences
- Materials Research

NRO Contracts

- NRC Staff Technology Training
- Fuel Qualification
  - TRISO (limited scope topical)
  - Metallic (legacy data)
  - MSRs
- Policy Resolution, Guidance Development
- Environmental Reviews
- RTR Guidance (MSR)
- ASME Section III Division 5

- Licensing Micro Reactors

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NRO Contracts - Continued

- Fuel Cycle
  - Fuel facilities
  - High level waste
- Security
- MC&A

- Technology specific barrier/consequence estimates

$$ST = MAR \cdot DR \cdot ARF \cdot RF \cdot LPF \qquad (1)$$

where ST is the source term (Bq), MAR is the total available material-at-risk (Bq), DR is the damage ratio (no units), ARF is the airborne release fraction (no units), RF is the respirable fraction (no units), and LPF is the leak path factor (no units).

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Break

Meeting/Webinar will begin shortly

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Licensing Modernization

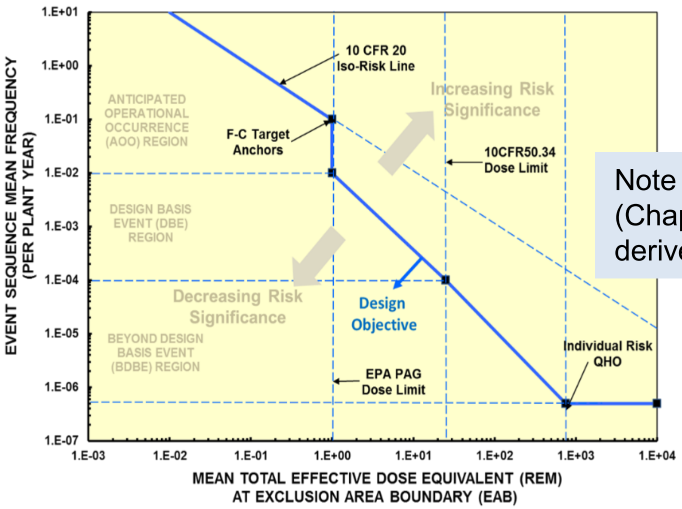
- Southern Company Presentation

Licensing Modernization

- ❑ Public Meeting – August 21, 2018
  - ❑ Revision to LMP Guidance (NEI 18-04)
    - Resolution of Questions/Comments
  - ❑ DG 1353
    - Endorsing LMP Guidance
    - Informing Content of Applications

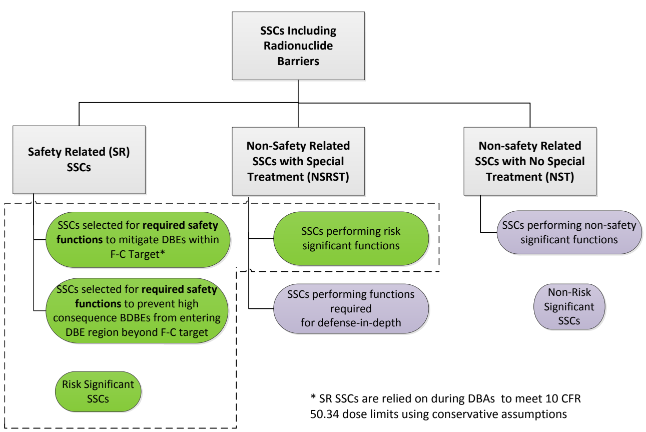
- ❑ September 30, 2018 – Draft Material to ACRS
  - October 30, 2018: ACRS Subcommittee
  - December 6-8, 2018: ACRS Full Committee
  - December 21, 2018: Issue DG 1353
  - Early 2019: Commission paper

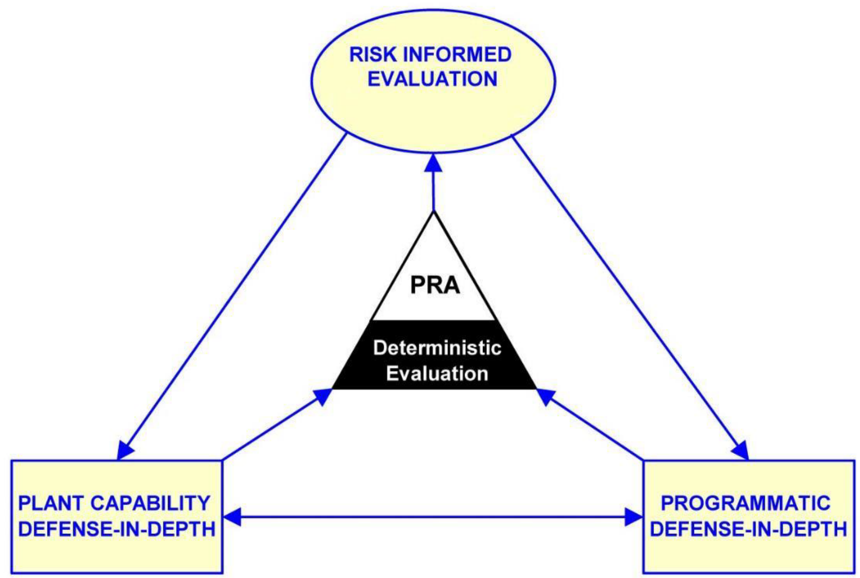
Licensing Modernization



Note that DBAs (Chapter 15) derived from DBEs

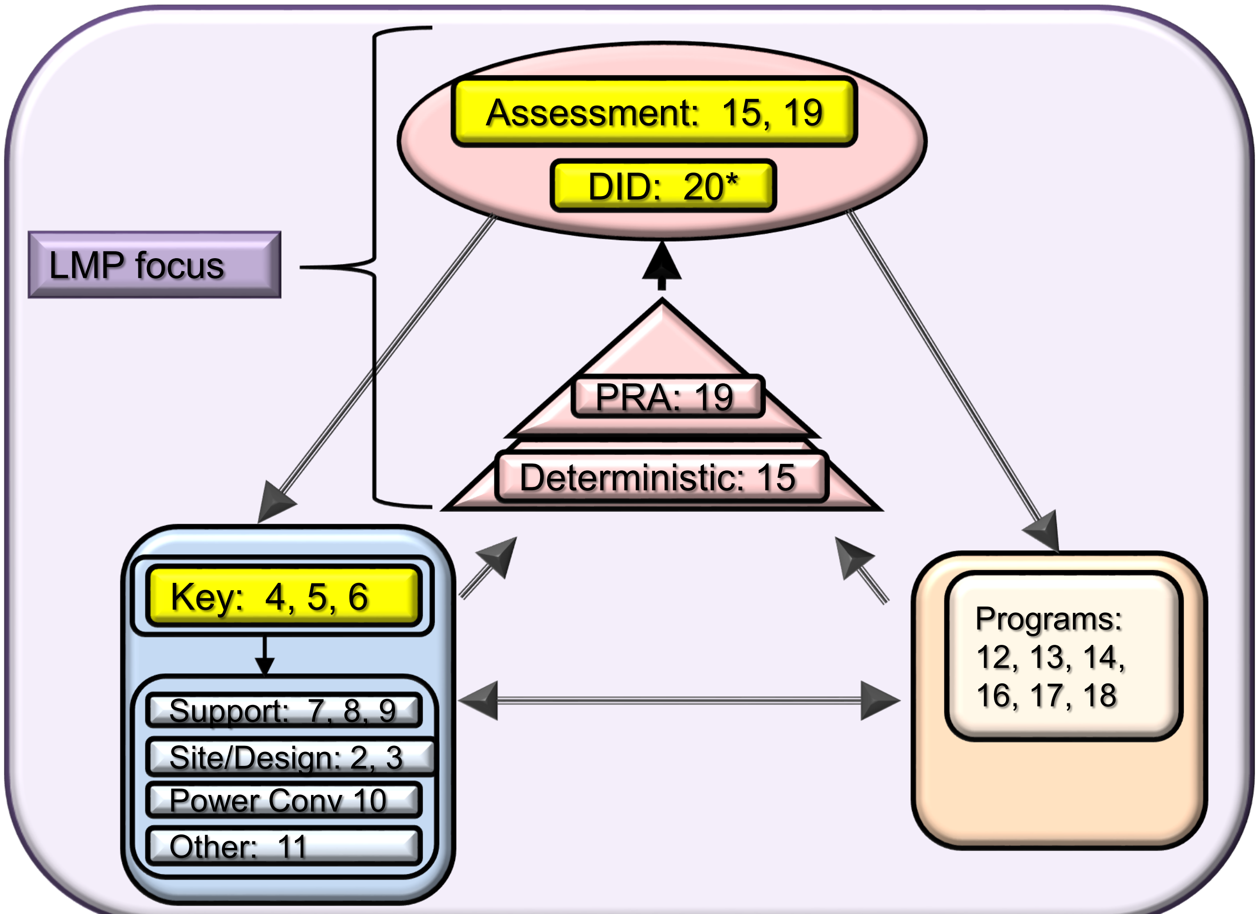
- Licensing Basis Events
- SSC Classification
- Defense in Depth





DG-1353 / SECY Paper

Informing Scope and Level of Detail in Applications



Related Commission Paper

- LBE categories – AOO, DBE, BDBE and DBAs
- F/C Target Figure – with demarcations between event categories, cutoff
- Aggregate safety goals
- SSC Classification scheme
- Defense in Depth assessments
- Scope and Depth of Applications
  - Focus on Fundamental Safety Functions
  - Potential radiological consequences
    - Mechanistic source term
  - Risk-Informed approach for key systems and support systems
  - Performance-based approach

Technology Working Groups

- Molten Salt Reactors
  - FLIBE Presentation

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Lunch

Meeting/Webinar will begin at 1:00pm

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Prioritization – O&M

- NEI Discussion

Break

Meeting/Webinar will begin shortly

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Natural Convection Shutdown Cooling

- INL
- ANL
- Framatome

Future Stakeholder Meetings Topics ?

Sept 13	TWG – Fast Reactors, Metallic Fuel
	Prioritization of Issues Considering Capital Costs
	Seismic Isolators
	Licensing Modernization/DG 1353
Oct 25	TWG - HTGRs
	Licensing Modernization/DG 1353
Dec 13	

ACRS Schedule (tentative)

Date	Committee	Topic
June 19	*Sub*	*RIPB Guidance*
Aug 22	Sub	EP Rulemaking
Oct	Full	EP Rulemaking
Oct 30	Sub	RIPB Guidance
Dec 6	Full	RIPB Guidance
2019		??

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Public Comments / Questions

Advanced Reactor Program

Southern Nuclear

Licensing Modernization Project (LMP) Guidance Document Update

Jason Redd, PE

July 26, 2018

LMP Guidance Document Introduction

- The LMP Guidance Document represents a framework for the efficient licensing of advanced non-light water reactors (non-LWRs).

- It is the result of the LMP led by Southern Company and cost-shared by the U.S. Department of Energy (DOE).

- The LMP prepared this document for establishing licensing technical requirements to facilitate risk-informed and performance-based (RIPB) design and licensing of advanced non-LWRs.

- Such a framework acknowledges enhancements in safety achievable with advanced designs and reflects current states of knowledge regarding safety and design innovation, creating an opportunity for reduced regulatory complexity with increased levels of safety.

LMP Guidance Document Recent Activities

- April – First table top demonstration of the LMP RIPB processes on a current advanced non-LWR design completed. Lessons learned and best practices identified during this demonstration were incorporated into the LMP Guidance Document.

- June 5-6 – NRC Public Workshop discussing LMP Guidance Document (Working Draft M). [ML18150A344 – LMP Guidance Document][ML18177A462 – meeting summary]

- June 18 – LMP members delivered a training opportunity on the LMP RIPB process for NRC Staff at the White Flint offices.
  - The Staff posed many excellent questions during this training opportunity and provided constructive feedback which is being addressed in ongoing updates to the LMP Guidance Document.

LMP Guidance Document Recent Activities

- June 19 – The LMP Guidance Document (Working Draft M) was reviewed and discussed by the Advisory Committee on Reactor Safeguards (ACRS) Future Plants Subcommittee.
  - As with the Staff, the ACRS FPS engaged in a robust discussion of the LMP Guidance Document and provided feedback to both the LMP team and the NRO Staff. Likewise, this feedback is being addressed in ongoing updates to the LMP Guidance Document.

LMP Guidance Document Upcoming Meetings and Milestones

- August 21 – NRC Public Workshop on LMP Guidance Document. Agenda focused on resolution of June NRC and ACRS comments.

- September 13 – NRC advanced reactors stakeholder meeting. LMP team to provide update on LMP progress to date.

- October 30 – ACRS Future Plants Subcommittee meeting to review and discuss the working draft of the LMP Guidance Document, draft NRC SECY, and draft NRC Regulatory Guide addressing the LMP Guidance Document.

- December 6-8 – Full ACRS meeting to review and discuss the working draft of the LMP Guidance Document, draft NRC SECY, and draft NRC Regulatory Guide addressing the LMP Guidance Document.

LMP Guidance Document Upcoming Opportunities for Industry and Public Participation

- August 21 – NRC Public Workshop on LMP Guidance Document. Agenda focused on resolutions of June NRC and ACRS comments.
  - Proposed comment resolutions will be shared with NEI ARRTF in advance; a full revision of the LMP Guidance Document will not be performed for this workshop.

- September 9 – Updated LMP Guidance Document working draft incorporating NRC and ACRS FPS feedback distributed to NEI ARRTF for two week review and comment cycle supporting September 28 submittal of updated document to ACRS FPS Chair for review.

- TBD – By 2Q19 we expect between four and six designs to have exercised the LMP RIPB processes on their designs to obtain potential insights. The LMP team is interested in demonstrating the LMP RIPB processes with additional vendors.

- Anytime – The LMP team always welcomes questions, comments, and feedback. Please contact me at jpredd@southernco.com or 205-992-6435.

Questions?

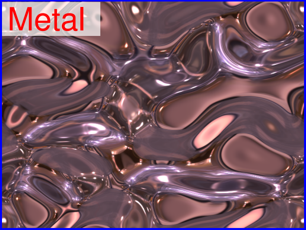
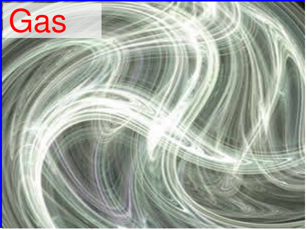
Southern Nuclear

Molten-Salt Reactor Technology

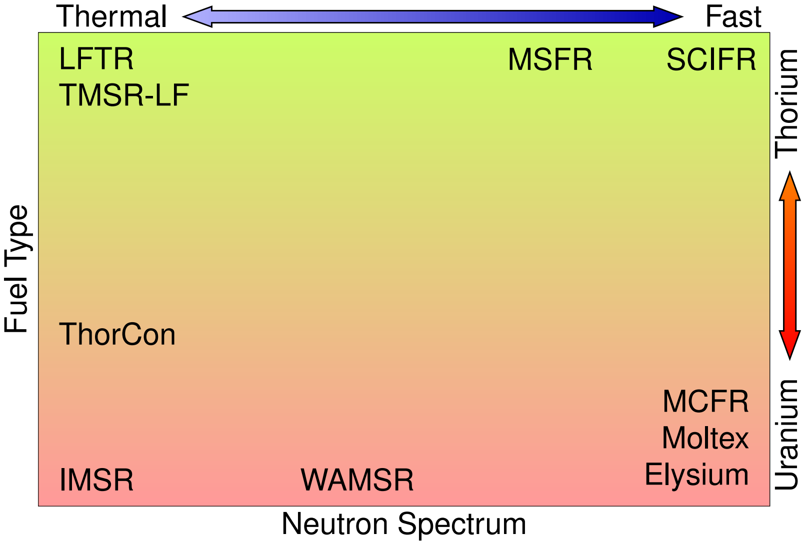
Matthew Lish
Flibe Energy

Nuclear Regulatory Commission
July 26, 2018

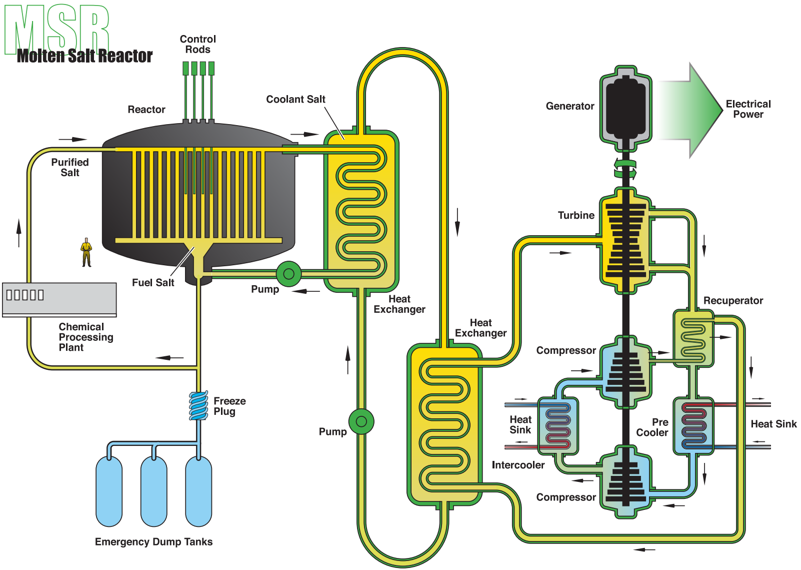
Coolant Choices for a Nuclear Reactor

	atmospheric pressure operation	high-pressure operation
moderate temperature (250-450°C)	Metal 	Water 
high temperature (650-900°C)	Salt 	Gas 

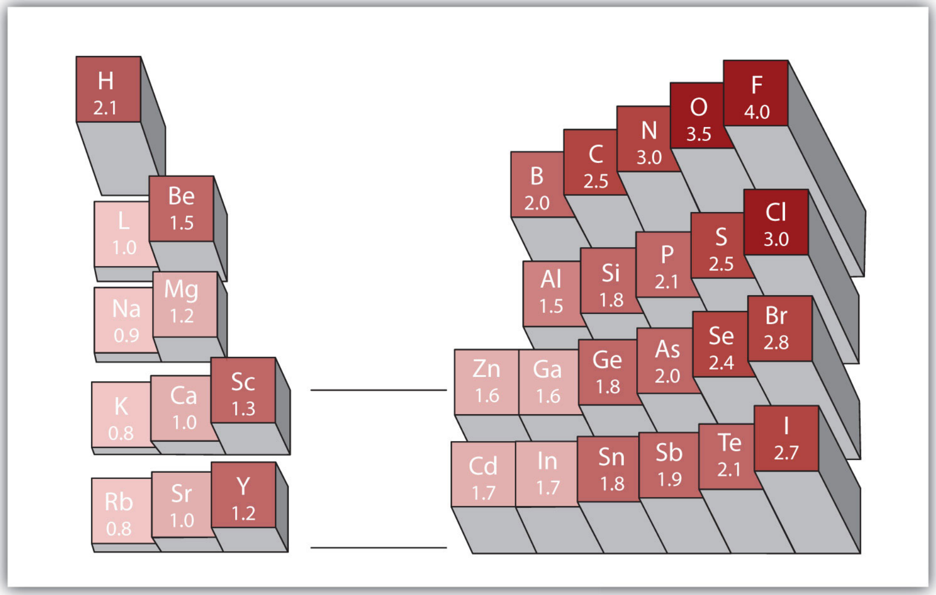
Molten Salt Reactor Design Space



Gen-4 Molten Salt Reactor Concept

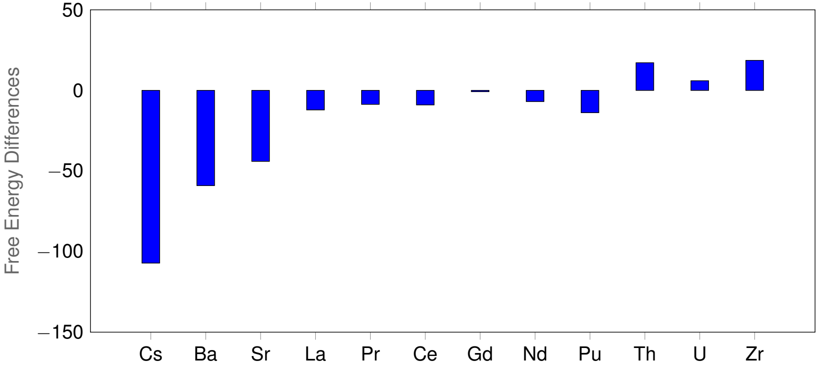


The MSRE successfully operated for over 20,000 hours, from 1965-1969.



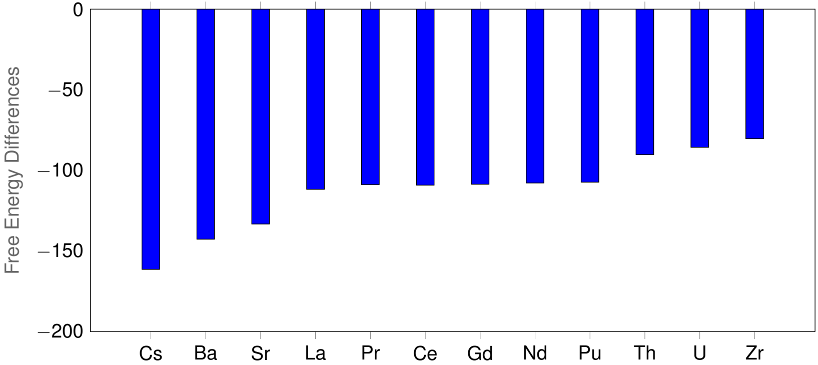
Oxygen is very electronegative and forms strong bonds with metals, however fluorine, and only fluorine, is even more electronegative.

Free energy differences (oxides/chlorides) at 1000 K



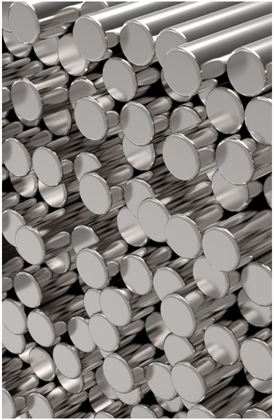
Alkaline fission products are stable in chloride salt, and will not volatilize if introduced to air. Actinides may form oxides in air, but will not volatilize.

Free energy differences (oxides/fluorides) at 1000 K



In fluoride form all actinides and alkaline fission products, most notably cesium and strontium, remain in fluoride salt form in the presence of air, do not form volatile species. **In molten salts, the first barrier to fission product release is the chemical form of the fuel salt, rather than the mechanical integrity of the fuel pin.**

MSR Material Compatibility



Through proper material choices, molten-salt reactors can operate in a state of fundamental chemical equilibrium. This was demonstrated by the MSRE with FLiBe salt, graphite, and Hastelloy-N alloy. This is very different than the environment inside PWRs.

Conclusions

- MSRs feature circulating fuel dissolved in stable form in the coolant.
- Molten salts chemically bind most fission products, but do not retain noble gas fission products at all, thus the standard operating approach for noble gases should bound potential accidents.
- Properly chosen materials operate in chemical equilibrium with the coolant without stored energy terms or driving forces for radionuclide release.
- Off-gas treatment and sequestration is of paramount importance.

Regulatory Framework Development

Passive Heat Removal

Jim Kinsey
Idaho National Laboratory

July 26, 2018

www.inl.gov

Idaho National Laboratory

Background

Fundamental Safety Functions

- Reactivity Control
- Heat Removal
- Radionuclide Retention

- Reactor technologies and associated designs address a set of fundamental safety functions
- The LWR-based operating fleet generally relies on a group of interrelated active systems for the heat removal function, as reflected in the GDCs:
  - Residual heat removal
  - Emergency core cooling
  - Containment heat removal
  - Cooling water systems

NRC Advanced Reactor Policy *(2008 - Excerpts)*

Commission policy encourages:

- Use of inherent or passive means of reactor shutdown and heat removal
- Longer time constants
- Simplified safety systems which reduce required operator actions
- Minimizing the potential for severe accidents and their consequences
- Safety-system independence from balance of plant
- Incorporation of defense-in-depth philosophy by maintaining multiple barriers against radiation release and by reducing the potential for consequences of severe accidents
- Using existing technology or technology that can be satisfactorily established by commitment to a suitable technology development program

Regulatory Framework - Areas of Focus

The "Regulatory Framework" consists of four key parts that are the areas of focus:

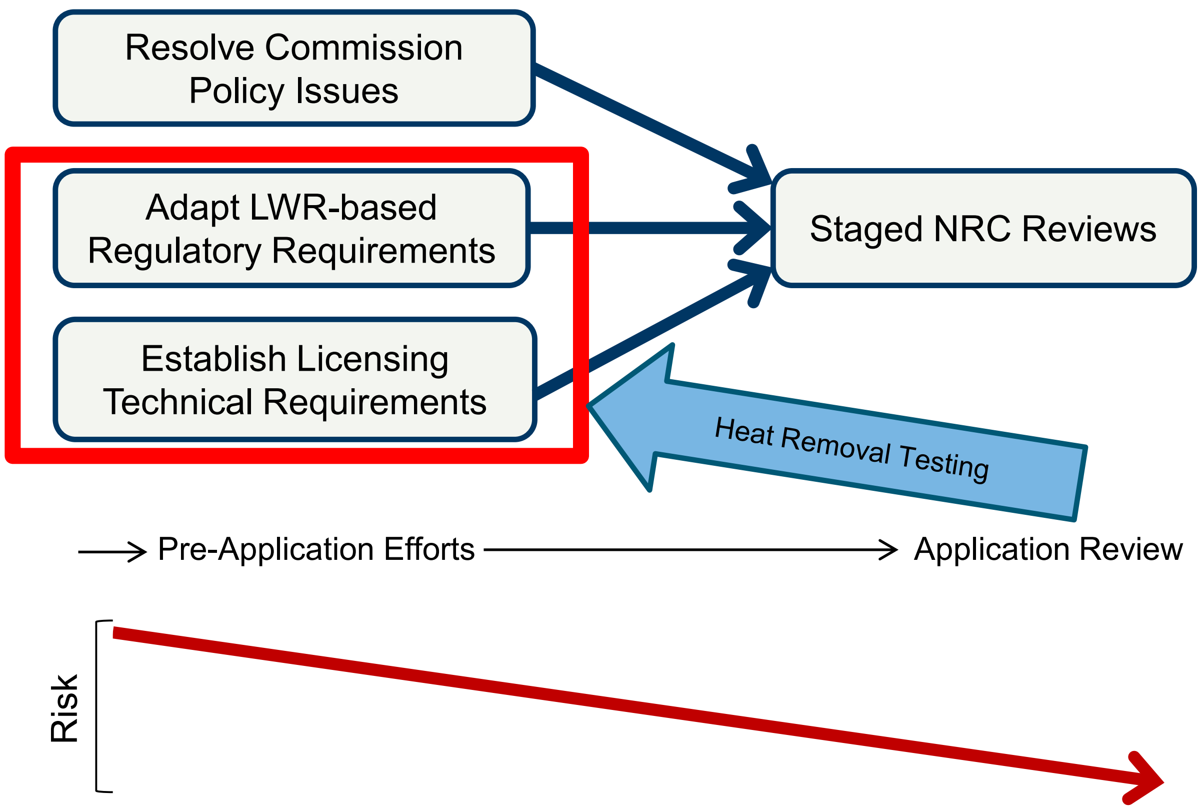
- What are the rules?
  1) Establish Commission policy on advanced non-LWR topics
  2) Develop adaptations and updates to NRC's existing LWR-based rules and regulatory guidance
- What are the technology-specific technical requirements for implementing those rules?
  3) Define requirements based on testing and R&D (fuel performance, high temperature materials, heat removal, etc.)
- What is the process for predictable and timely NRC review of a license application?
  4) Establish method for incremental and frequent NRC feedback on specific technology development and early design efforts ("staged licensing review")

Passive Heat Removal System Testing

- NRC's Non-Light Water Reactor Near Term Implementation Action Plans highlight the need to establish "Decision Criteria" as a key part of the framework
  - ***Criteria must be established for non-LWRs that allow the NRC to reach a safety, security, and environmental finding for a particular technology and design.***

- Today's presentation material will summarize DOE Advanced Reactor Technology Program testing underway to gather representative performance data to inform passive heat removal system design and modeling efforts
  - Core heat removal path to Ultimate Heat Sink
  - Passive system doesn't rely on active components
  - Informs reactor developers, future license applicants, and NRC

Support of Regulatory Framework Development



INL
Idaho National Laboratory

Reactor Cavity Cooling System

Matthew Miller

Regulatory Process Improvements for Advanced Reactor Designs

NEI - Washington, DC.
July 26, 2018

Topics

- Overall SC-HTGR Description
- SC-HTGR RCCS Description
- SC-HTGR RCCS Pre-Conceptual Performance
- Importance of RCCS R&D
- Conclusions

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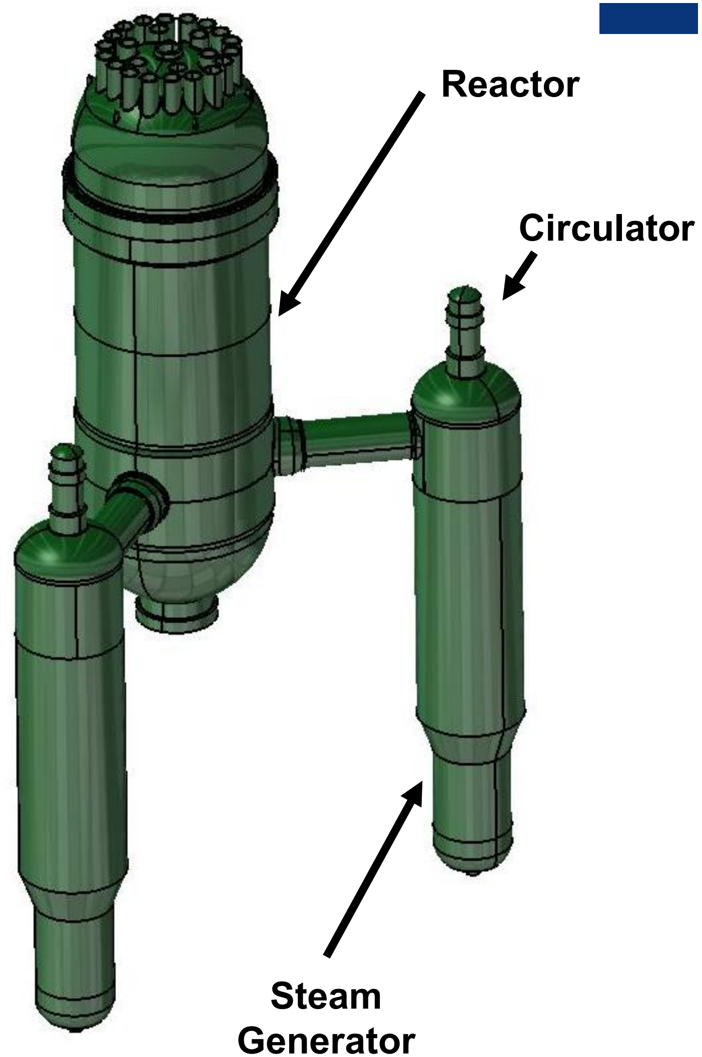
Overall SC-HTGR Description
Key Features

- Prismatic block annular core
- Conventional steam cycle
- Modular reactors
- Inherent safety characteristics
  - Passive decay heat removal
  - Large thermal inertia
  - Negative reactivity feedback
- Minimal reliance on active safety systems
- Sized to minimize steam production cost (625 MWt)
- Fully embedded reactor building



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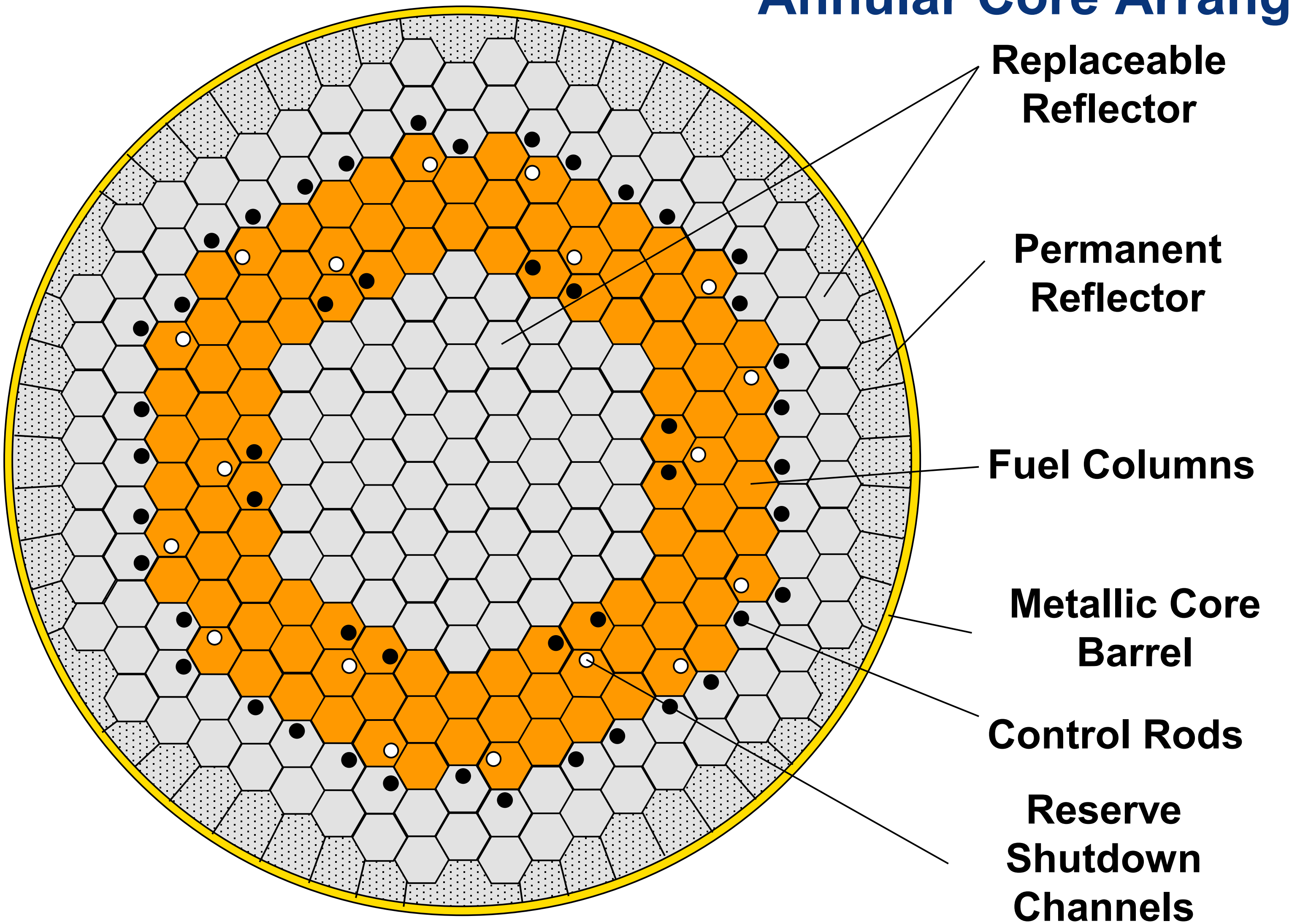
Overall SC-HTGR Description
Annular Core Arrangement



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Overall SC-HTGR Description
Passive Heat Removal Considerations

- Passive cooling is a key characteristic of modular HTGRs
  - Loss of forced circulation
  - Loss of all coolant
  - No power or system actuation required
- Passive cooling capability is inherently determined by fundamental HTGR design characteristics
  - Reactor geometry
  - Reactor materials
  - Reactor power level
  - Reactor operating temperature
  - Passive reactor cavity cooling
- These fundamental characteristics must be established early in the design process (before detailed safety analyses are available)

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Overall SC-HTGR Description
SC-HTGR Passive Cooling Design

- SC-HTGR is in Conceptual Design phase
- Scoping evaluations of passive cooling design important at this design stage
- Depressurized Loss of Forced Circulation (DLOFC) is used as representative limiting event (aka "Depressurized Conduction Cooldown" or DCC)
  - Maximum fuel temperature
  - Maximum vessel temperature
- Scoping criteria established to screen results
- Results (fuel temperatures) depend primarily on reactor configuration, power level, and initial conditions
- RCCS important to maintaining vessel and concrete temperatures

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Overall SC-HTGR Description
Reactor Cavity Cooling System Design Considerations

- **Modular HTGR designers have considered a variety of RCCS configurations**
  - Air-cooled
  - Water-cooled (various different concepts)
  - Natural circulation
  - Active cooling
- **Various tradeoffs must be addressed in selecting configuration**
  - Functionality (normal operation and accidents)
  - Robustness
  - Passive cooling duration (unlimited or "n" days)
  - Physical interfaces
  - External hazards
  - Constructability and cost

Framatome SC-HTGR utilizes a water cooled RCCS design.

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Topics

- Overall SC-HTGR description
- SC-HTGR RCCS Description
- SC-HTGR RCCS Pre-Conceptual Performance
- Importance of RCCS R&D
- Conclusions

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SC-HTGR RCCS Description
SC-HTGR RCCS System Functions

- **Safety Functional Requirements**
  - **Maintain reactor pressure vessel mean wall temperatures within ASME limits during all DBE**
  - **Maintain reactor cavity concrete temperatures within acceptable limits during all DBE**
- **Normal Operation Functional Requirements**
  - **Maintain acceptable reactor pressure vessel mean wall temperatures limits during power operation, startup and shutdown, and AOOs**
  - **Maintain acceptable reactor cavity concrete temperatures during power operation, startup and shutdown, and AOOs**
- **Cooling vessel supports at building interface**
  - **Local thermal protection strategy being developed as design progresses**
  - **Vessel supports are not at hottest location**
  - **RCCS role for supports still to be defined**

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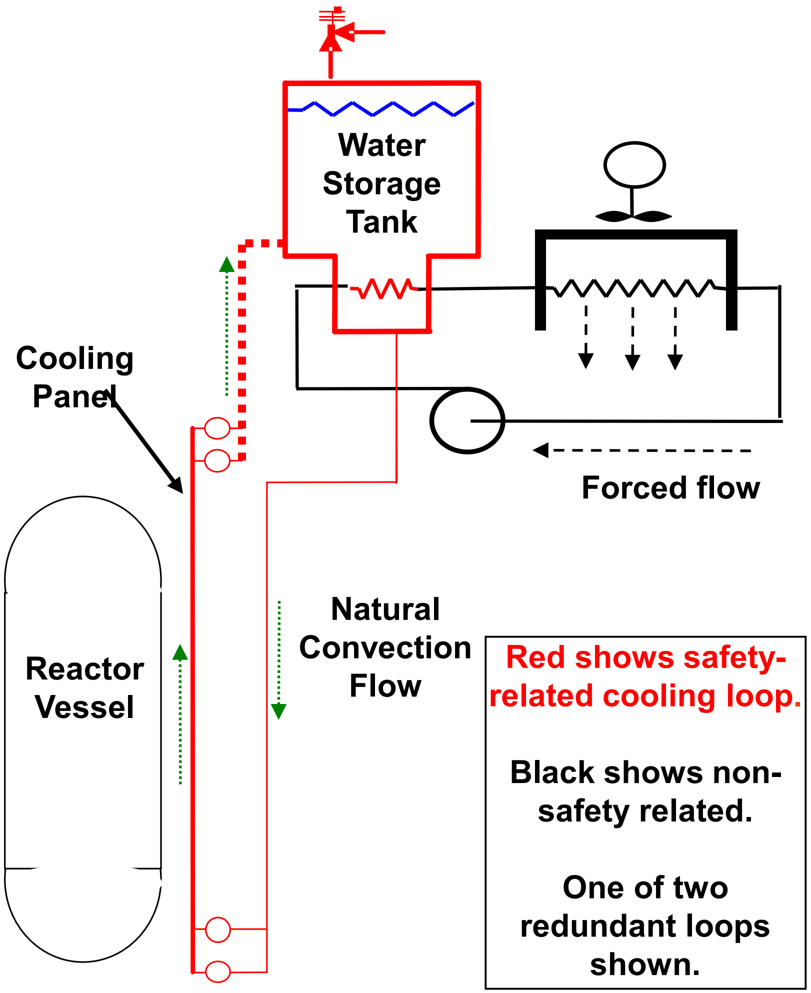
SC-HTGR RCCS Description
SC-HTGR RCCS Concept Overview

- **Reactor Cavity Cooling System**
  - Safety-related heat removal system
  - Passive cooling of vessel and surrounding cavity (operates continuously)
  - Active cooling of water storage tank during normal operation (non-safety)
- **Initial RCCS analysis and design focused on cavity natural circulation loop**
  - Building integration
  - Component sizing
  - Performance evaluation



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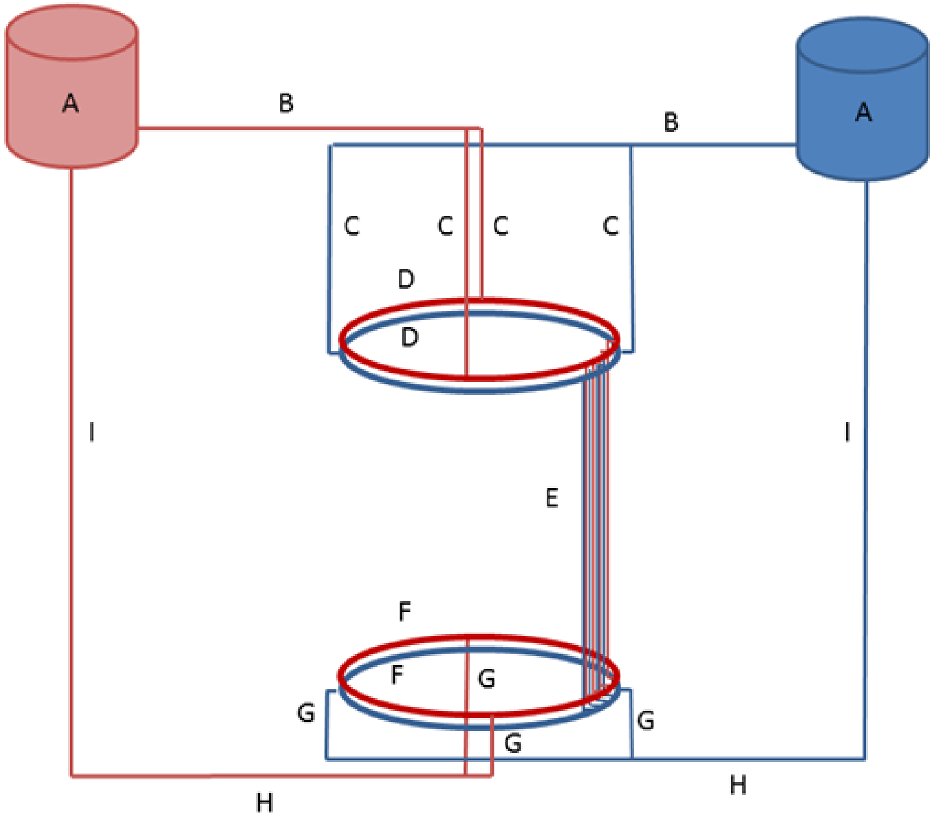
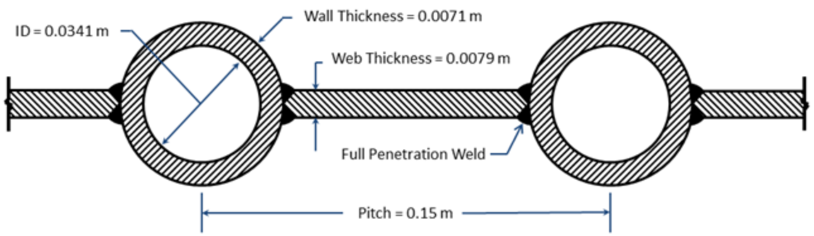
SC-HTGR RCCS Description

SC-HTGR RCCS Design Elements



RCCS includes redundant and separate loops



RCCS panel collects heat and transfers it to water loop

(panel cross section shown)

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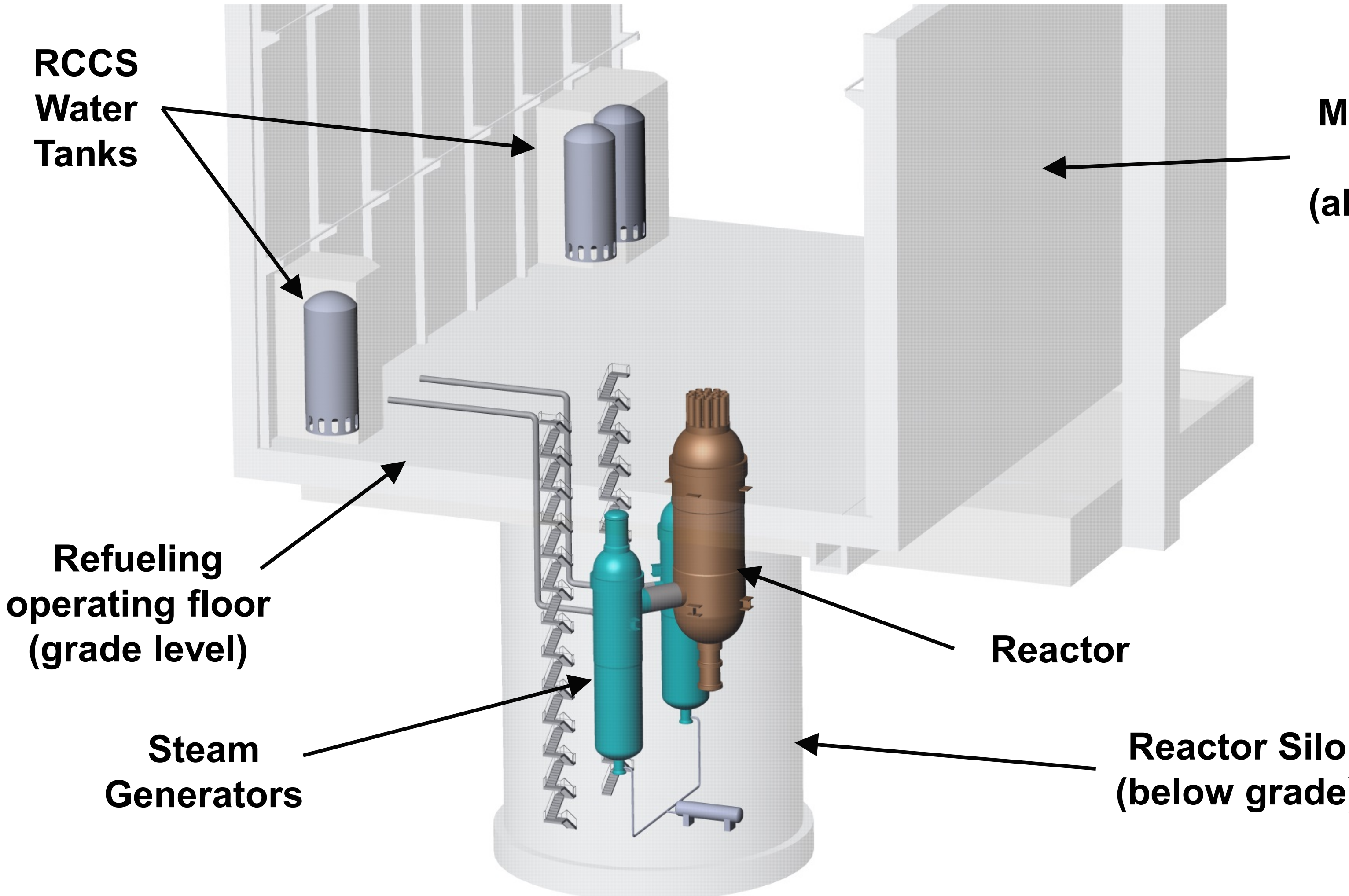
SC-HTGR RCCS Description

Single Reactor Module - Arrangement



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SC-HTGR RCCS Description
Operating Modes

- **Normal System Operation**
  - Two loop operation
  - Nominal heat load (~1.4 MWt)
  - Natural circulation in cavity loop
  - Active cooling of water tanks
- **Passive Accident System Operation**
  - Two loop operation
  - Variable heat load (~2.1 MWt max.)
  - Natural circulation in cavity loop
  - Evaporation from water tanks
- **Active Accident System Operation**
  - Two loop operation
  - Variable heat load (~2.1 MWt max.)
  - Natural circulation in cavity loop
  - Active cooling of water tanks
- **DBA System Operation**
  - Single loop operation
  - Variable heat load (~2.1 MWt max.)
  - Natural circulation in cavity loop
  - Evaporation from water tanks

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SC-HTGR RCCS Description
Key RCCS Technical Requirements

- Passive cooling during accidents
- Water heat sink cooling
  - Active secondary cooling during normal operation
  - Evaporation cooling during accidents (assume active cooling and power supply not available)
- No change in component state for accident cooling
  - Cavity cooling natural circulation for normal operation and accidents
- Redundant independent loops
- Required water inventory refill interval
  - Single loop operation: ≥ 7 days
  - Two loop operation : ≥ 14 days
- Continuous performance monitoring
- Must accommodate reactor building structural interfaces

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Topics

- Overall SC-HTGR description
- SC-HTGR RCCS Description
- SC-HTGR RCCS Pre-Conceptual Performance
- Importance of RCCS R&D
- Conclusions

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SC-HTGR RCCS Pre-Conceptual Performance
RCCS Thermodynamic States

- Normal operation
  - Subcooled natural circulation
  - Steady system temperatures (controlled by active tank cooling)
- Initial heatup conditions
  - Subcooled natural circulation, but
  - Gradually increasing loop temperatures
- Approaching saturation conditions
  - Downcomer and lower riser subcooled
  - Saturation reached in heated riser panels
  - Boiling occurs in hot part of riser
  - Very low quality two phase natural circulation
- Saturation conditions
  - Tank at saturation condition
  - Downcomer single phase flow
  - Low quality two phase natural circulation
- Tank empty
  - Circulation blocked (stagnant loop)
  - Downcomer single phase
  - "Pool" boiling in hot leg
  - Water gradually boils out of panels
- Refill water tank (stagnant loop)
  - Water goes down downcomer, collects in bottom of loop, rises in hot leg riser and panel inlet
  - Flashing occurs when water reaches heated sections
  - Depending on geometry, may have to purge trapped gases

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SC-HTGR RCCS Pre-Conceptual Performance
RCCS Operating Modes and TD States

		Thermodynamic State					
		Normal Operation	Initial Heatup	Approach Saturation Conditions	Saturation Conditions	Tank Empty	Refill Empty Loop
Operating Mode	Normal Plant Operation						
	Active Accident System Operation						
	Passive Accident System Operation						
	DBA System Operation						
	System Dryout and Long-Term Recovery (outside design envelope)						

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SC-HTGR RCCS Pre-Conceptual Performance
Preliminary Performance Characteristics

- **For subcooled operation**
  - Cold leg ΔP is ~80% of total ΔP
  - System ΔT is ~10-20°C
- **For saturated operation**
  - Cold leg ΔP is less than 50% of total ΔP
  - System return quality is < 1% (but still significant void fraction)
  - Stability not expected to be concern for overheating/burnout
  - Dynamic structural loading must be addressed
- **Panel performance (conduction heat transfer)**
  - Large temperature variations for single loop operation (especially w/ SS)
  - RPV cooling not particularly sensitive to panel temperature variations
  - Thermal stresses in panel are detailed design challenge to be addressed
  - Impact of large panel temperature variations on concrete surfaces and necessary thermal protection still to be evaluated

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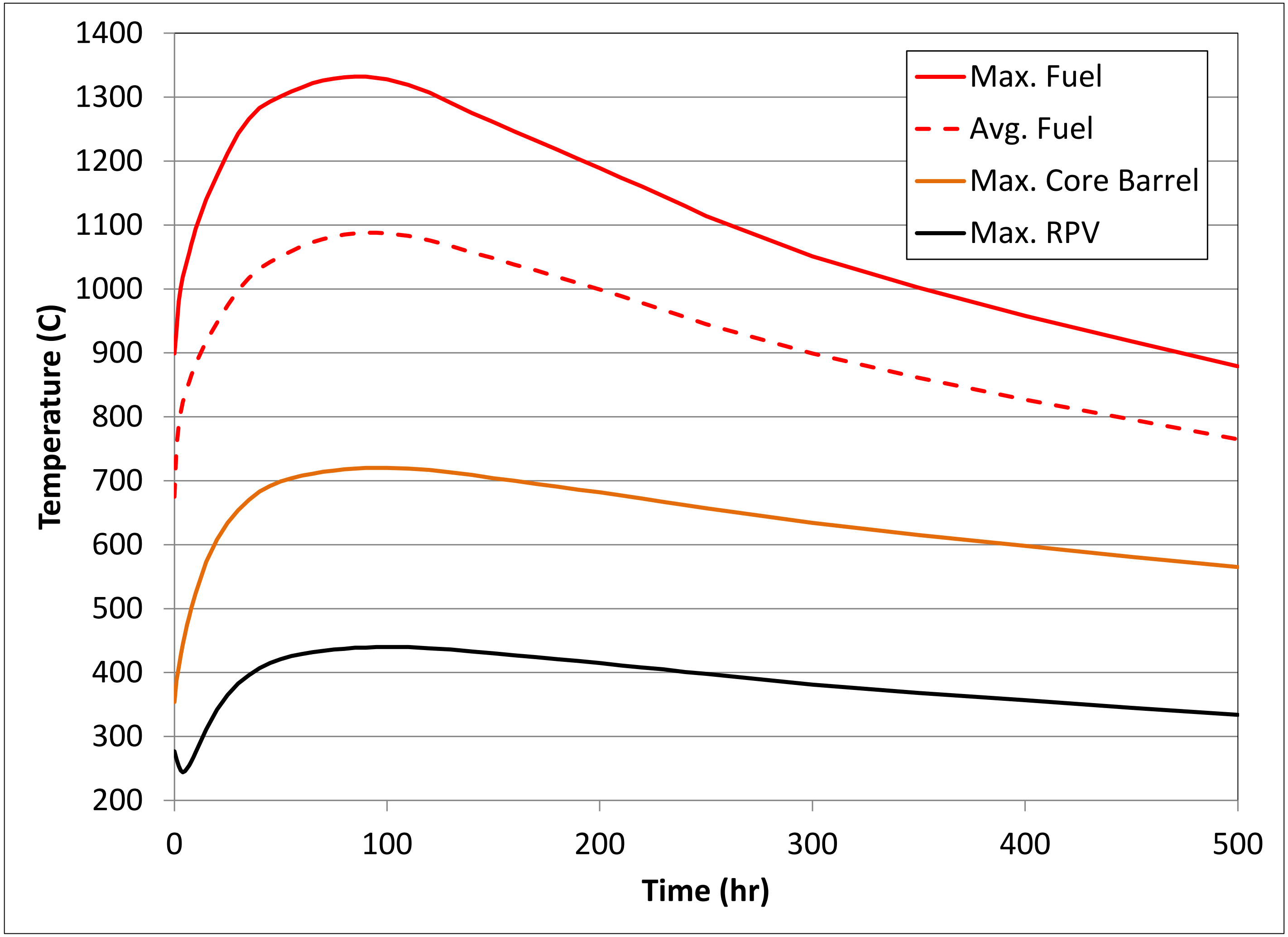
SC-HTGR RCCS Pre-Conceptual Performance
Nominal DLOFC Results



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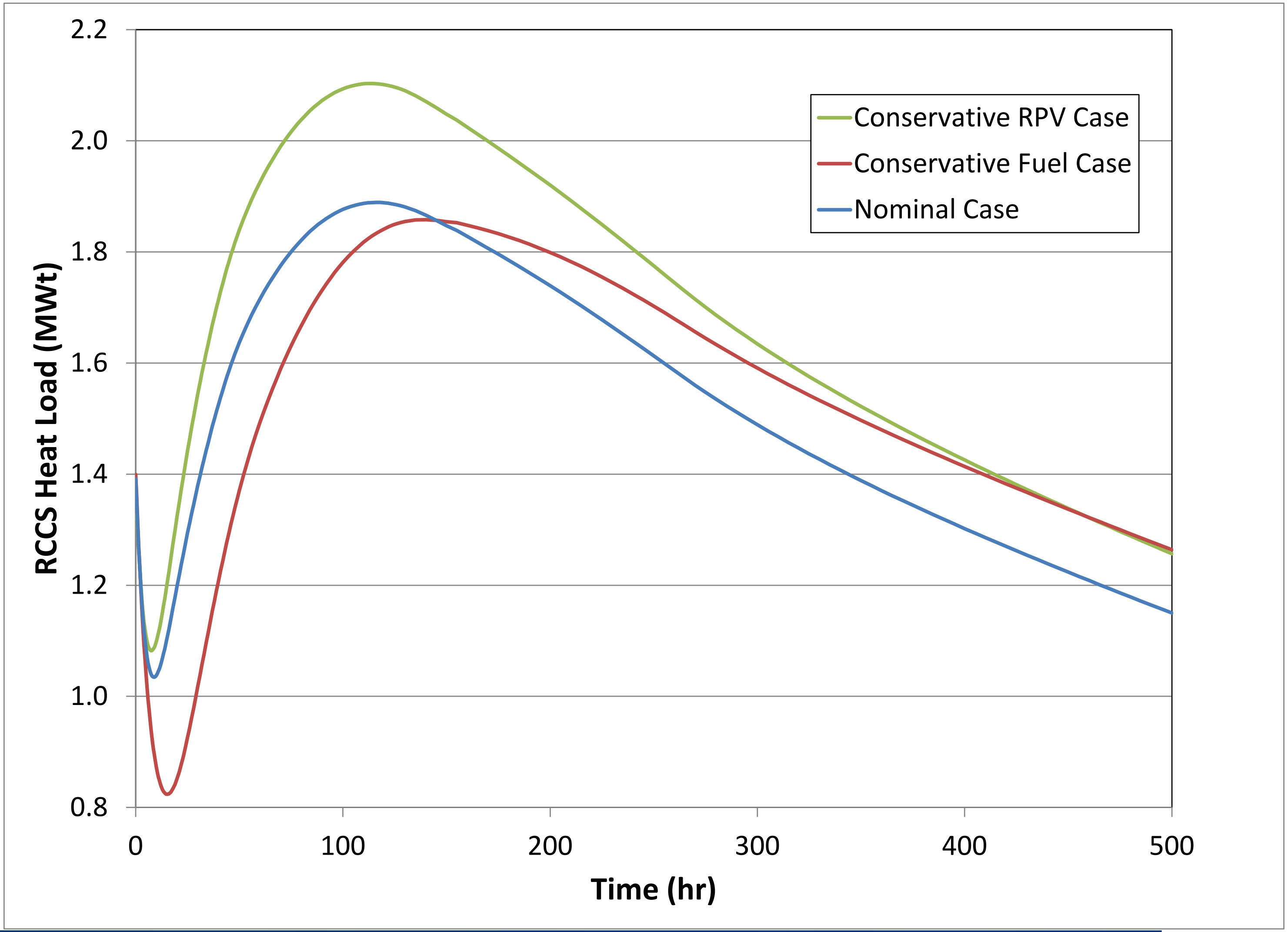
SC-HTGR RCCS Pre-Conceptual Performance
RCCS Heat Load During DLOFC



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SC-HTGR RCCS Pre-Conceptual Performance
Summary of Results

Component	Nominal Case	Conservative Case*	Scoping Criterion
Fuel peak temperature	1332°C	1635°C	1650°C
Core Barrel peak temperature	720°C	784°C	800°C
RPV peak temperature	440°C	482°C	538°C
Duration RPV above 371°C	305 hr	446 hr	750 hr
Duration RPV above 427°C	96 hr	233 hr	250 hr

* Different conservative case for each Figure of Merit

- **All scoping criteria satisfied**
  - **Safety functions are not impaired**
  - **Components remain within design limits**
  - **Meeting these criteria provides confidence that final design will be successful**

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Topics

- Overall SC-HTGR description
- SC-HTGR RCCS Description
- SC-HTGR RCCS Pre-Conceptual Performance
- Importance of RCCS R&D
- Conclusions

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Importance of RCCS R&D

- **Need for RCCS R&D**
  - **Provide data to qualify RCCS analysis tools**
  - **Provide data to address specific design issues**
  - **Provide confidence in overall system concept**

Designer perspective:

- **Basic performance of buoyancy-driven natural circulation loop is well understood**
- **Basic performance of radiation heat transfer from RPV to RCCS is well understood**
- **Main areas of interest are with specific details**
  - **Impact of specific design details on system performance**
  - **Dynamics associated with two phase operating modes**

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Importance of RCCS R&D
Points of Interest

- **Impact of riser panel tube dimensions on system performance and dynamic stability**
- **Need for inlet orificing (at riser tube inlets from bottom header)**
- **Dynamic performance characteristics**
- **Impact of system piping details due to building interface issues, etc.**
- **Impact of panel riser tube discontinuities**


20004-021 (01/30/2014)

AREVA Inc.

Technical Data Record

Document No.: 12 - 9239789 - 000

RCCS Designer Input Report

Disclaimer

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RCCS Designer Input Report

12-9239789-000

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Topics

- Overall SC-HTGR description
- SC-HTGR RCCS Description
- SC-HTGR RCCS Pre-Conceptual Performance
- Importance of RCCS R&D
- Conclusions

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Conclusions

- SC-HTGR being developed for a variety of process heat, electricity, and cogeneration markets
- Reactor Cavity Cooling System (RCCS) is only safety-related heat removal system for SC-HTGR
- Preliminary analytical assessments indicate RCCS maintains acceptable system temperatures
  - Reactor cavity wall (normal operation and accident)
  - Reactor vessel (accident)
- Basic behavior of natural circulation system and radiation heat transfer well understood
- RCCS R&D needed to
  - Provide data to qualify design and safety analysis evaluation models
  - Provide data to address specific system characteristics
  - Provide confirmation of overall system concept

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Wrap-up

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Wrap-up

- **Industry is working with the national labs to develop testing and the associated test plans to support design validation**

- **Industry needs the data developed in the national labs to support future license applications and submittals:**
  - **Demonstrate basic concept feasibility**
  - **Provide insights on detailed design issues for RCCS designers**
  - **Generate data required to validate general computational methods for RCCS analysis**

- **Current data gathering and proposed test plans are expected to meet the necessary quality requirements specified by industry standards and the regulator**

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Natural convection Shutdown heat removal Test Facility (NSTF) Overview

Darius D. Lisowski
Nuclear Science & Engineering Division – Argonne National Laboratory

presented at:

Nuclear Regulatory Commission

July 26th 2018

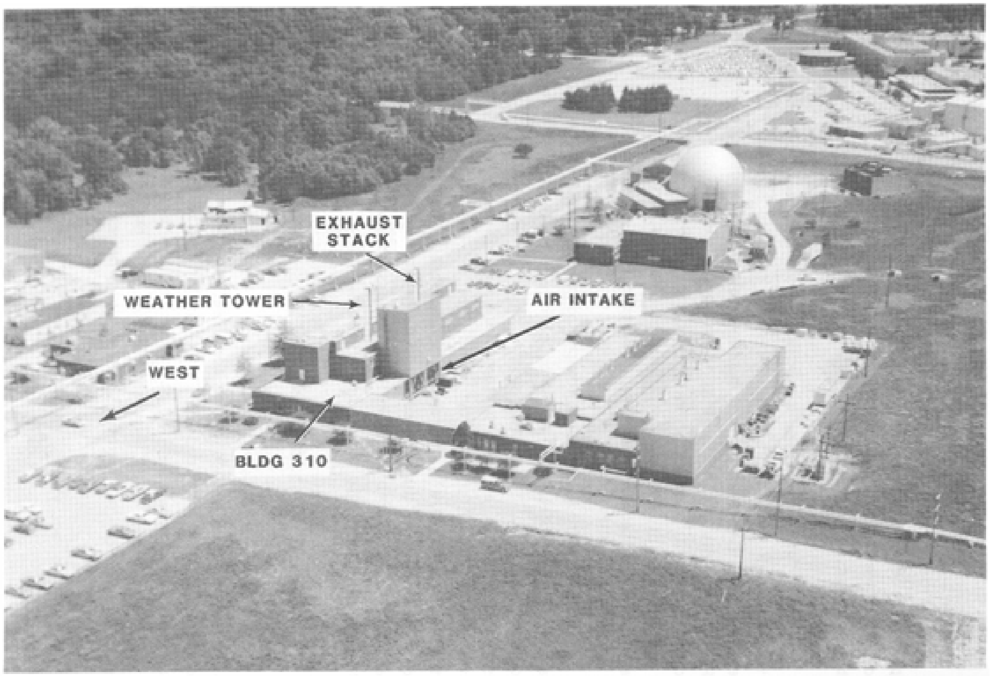
Washington, DC. USA.

Introduction

- 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 simple 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
- Multi-institutional effort has brought together federal, industry, national laboratories, universities, and countries.

NSTF at Argonne (legacy)

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



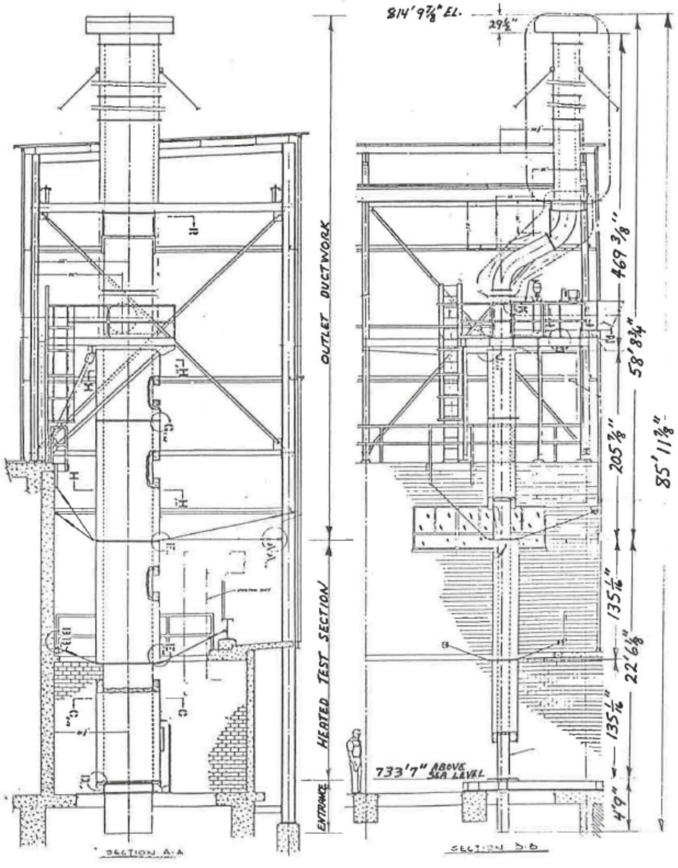


Figure 3-1. ANL Shutdown Heat Removal Test Assembly (Reduction of ANL Dwg. No. R0408-0004-DE, Sheet 1 of 4).

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…

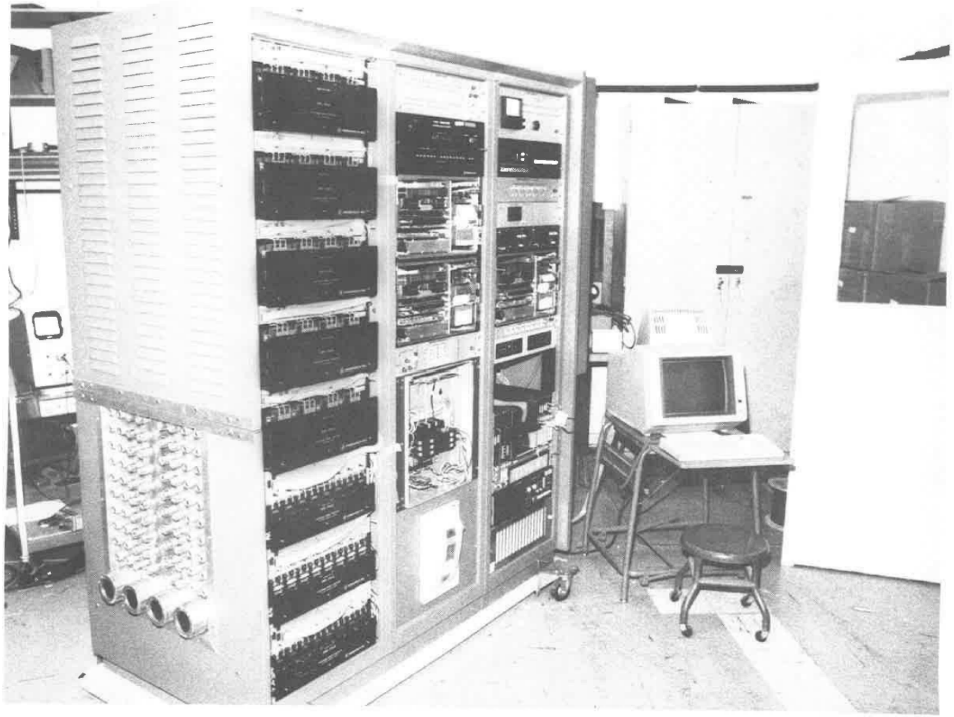
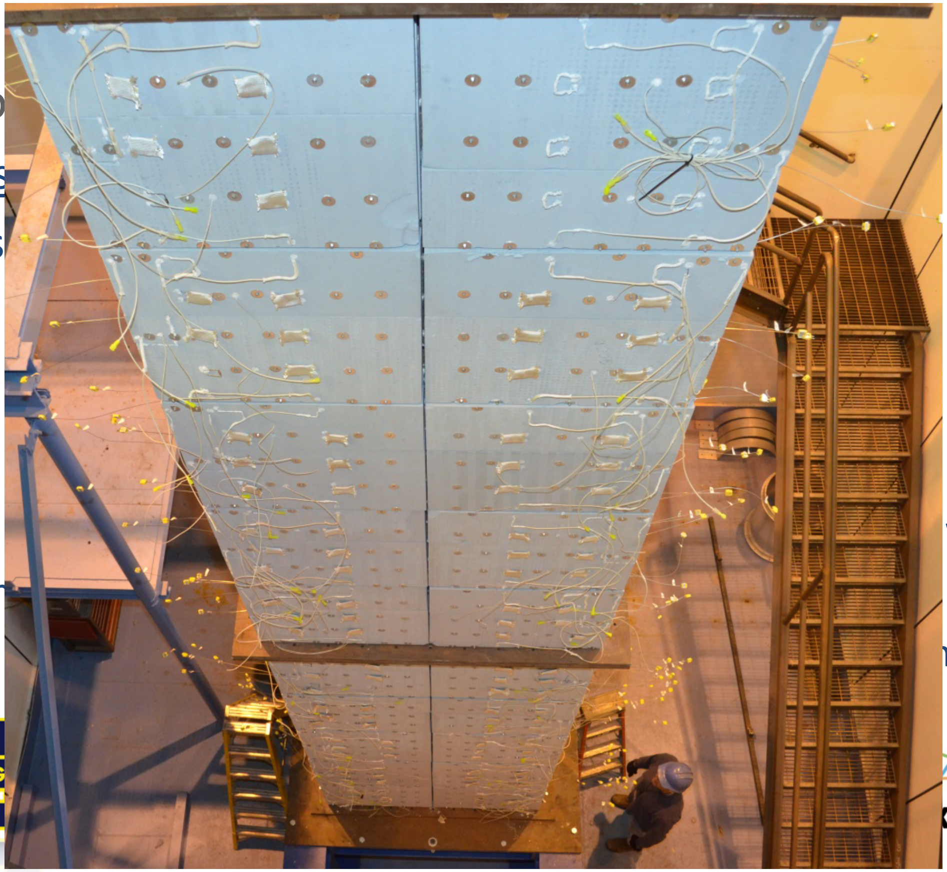


Figure 3-17. Computer Control and Data Acquisition Console.

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 is compliant to Nuclear Quality Assurance (NQA)-1 2008/2009a



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  3. generate be

- Concurrent col
  - Experimental … water designs
  - Complimentin
  - Collaborating … ne RCCS concept

Argonne National Laboratory

NSTF 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

- Audit frequency
  - Management assessments are conducted by Argonne leadership every 3 – 9 months
  - Internal audits by NQA-1/ASQ certified staff every 12 – 18 months
  - External audits by NQA-1 certified consultants every 18 – 24 months or after major programmatic changes

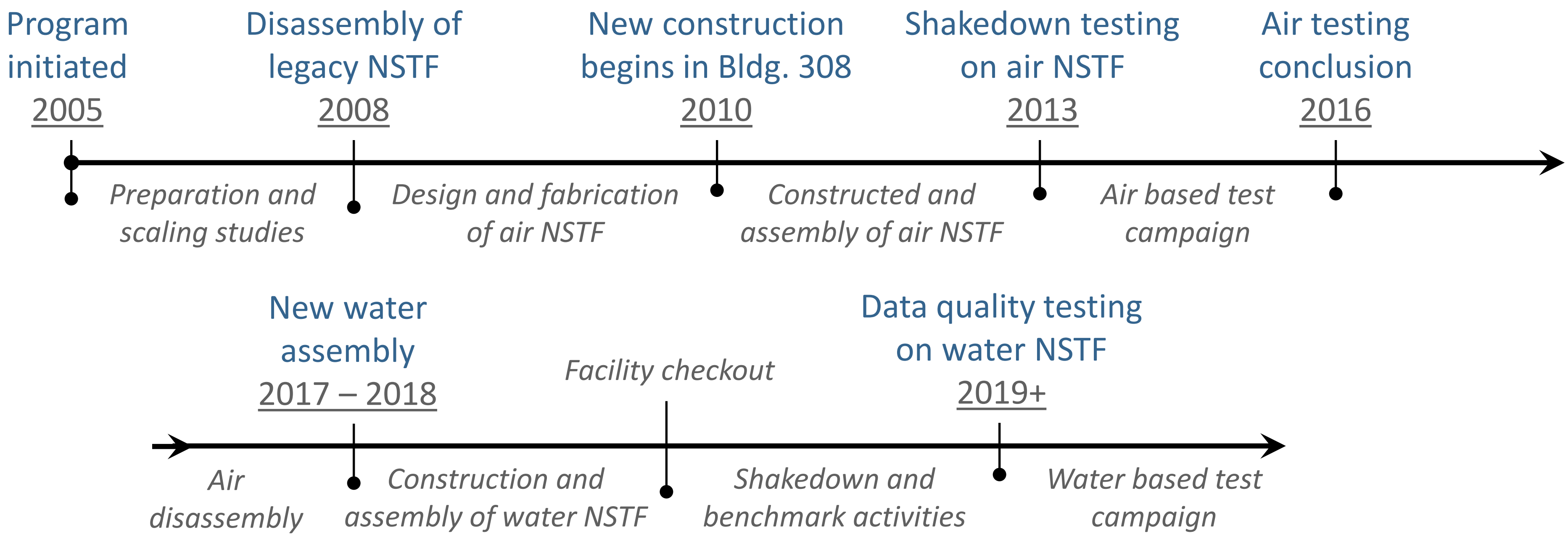
- Compliance status
  - *"All required ASTM-NQA-1-2008/1a-2009 criteria are addressed and compliant. The overall effectiveness rating of the ANL NTSF Program is Effective."* - ASMT 2018-022

- Program will maintain NQA-1 compliance through entire active program period

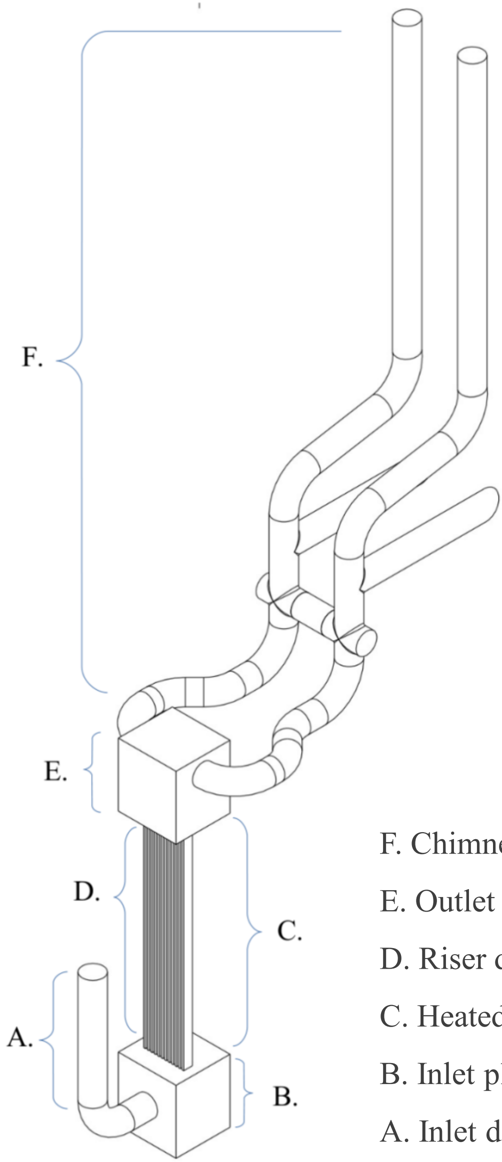
NSTF Project Documentation

- We document all aspects of the project and engineering details of our facility
  - 80+ documents on programmatic structure, technical specifications, procurement reports, etc.
  - 300+ engineering drawings of facility design (machine shop delivery)
- Published report on scaling studies and preparation tasks
  - "RCCS Studies and NSTF Preparation Air-Cooled Option" – ANL-GenIV-142 (2010)
  - "Progress Report on Water Conversion of the NSTF" – ANL-ART-69 (2016)
- Compiled technical document outlining test matrix for air & water installations
  - "NSTF Data Test Matrix and Operating Parameters" – ANL-NSTF-000000-TECH-010-R1 (2014, 2015)
  - "Water-based NSTF Data Quality Testing Objectives" – ANL-NSTF-000000-TECH-021-R (2017)
- Published detailed design report that provides key dimensions of significant features and components of NSTF
  - "Design Report for the ½ Scale Air-Cooled RCCS Tests in the NSTF" – ANL-SMR-8 (2014)
  - "Water NSTF Design, Instrumentation, and Test Planning" – ANL-ART-98 (2017)
- Active contributions to scientific community
  - Regular attendance and publication in conferences, journal submissions in-review

High-Level Status of NSTF Program



(Air) Facility Overview



F. Chimney ductwork

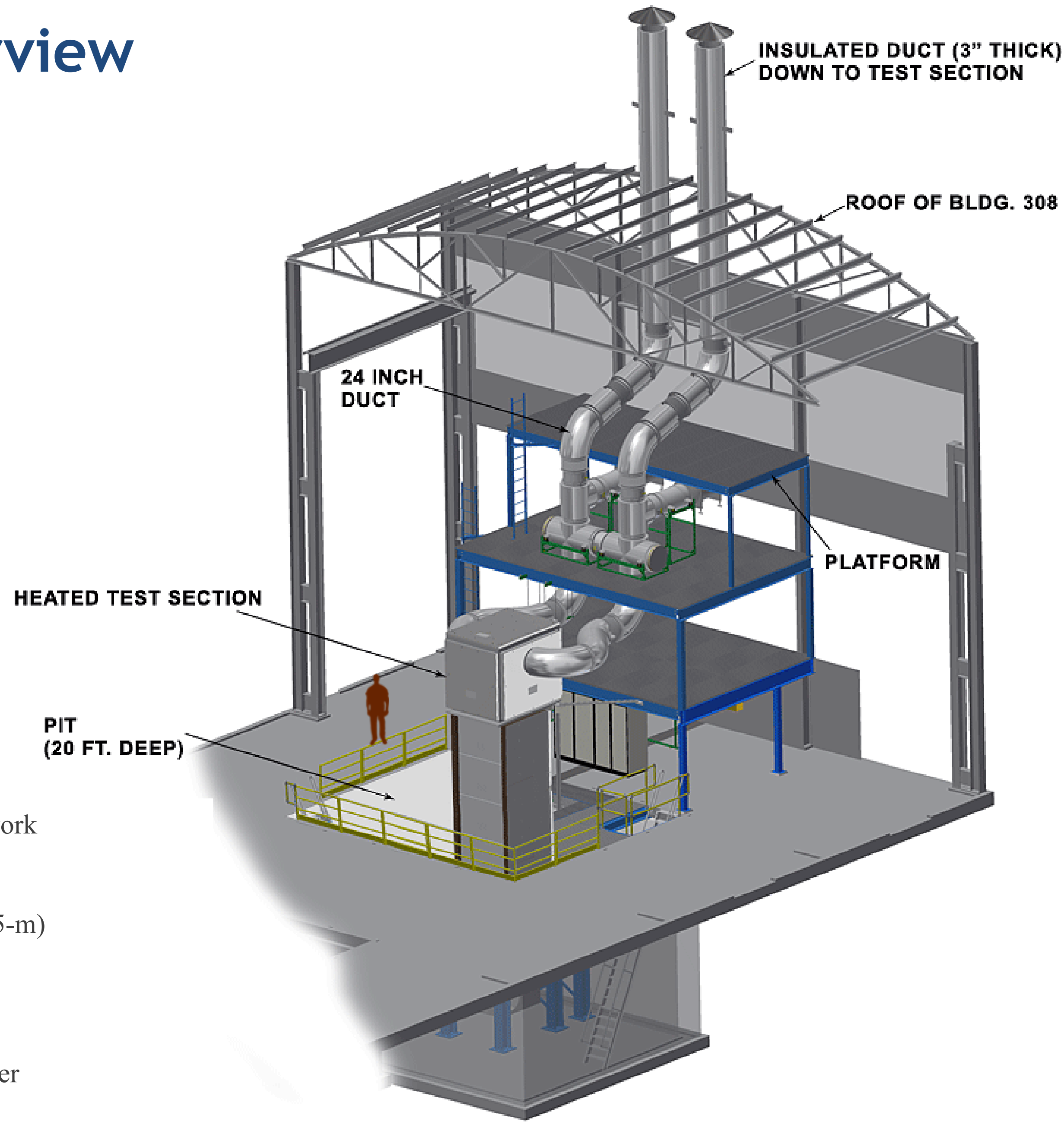
E. Outlet plenum

D. Riser ducts (7.5-m)

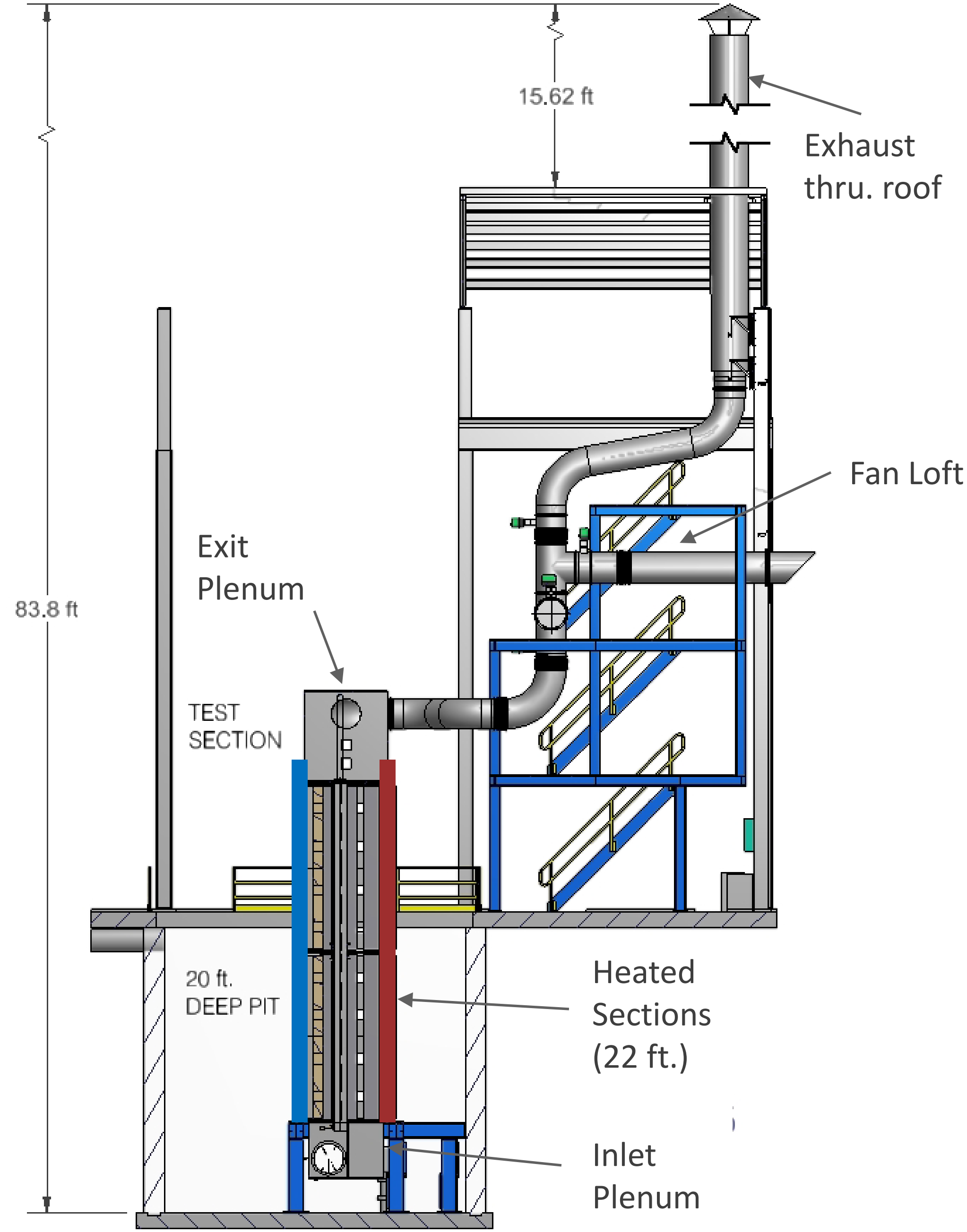
C. Heated cavity

B. Inlet plenum

A. Inlet downcomer



(Air) Facility Overview



Matrix Testing Procedures

- All matrix tests are performed with strict procedures and are documented in full
  - Test procedure (20+ pages)
  - Engineering drawings of all instrumentation positions
  - Channel listing for all instruments (NIST calibrated) into data acquisition
  - Software configuration listing
  - Archived computer software (e.g. LabVIEW .vi)
  - Full data sets saved in raw format (e.g. original voltage signals for flow instruments)
- Facility and instrument check outs are performed prior and after each test, verifying working measurements and physical connections
- If a completed test meets the stated test objective, it is suggested for classification as "Type-A" data and is followed by a Preliminary test acceptance report (PTAR)
- Those tests that do not meet objective may be classified as "Trending"

Completed Air Testing Parameters

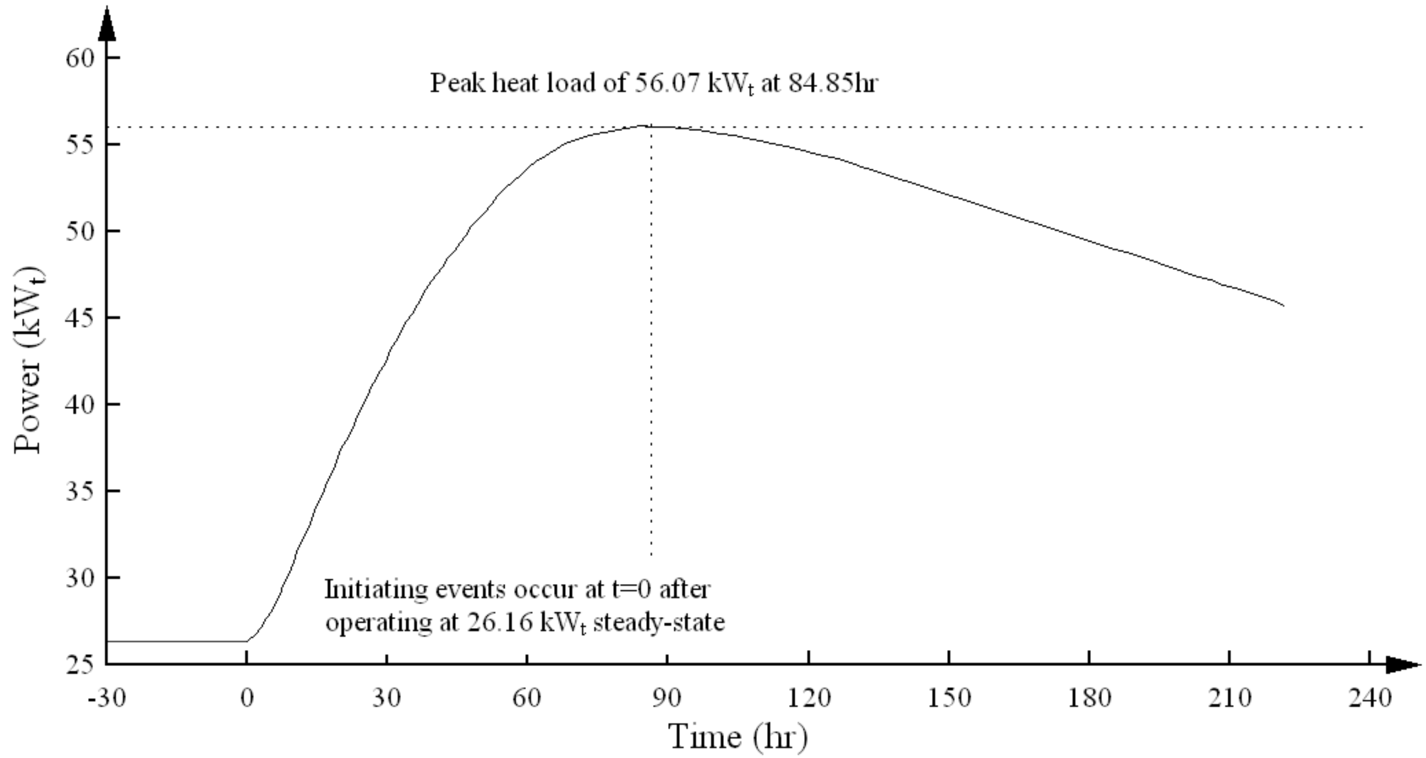
1. Shakedown/Calibration/Isothermal Characterization
2. Baseline testing (Q_R = 1, $\Delta T = 1$)
3. Scaling verification
   - Integral power variation
   - Reduced physical scale
4. Heated profile shaping
5. GA-MHTGR accident scenario
   - Full time history of decay power profile
6. Performance testing
   - 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)
7. 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

GA-MHTGR Accident Scenario

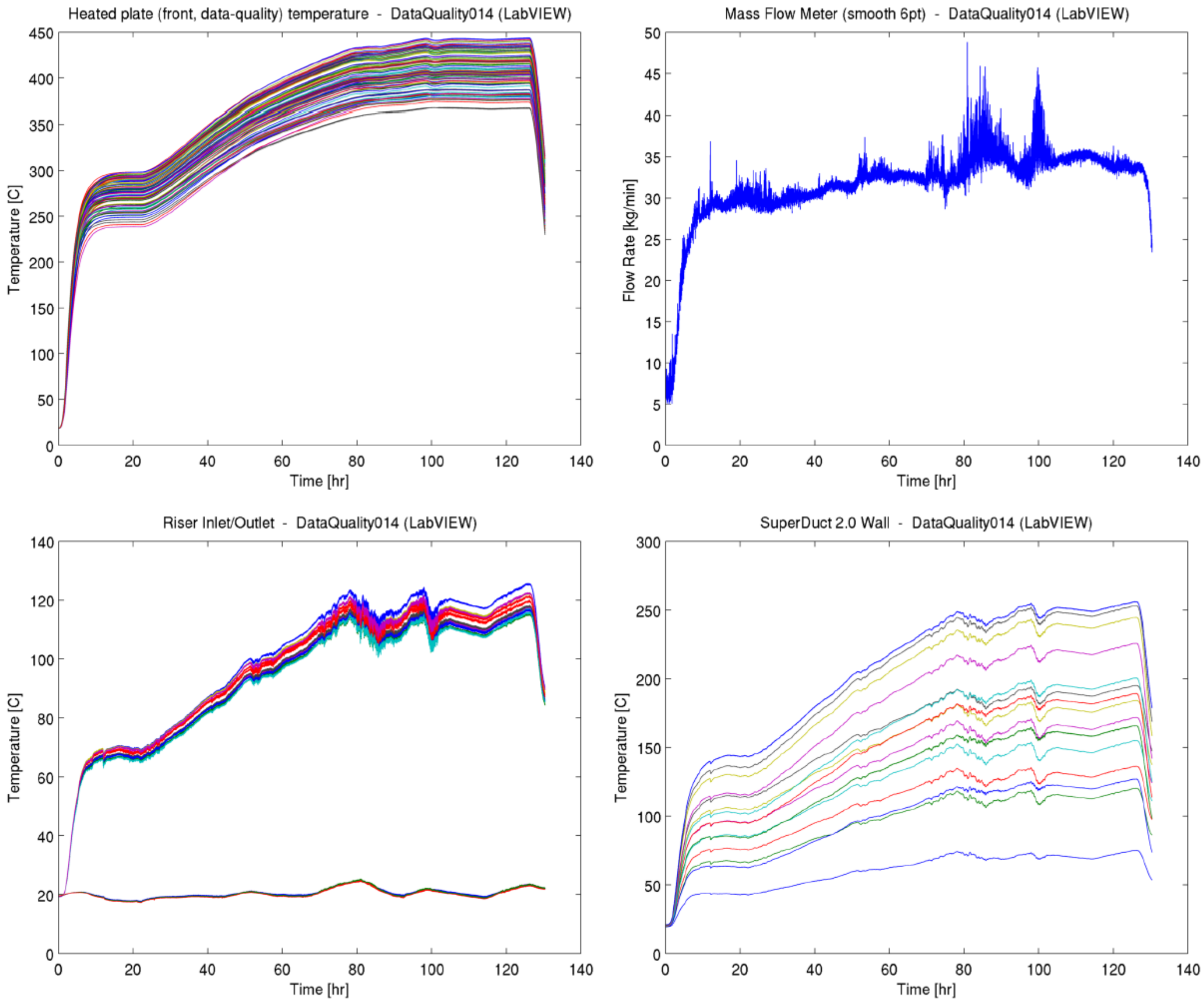
RCCS heat removal is a function of vessel temperature and ambient air temperature. A constant 43°C (110°F) ambient air temperature is assumed for this analysis. For the depressurized cooldown accident, there is very little convective heat transfer from the core to the top head. Decay heat is primarily 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)

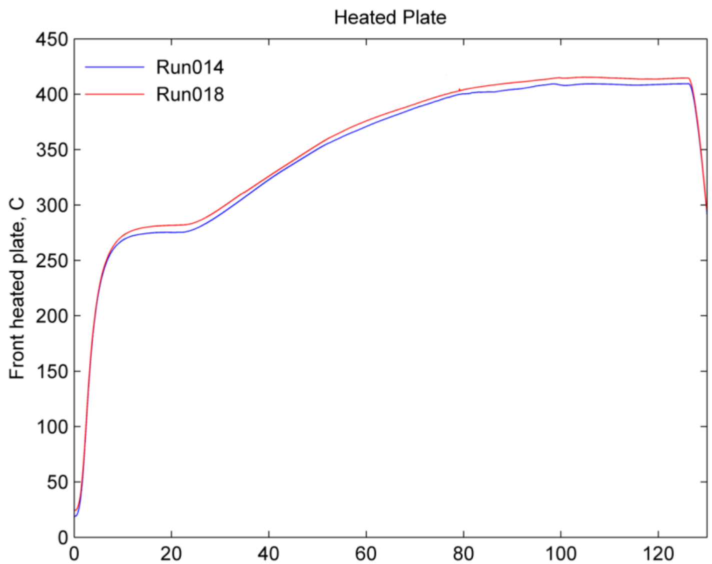
"Preliminary Safety Information Document for the Standard MHTGR," HTGR-86-024, Vol. 1, Amendment 13, U.S. Department of Energy, (1992)

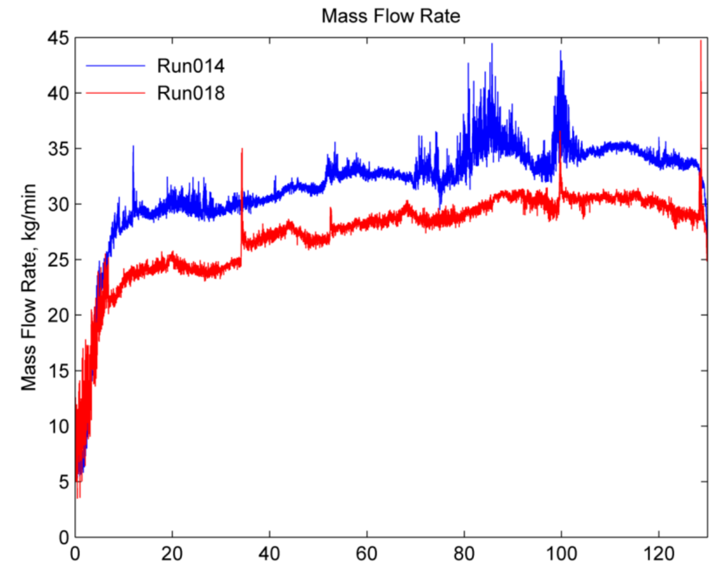


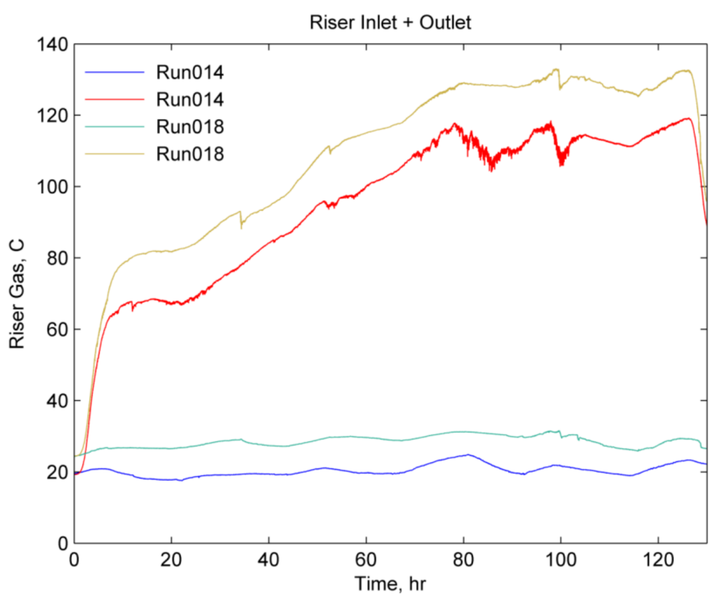
GA-MHTGR Accident Scenario

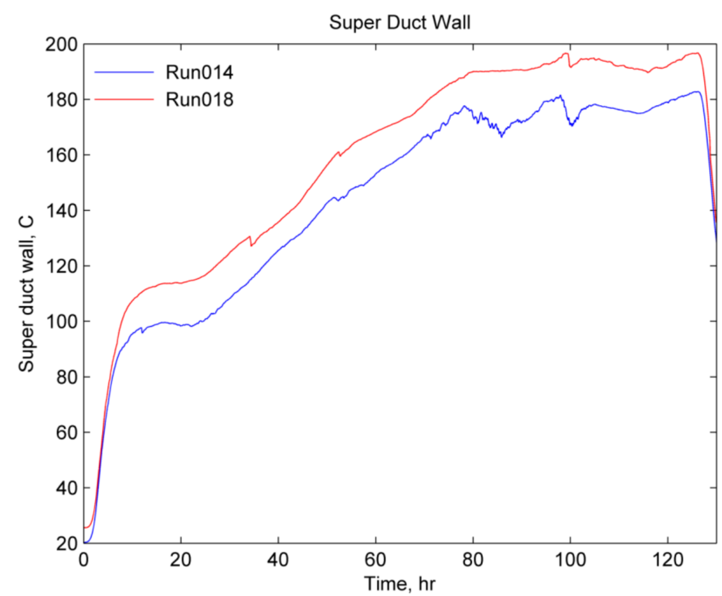


GA-MHTGR Weather Influences

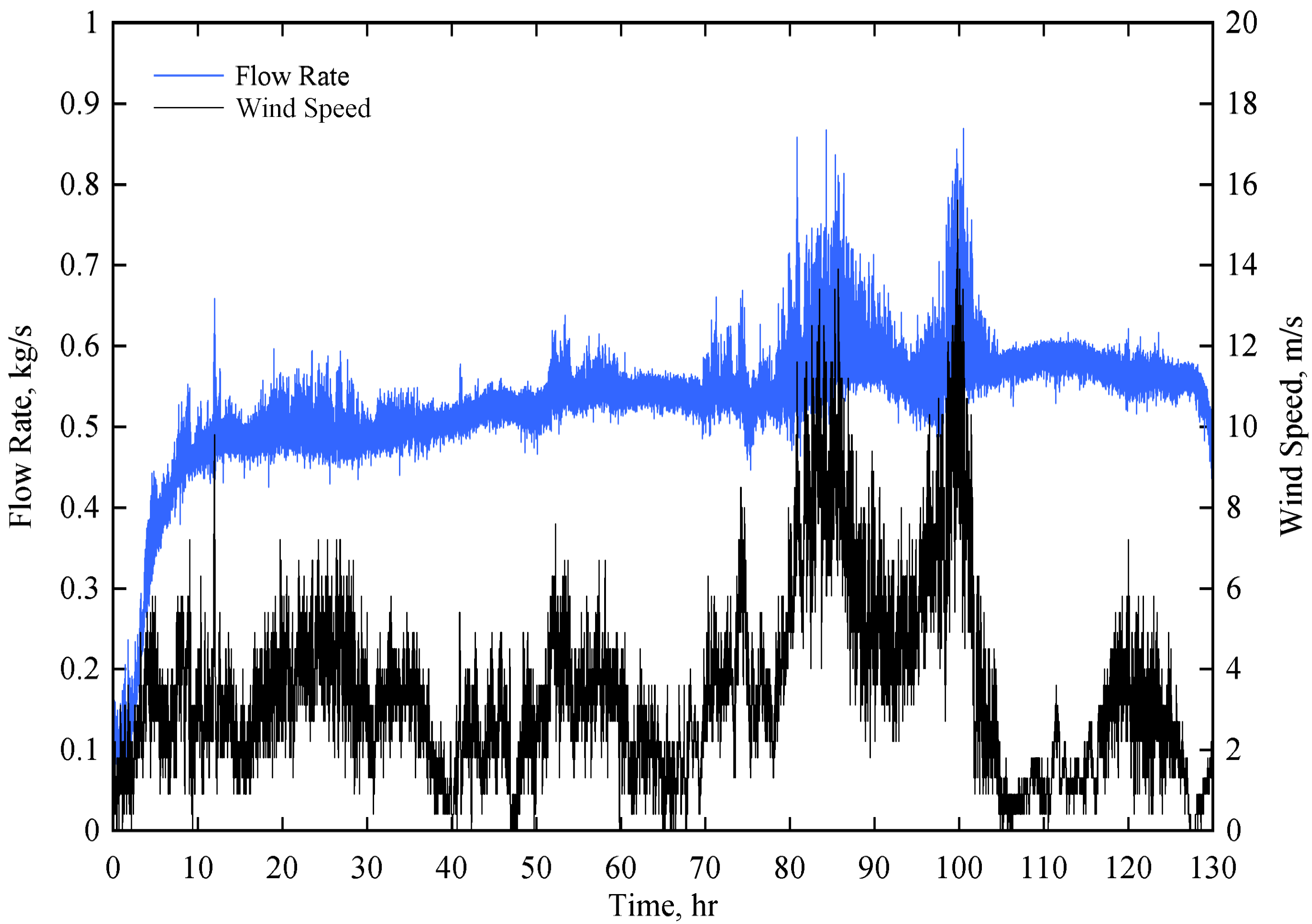








Influences of Wind



Summary of Accepted Air-Based Test Runs

Test Type	Test Number	Date	Duration	Classification	Primary Objectives	Flow Path
Baseline	DataQuality004	April 2014	49h 52m	Accepted	Test series kick-off	Natural, Dual vertical
	DataQuality011	January 2015	52h 47m	Accepted	Mid-project baseline	Natural, Dual vertical
	DataQuality020	September 2015	52h 8m	Accepted	Hot weather baseline	Natural, Dual vertical
Scaling	DataQuality005	May 2014	30h 05m	Accepted	Low power study	Natural, Dual vertical
	DataQuality008	July 2014	51h 09m	Accepted	Reduced chimney discharge	Natural, Reduced discharge
Chimney roles	DataQuality017	June 2015	58h 38m	Accepted	Adjacent chimney study	Natural, Adjacent
	DataQuality024	April 2016	145h 50m	Accepted	Single chimney	Natural, Single vericcal.
Power Shaping	DataQuality013	March 2015	72h 05m	Accepted	Mid-plane cosine	Forced, Reduced discharge
	DataQuality022	January 2016	120h 8m	Accepted	Bottom-peaked cosine	Natural, Dual vertical
	DataQuality026	May 2016	97h 38m	Accepted	Azimuthal, 65/35%	Natural, Dual vertical
GA-MHTGR	DataQuality014	April 2015	130h 28m	Accepted	SRDC-II, winter months	Natural, Dual vertical
	DataQuality018	August 2015	129h 55m	Accepted	SRDC-II, summer months	Natural, Dual vertical
Performance	DataQuality015	May 2015	82h 53m	Accepted	Blocked riser tubes	Natural, Single vertical
	DataQuality027	June 2016	30h 07m	Accepted	Heavy gas (argon) ingress	Natural, Single vertical
Weather	DataQuality007	June 2014	13h 28m	Accepted	Inclement weather start-up	Natural, Reduced discharge
Collaboration driven	DataQuality023	February 2016	190h 20m	Accepted	INERI test series	Forced, Reduced discharge

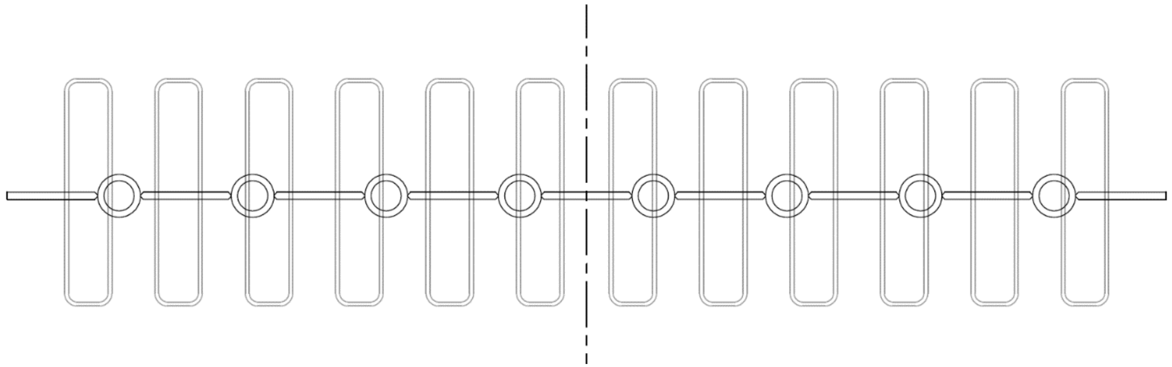
Air-based Program Summary

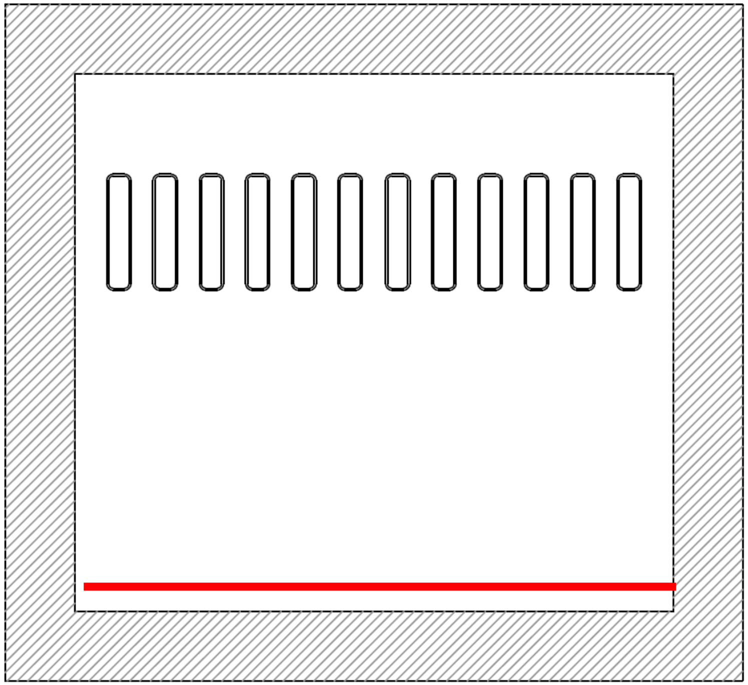
- Air-based testing program officially concluded on July 5th 2016
  - Final modeling report documented in ANL-ART-46 (M2AT-16AN1702078)
  - Final project report documented in ANL-ART-47 (M2AT-16AN1702077)
  - Formal internal audit for all 18 elements of NQA-1 2008 June 29th 2016
- All program requirements 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
    - Stenographer hired and transcribed full meeting minutes
- 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)

Water based transformation & Design study

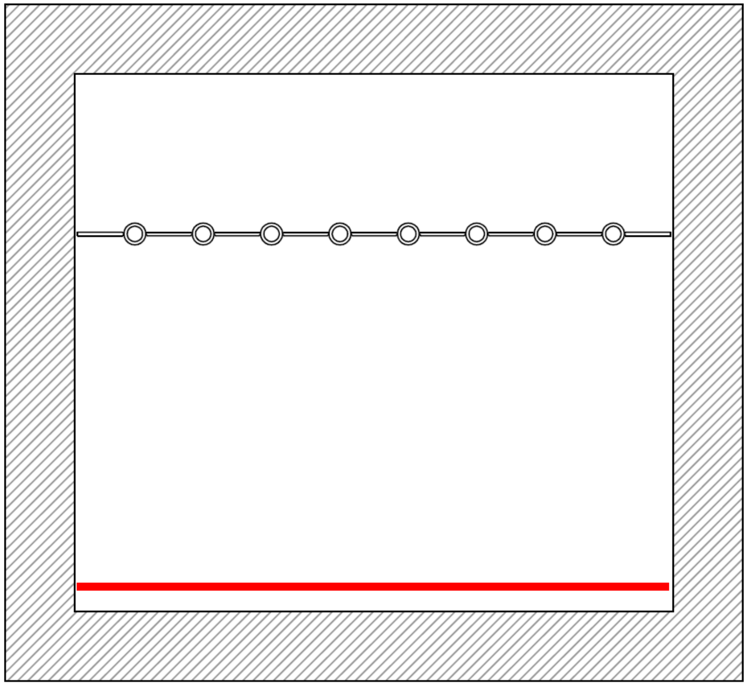
- Water-cooled NSTF is based on concept design for Framatome's water based RCCS
  - DOE sponsored HTGR Technology Economic/Business Analysis and Trade Studies
  - RCCS team performed scaling studies, geometric simulations, thermal and stress calculations, tank depletion time estimates, steam quality/flow rate determinations, etc.
- Close collaboration with Frametome, whose RCCS included as part of their 625 MW_t SC-HTGR served as the primary design basis for incorporation into the NSTF
  - "RCCS Designer Input Report, Technical Data Record, 12-9239789-000, AREVA"
  - "Design Proposal for the Water-Based NSTF Test Section and Network Piping Argonne National Laboratory", Technical Report, ANL-NSTF-000000-TECH-016-R0, ANL"
  - "Water-Cooled RCCS R&D Designer Observation Report, Technical Data Record, 12-9237246-000, AREVA"
  - "Design Proposal for the Water-Based NSTF Test Section and Network Piping Argonne National Laboratory", Technical Report, ANL-NSTF-000000-TECH-016-R1, ANL"
- Participation from Framatome, INL, DOE, NRC, and US Universities
  - Design review meeting held at Argonne in February of 2015
  - Test planning and program readiness meeting held March of 2018
  - Consensus reached on a design and test plan that reflects a representative yet bounding configuration for future implementation into a full scale design
- The final facility meets ANL/DOE project goals, and will provide industry with data suitable for characterizing the RCCS of their full scale HTGR design

Air / Water Comparison





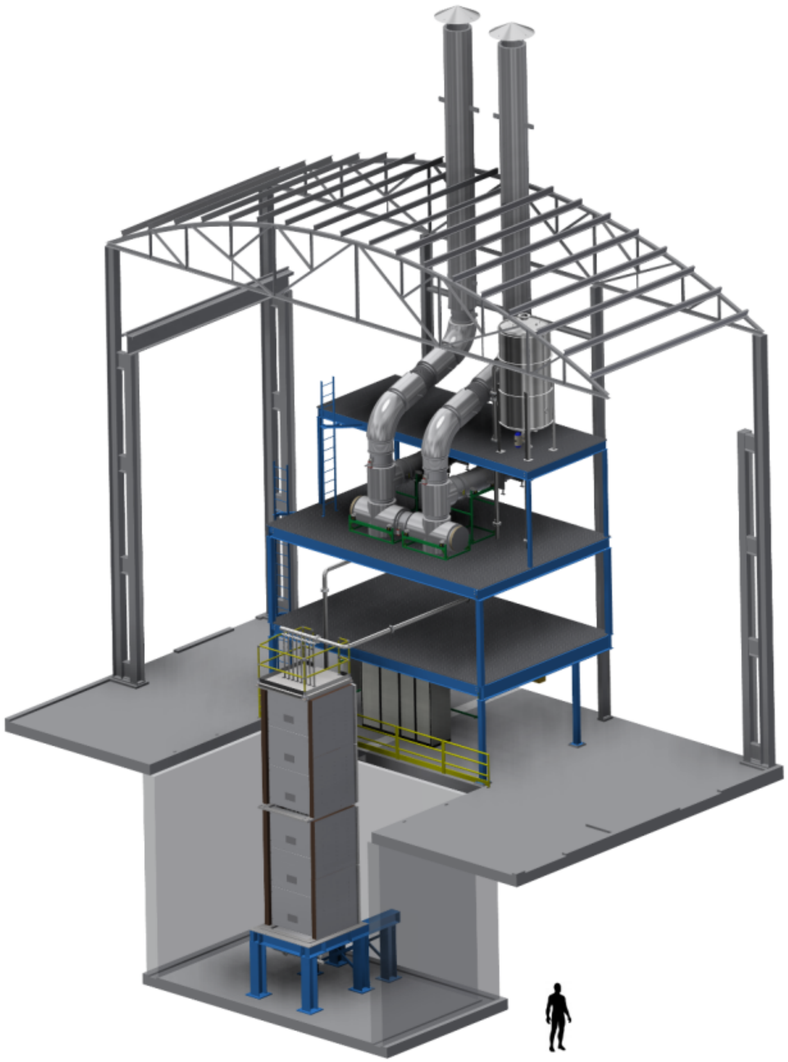
Air, 2010 – 2016



Water, 2017+

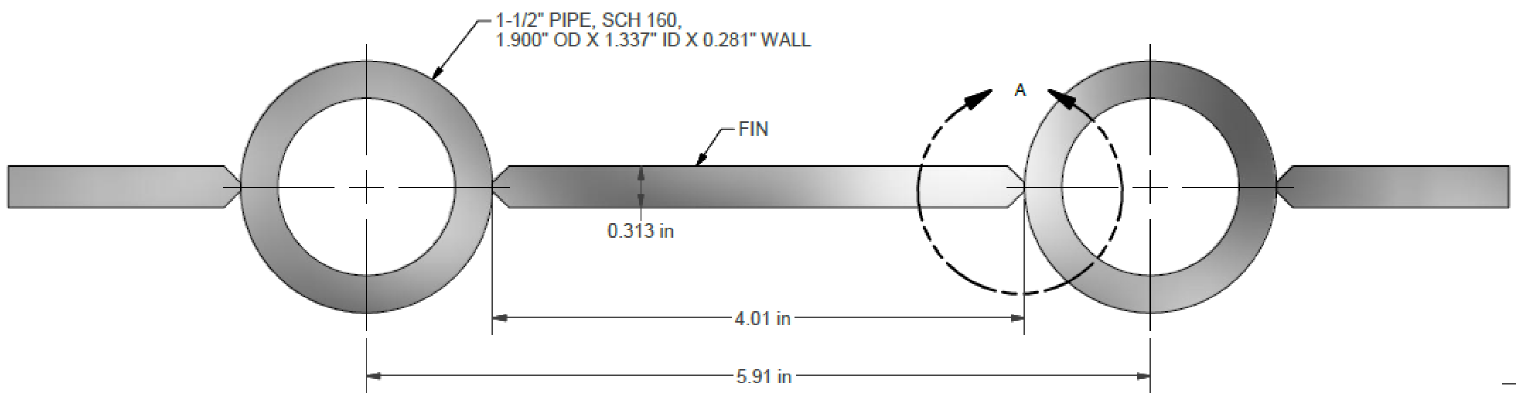
Water Facility Overview

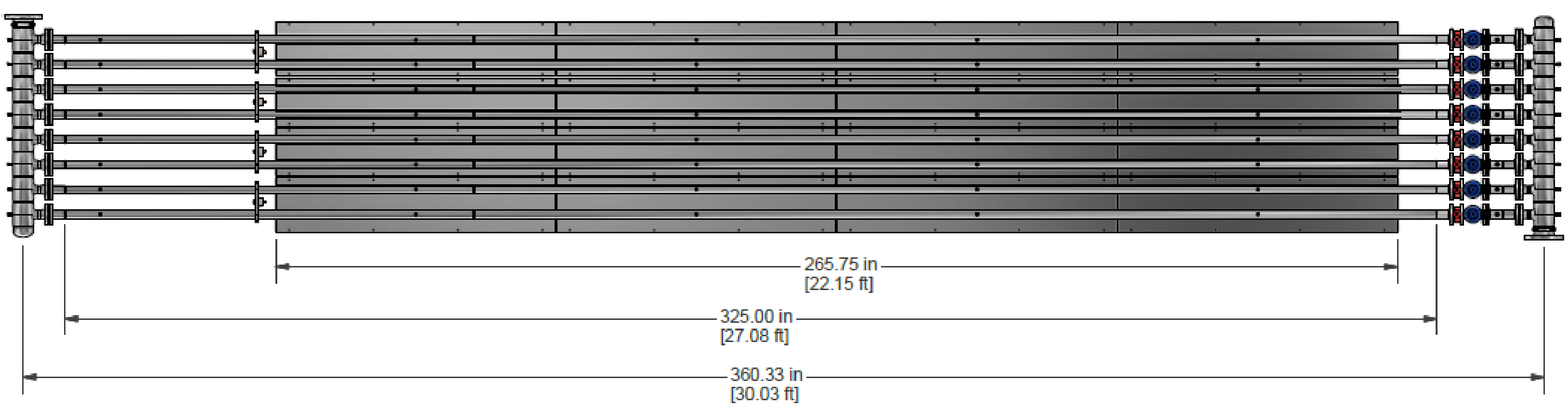
- ½ axial scale
  - Total height of 18 m (59-ft)
  - Heated length of 6.7 m (22-ft)
- Natural circulation boiling water test loop
  - Operating modes of natural or forced
- 4,260 liter water storage tank
  - H/D ratio of 2.0, rated to 2 bar over pressure
- Heat transfer panel:
  - Eight riser tubes and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



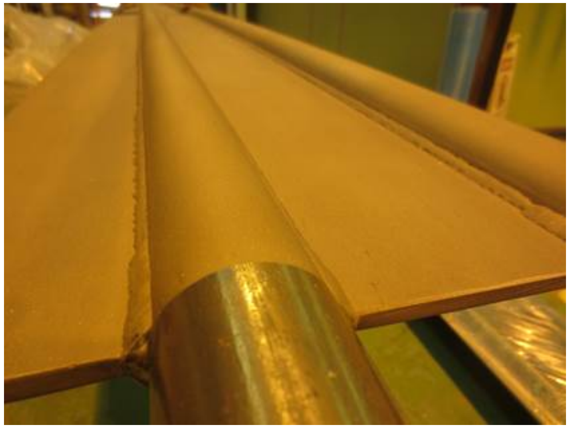
Cooling Panel Design

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

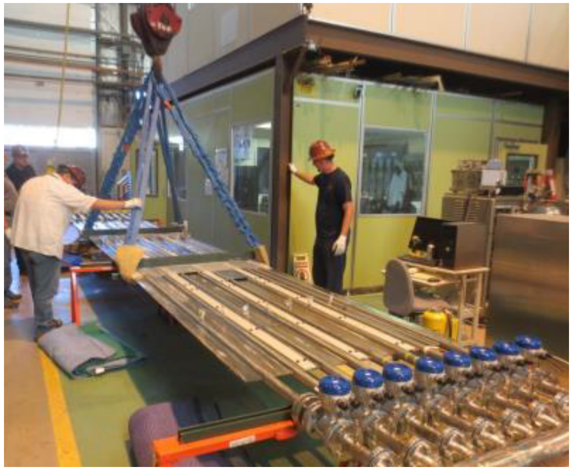




Cooling Panel Installation



Bead blasted cooling panel surface



Assembled panel staged for 180° flip

Panel hoisted vertical prior to install

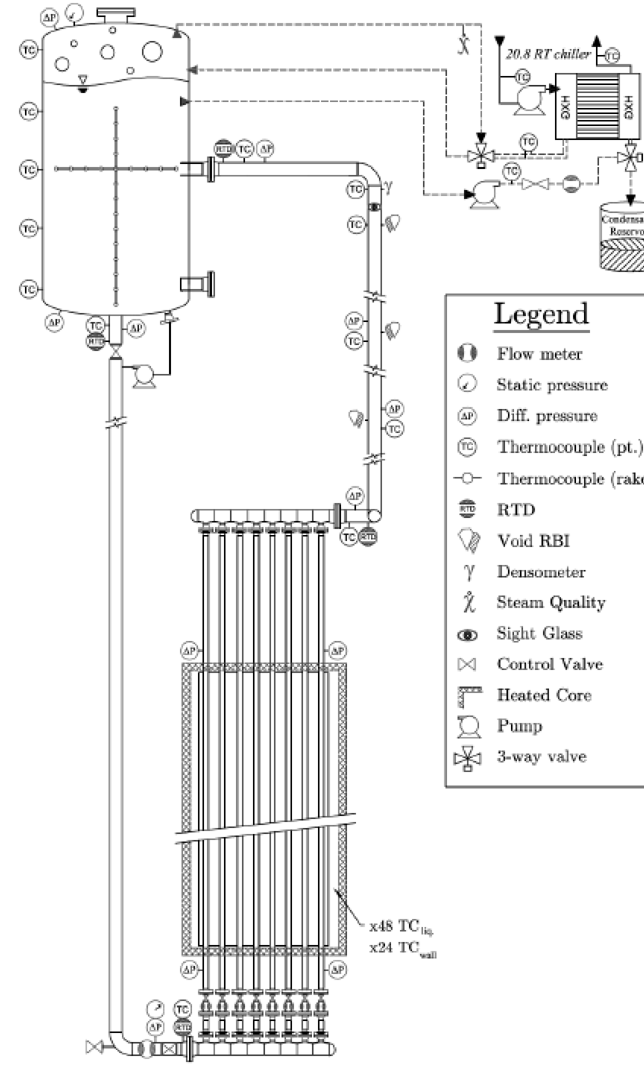
Installed test section, view in heated cavity

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 densometer

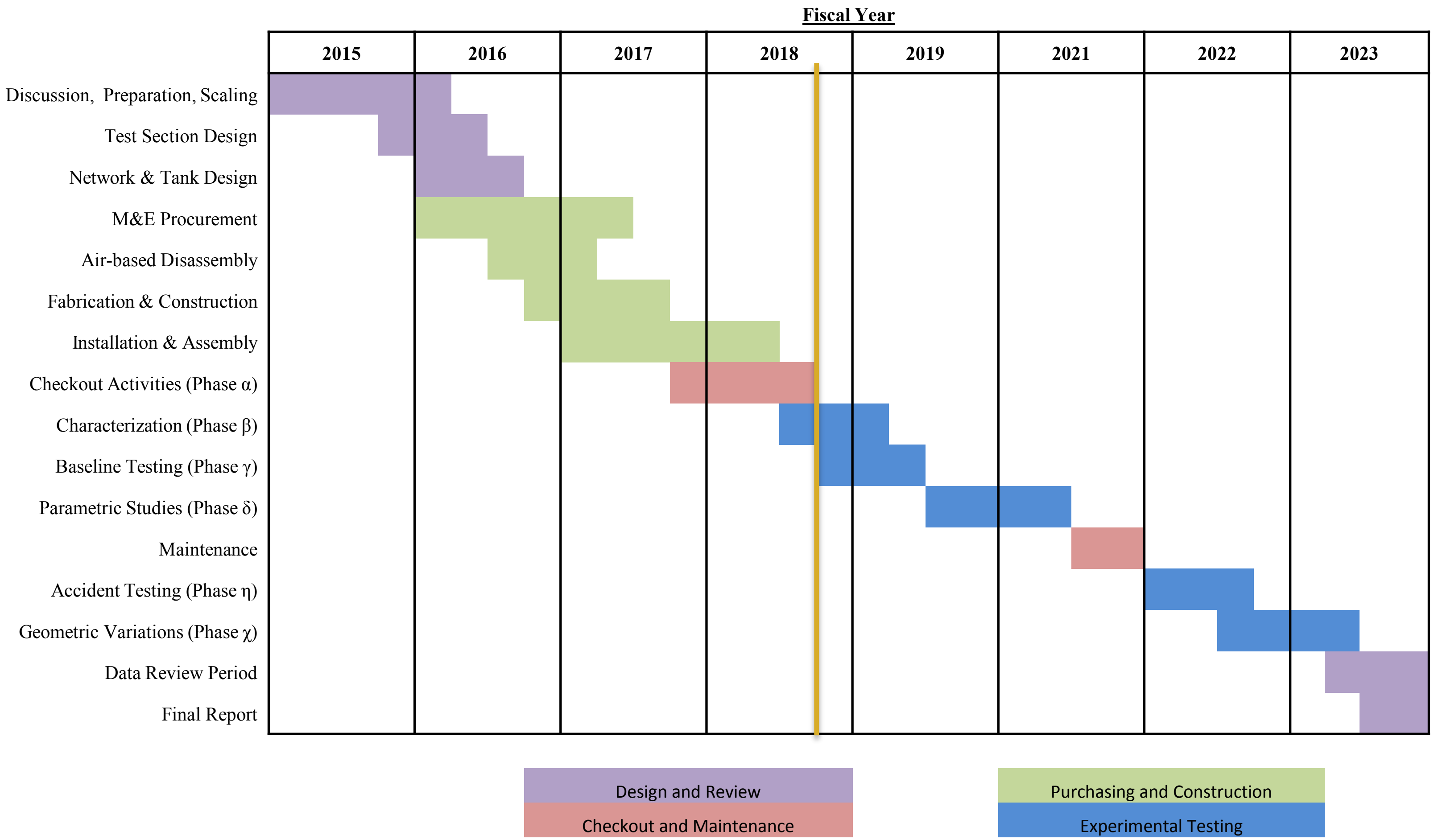


Path forward for Water Testing

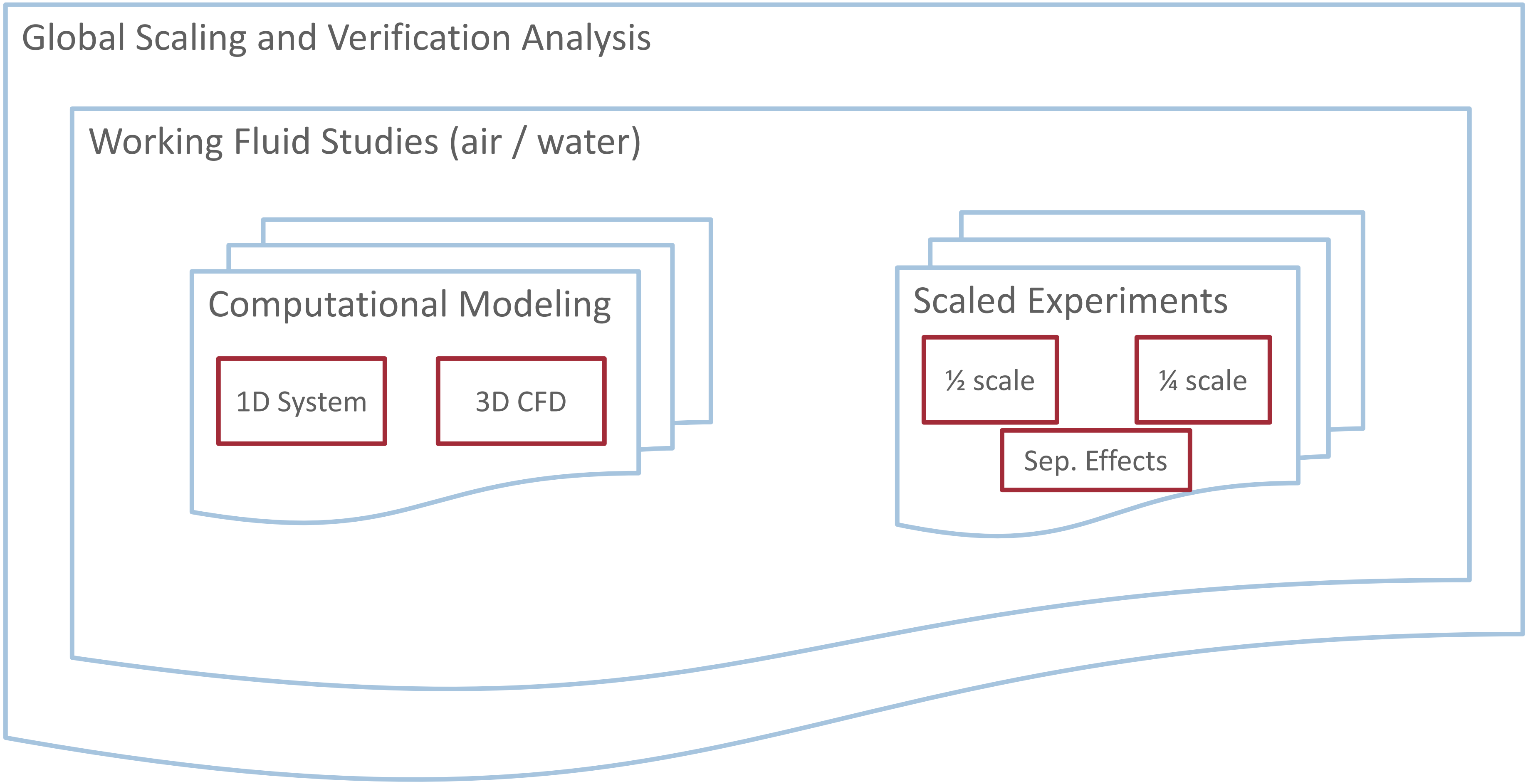
- Basis and detail of test planning included in ANL-ART-98 (M2, August 2017)
  - Checkout activities are in-progress
- Test planning & review meeting has been held prior to initiating matrix testing
  - Invitation included programs to key players
- External audit of program and test procedures prior to initiating matrix testing
  - Completed without any findings
- Baseline testing to begin by FY2019
- Continue communication with industry & NRC

Phase	Activities Conducted	Duration
I	Power, electrical, data acquisition checkout, hydrostatic leak testing	6 mo.
II	Gross system mass and energy balance, isothermal testing	9 mo.
III	Single- and two-phase baseline test cases	6 mo.
IV	Single parameter variations of power, inventory, pressure	24 mo.
V	Accident scenarios (design-basis)	6 mo.
VI	Geometric variations, off-normal scenarios	12 mo.

Water Program Timeline



Realization of Full Scale Deployment of the RCCS



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Questions?

http://www.ne.anl.gov/capabilities/rsta/NSTF