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U.S. High Temperature Materials Highlights

March 2022

Changing the World's Energy Future

Ting-Leung Sham

Idaho National Laboratory

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U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

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U.S. High Temperature Materials Highlights

GIF VHTR Materials PMB Meeting, Virtual
March 9, 2022

Advanced Reactor Technologies Program

Advanced Materials R&D

Sam Sham

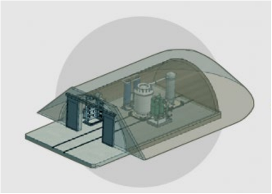
Idaho National Laboratory

U.S. Gas-cooled Reactors Program Status

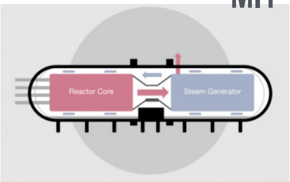
- U.S. GIF VHTR work is continuing on graphite qualification, Alloy 617 regulatory issues beyond the Code space, Alloy 800H weldments, and ASME Codes and Standards
  - R&D is still considering both pebble bed and prismatic and steam generator and heat exchanger
- U.S. DOE Advanced Reactor Demonstration Program (ARDP)
  - Two U.S.-based teams were selected to demonstrate advanced nuclear reactors in the United States that can be operational by 2027
    - One of the teams is X-energy (Rockville, MD) which will demonstrate a modular gas-cooled reactor design (Xe-100) with four 80 MWe, TRISO fuel, pebble bed reactors
  - A number of U.S.-based teams were selected to design and develop safe and affordable reactor technologies that can be licensed and deployed over the next 10 to 14 years (Risk Reduction)
    - One of the teams is BWXT Advanced Technologies, LLC which will develop a commercially viable transportable microreactor with the design focused on using TRISO fuel particles and silicon carbide (SiC) matrix
  - A number of U.S.-based teams were selected to assist the progression of advanced reactor designs in their earliest phases (Advanced Reactor Concepts-20)
    - One of the teams is Massachusetts Institute of Technology which will mature the Modular Integrated Gas-Cooled High Temperature Reactor (MIGHTR) concept with a horizontal compact design from a pre-conceptual stage to a conceptual stage to support commercialization

X-Energy

BWXT



MIT



Components of the High Temperature Alloys Program

- High Temperature Design Methodologies
  - *EPP design methods*
  - New EPP+SMT creep-fatigue evaluation method
  - *Constitutive models for inelastic analysis design method*
- Addressing Potential Regulatory Issues
  - *Transition of notch strengthening to notch weakening creep rupture behavior*
  - New weld consumable to improve creep rupture resistance of Alloy 800H weldment
  - Mechanical properties of diffusion welded Alloy 617 sheets to support compact heat exchanger applications
- Generation IV International Forum Materials Handbook
  - Support handbook infrastructure

Modernization of Division 5 High Temperature Design Methods

- EPP methods represent a significant advancement of the Division 5 design evaluation methods
  - Intended as an alternative to the elastic analysis methods and used as simplified "screening" tools
  - No stress classification and stress linearization are required
    - Significant simplifications
  - Applicable for any geometry or loading and over full temperature range
  - Simpler to implement and easily adaptable to modern finite element technology

Design Methods	Status
• EPP Strain Limits Code Case • EPP Creep-Fatigue Code Case	• Rev 1: Alloy 617, Type 304H and 316H stainless steels • Rev 2: Grade 91 • Rev 3: Alloy 800H, 2.25Cr-1Mo
• EPP Primary Load Code Case	• Alloy 617, 304H, 316H, Alloy 800H, Grade 91, 2.25Cr-1Mo

Development on Inelastic Analysis Methods

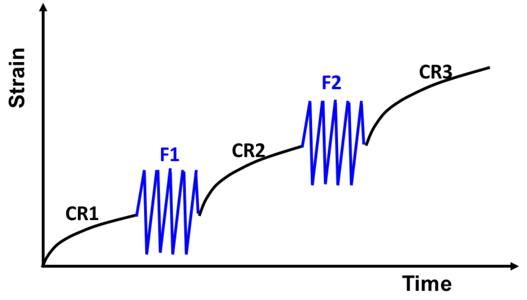
- Current Division 5 status
  - Division 5 does not provide reference inelastic models for any of the Class A materials
  - Specification of the material model left to owner’s Design Specification or designers
  - Limits application of the inelastic rules
    - Significant barrier to use inelastic analysis methods to support licensing effort
- Historical experience on the Clinch River Breeder Reactor Project shows that inelastic analysis is:
  - The least over-conservative of the Division 5 design evaluation options
  - Necessary in critical locations where design by elastic analysis is too conservative to produce a reasonable design

Design Methods	Status

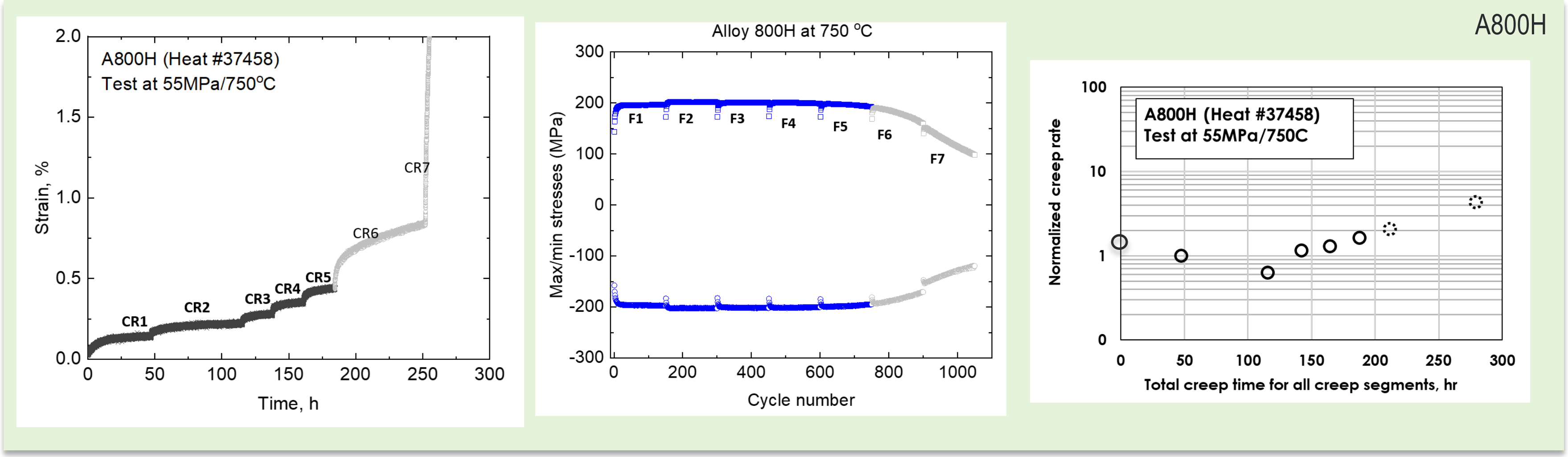
• Division 5, Appendix HBB-Z,
  • Inelastic Analysis Methods
  • Viscoplastic Constitutive Models
	• Rev 1: General guidance, Grade 91 model
	• Rev 2: Alloy 617 and 316H models
	• Rev 3: Alloy 800H model

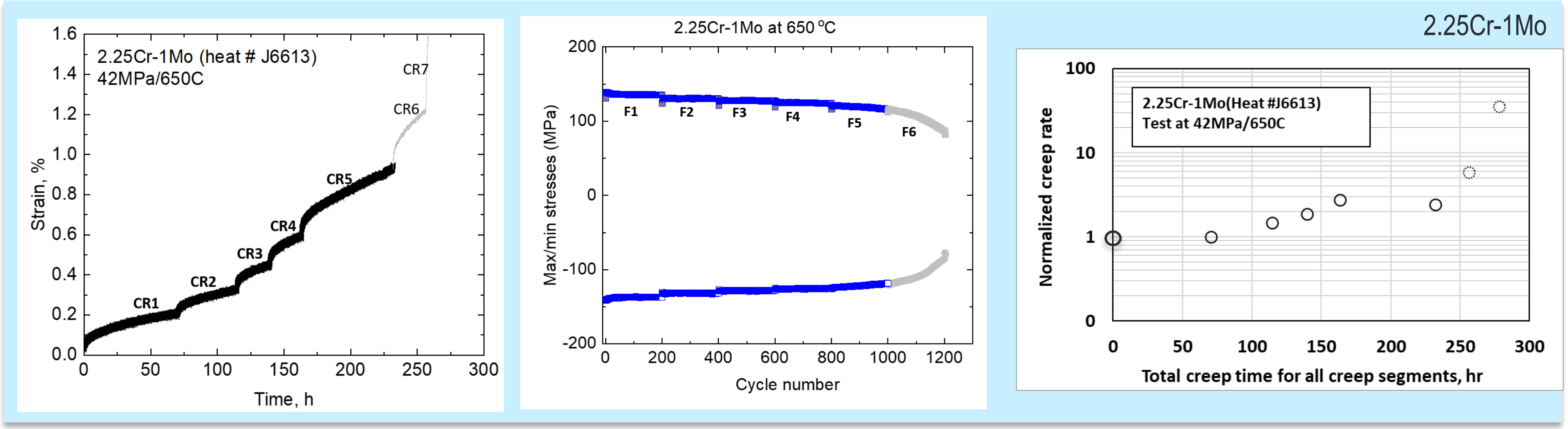
Added Alloy 800H and 2.25Cr-1Mo to Code Case N-861 (EPP Strain Limits CC)

Schematics of the sequential creep and fatigue experiments

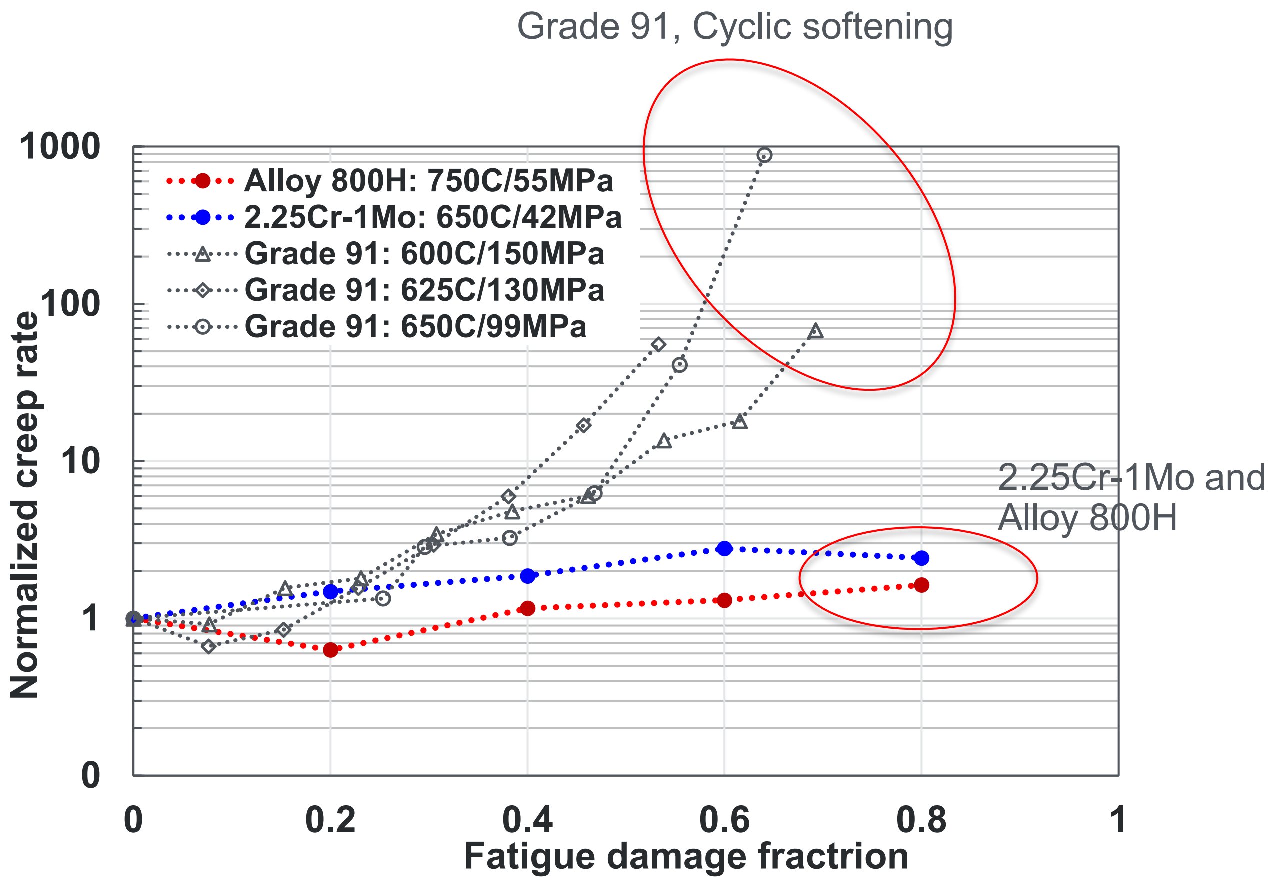


- Fatigue loading segments are introduced to a standard creep test
- Effects of fatigue loading on the creep rates of each creep segments are evaluated





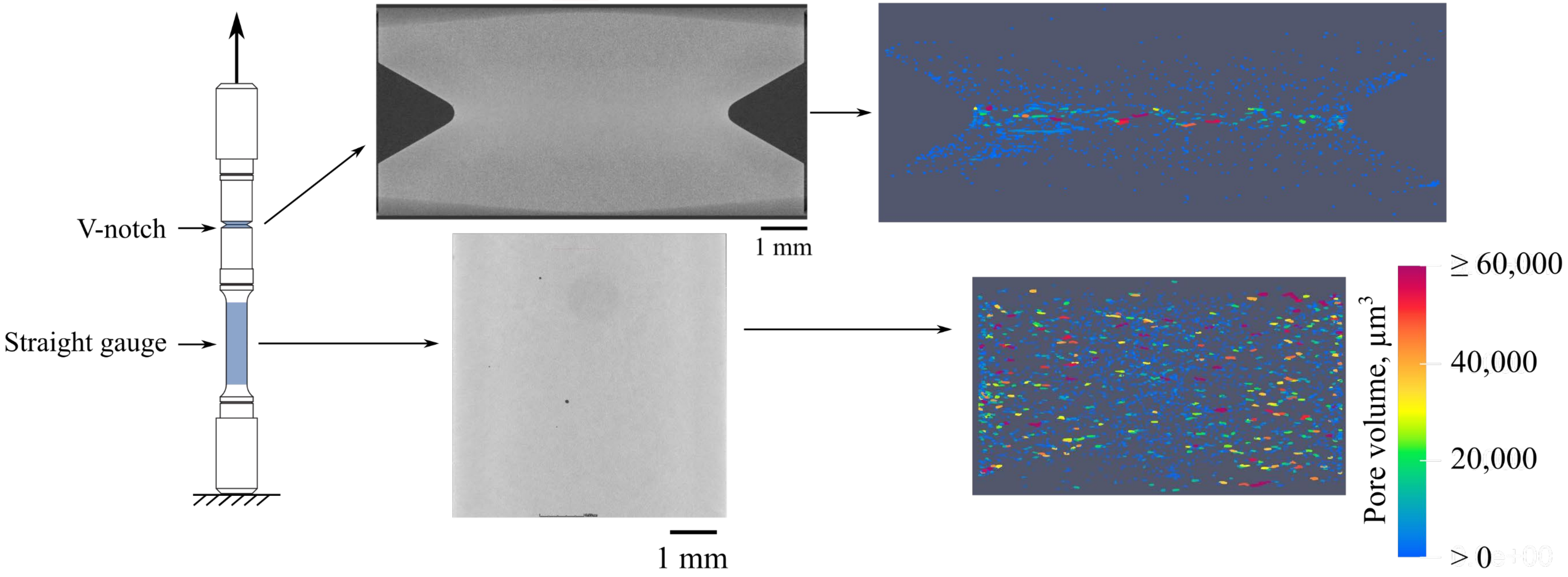
Comparison with Cyclic Softening Material (Grade 91)



- Prior cyclic deformation has an insignificant effect on the minimum creep rates for Alloy 800H and 2.25Cr-1Mo
- Reduction factors on the isochronous stress strain curves are not recommended when incorporating Alloy 800H and 2.25Cr-1Mo to the EPP analysis suite

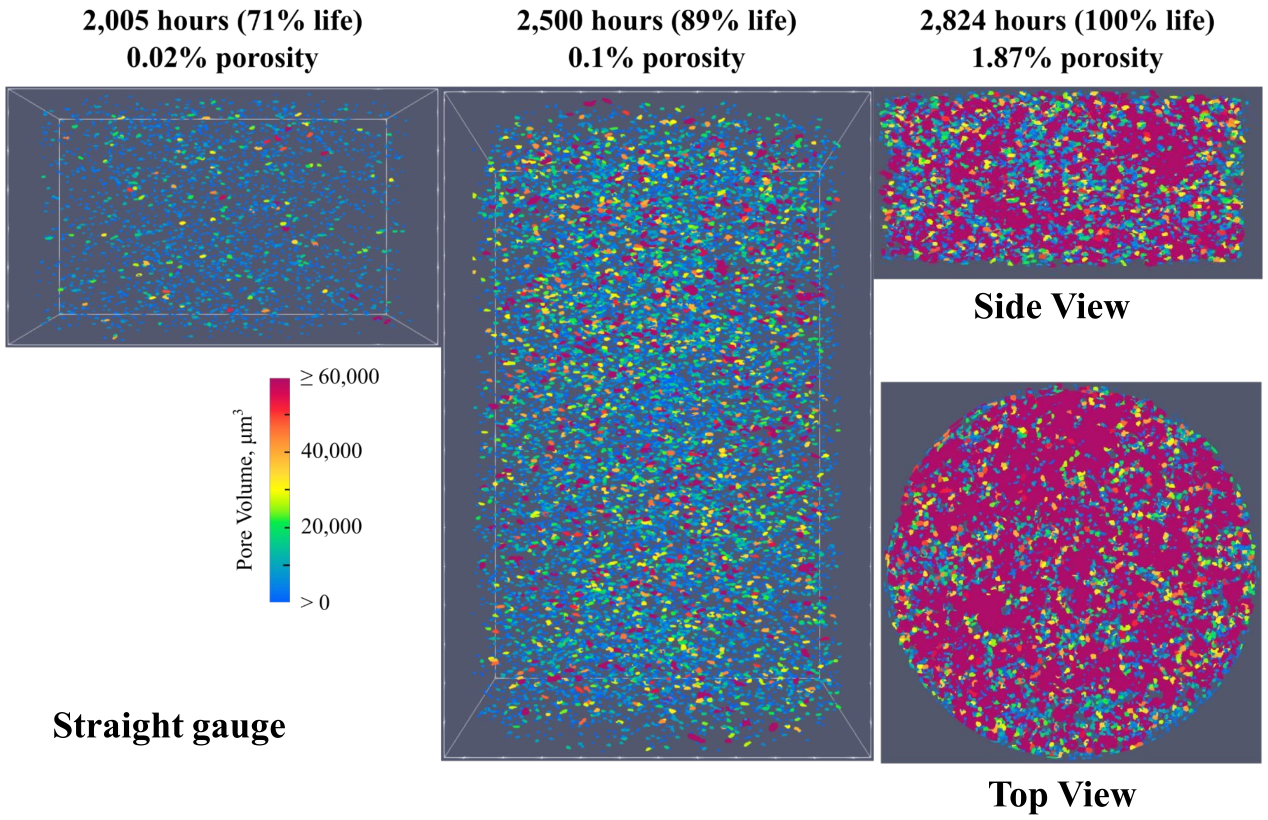
X-Ray CT Characterization Technique

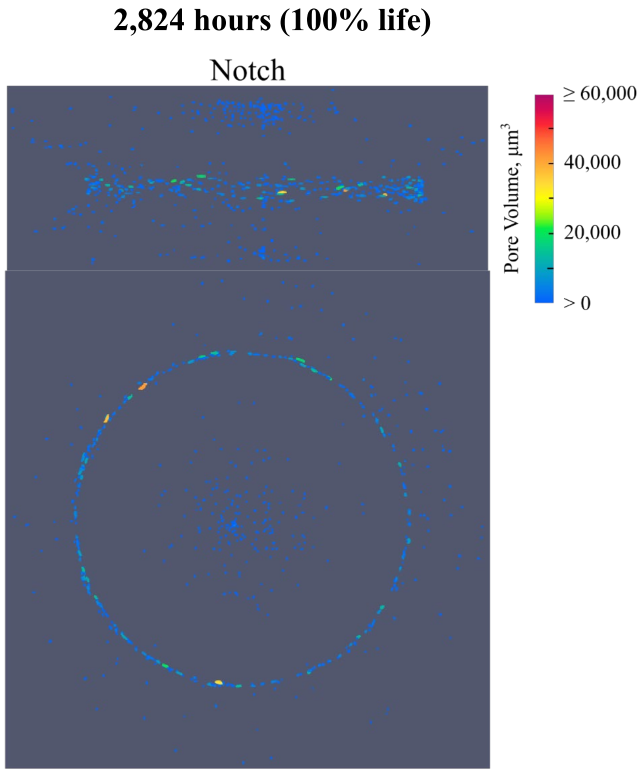
- A technique utilizing X-ray computed tomography (CT) was developed with the goal of being able to identify the failure location prior to rupture



X-Ray CT Characterization of Baseline V-notch Creep Test

- A base-metal V-notch specimen tested at 800℃ and 65.3 MPa ruptured in the straight gauge. As the test progressed, the number and size of the cavities increased. Damage in the notch was primarily limited to surface at the notch tip.

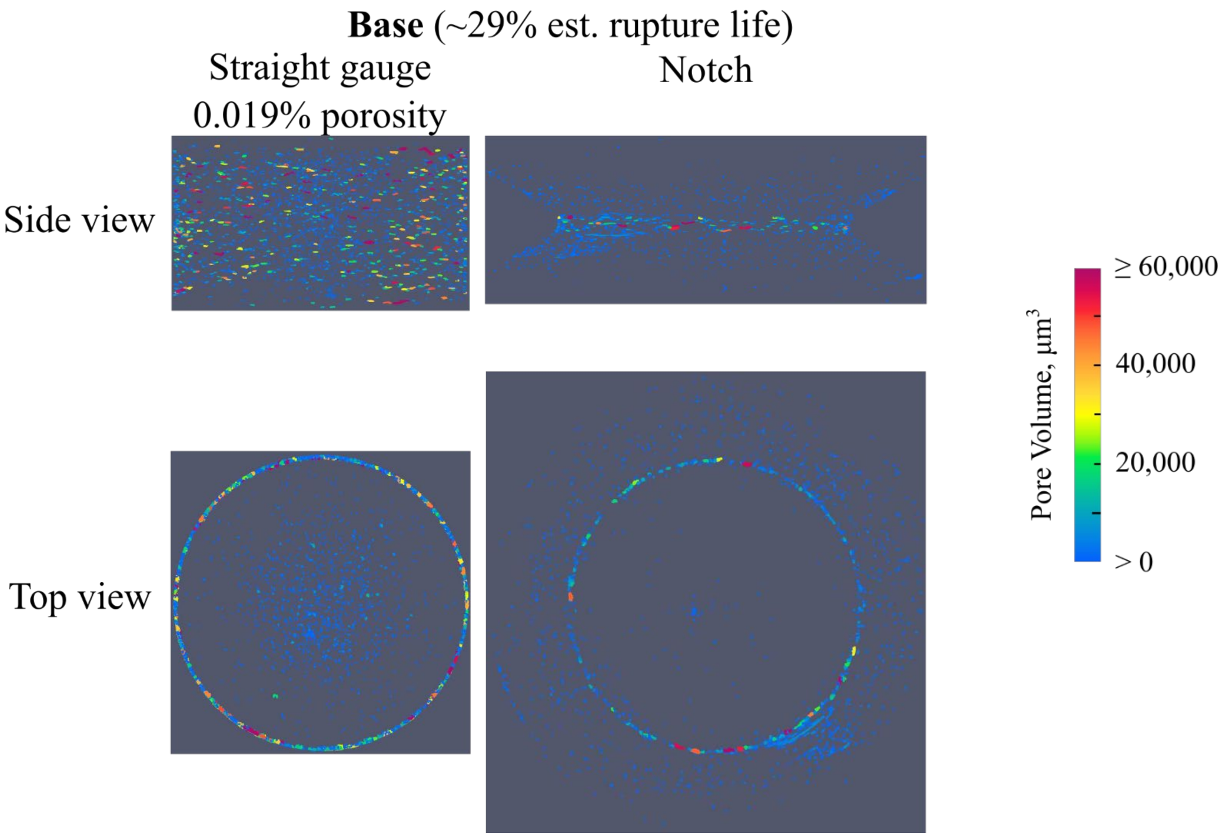




X-Ray CT Characterization of Long-Term V-notch Creep Test

- Creep damage in both the straight gauge and notch has been primarily limited to the surface for the base-metal specimen

800℃, 35 MPa 100,000-hour estimated rupture life



U.S. Graphite Program: Progress since September 2021

Licensing & Code

- Establishes an ASME approved code (for 1st time)
- Develops property values for initial components and irradiation induced changes

Behavior models

- Predicts irradiated material properties and potential degradation issues
- Irradiation behavior for continued safe operation

Graphite R&D Program

Defines the safe working envelope for nuclear graphite and protection of fuel

Virgin Properties

- (Statistically) Establishes as-received material properties
- Baseline data used to determine irradiation material properties

Mechanisms and Analysis

- Data analysis and interpretation
- Understanding the damage mechanisms is key to interpreting data

Irradiation

- Determines irradiation changes to material properties
- Irradiation behavior for continued safe operation

Unirradiated Graphite Properties

- Baseline (unirradiated) material properties
  - As-manufactured material property data for all major AGC graphite grades
    - Baseline to changes resulting from irradiation, oxidation, molten salt interaction
  - Unirradiated data being used for ASME code rules
    - Developing graphite qualification rules for nuclear applications
    - Sensitivity studies on unirradiated material properties

- Used for graphite qualification data in new reactor construction

Graphite	Laboratory	Billet #	Percent Complete					Data Report	Analysis Reports
			Machining	Mass and Density	Elastic Testing	Mechanical Testing	Thermal Testing		
PCEA	ORNL	XPC01S8-11	100%	100%	100%	100%	100%	ORNL	ORNL
PCEA	INL	XPC02S8-7	100%	100%	100%	100%	100%	ECAR-3725	INL/EXT-13-30011
PCEA	INL	XPC01S8-9	100%	100%	100%	100%	100%		INL/EXT-14-33120, INL/EXT-13-30011
PCEA	INL	XPC02S8-5	100%	100%	100%	100%	100%		INL/EXT-14-33120, INL/EXT-13-30011
PCEA	INL	XPC01D3-35	Sectioned	0	0	0	0		
PCEA	INL	XPC01D3-36	100%	100%	100%	100%	100%	ECAR-3677	INL/EXT-16-39604
PCEA		Multiple Other Billets Available							
NBG-18	INL	635-4	100%	100%	100%	100%	100%	ECAR-3726	INL/EXT-14-33120, INL/EXT-13-30011
NBG-18	INL	635-14	100%	100%	100%	100%	100%	ECAR-1930	INL/EXT-10-19910, INL/EXT-13-30011
NBG-18	ORNL	635-6	100%	100%	100%	100%	100%	ORNL/TM-2010/219	INL/EXT-13-30011, ORNL/TM-2010/219
NBG-18		Multiple Other Billets Available							
2114	INL	A20568	100%	100%	100%	50%	100%		
2114	INL	A20570	100%	100%	100%	100%	100%	ECAR-4322	INL/EXT-14-33120
2114	ORNL								
2114		Multiple Other Billets Available							
NBG-17	INL	830-3	100%	100%	100%	100%	100%	ECAR-3727	INL/EXT-14-33120
NBG-17	INL	005-04							
IG-110	INL	08-9-052 (Partia	100%	100%	100%	100%	100%	ECAR-3621	INL/EXT-14-33120
IG-110	INL	10X69	100%	100%	100%	100%	100%	ECAR-4182	
IG-110	INL	10X63							
IG-430		08-Y-38							

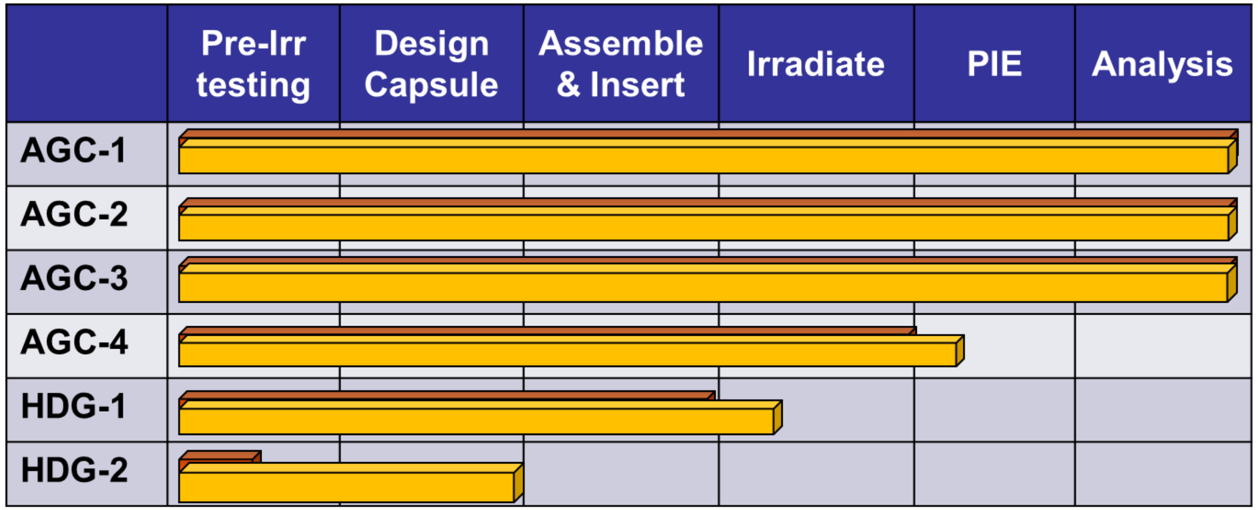
Complete 2022

Initiated 2022

Irradiated Graphite Properties

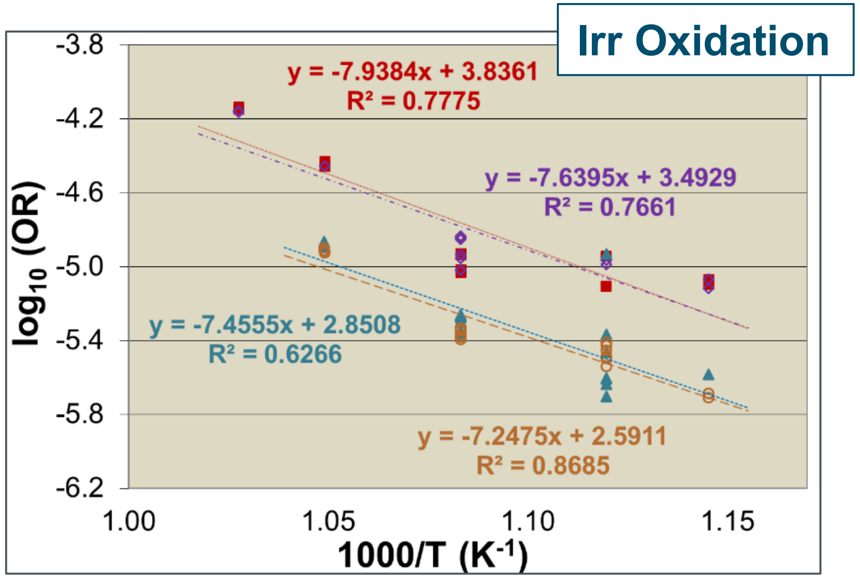
AGC Experiment Status:

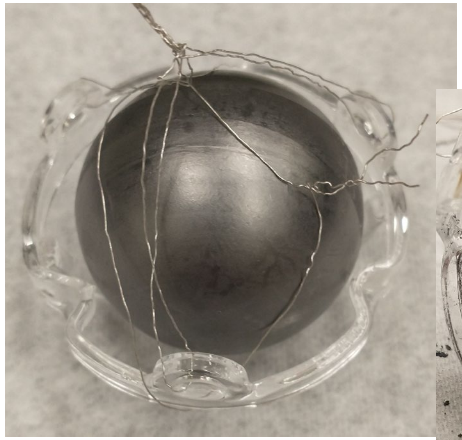
- **AGC-1 & AGC-2 :** 600C (0.5 to 7 dpa)
  - Initial irradiation, PIE, and analysis is complete
- **AGC-3 :** 800C (0.5 to 3.5 dpa)
  - Initial irradiation, PIE, and analysis is complete
- **AGC-4 :** 800C (3 to 8.5 dpa)
  - Irradiation complete (February 2020)
  - Disassembled July 2021
  - ***PIE has begun*** (2022-2023)
  - Analysis and data to Handbook (2022)
- **HDG-1 :** 600C (7 to 15 dpa)
  - ***Back in reactor***: 2 more years = 15 dpa
  - Re-irradiation of AGC-2 specimens
- **HDG-2 :** 800C (7 to 15 dpa)
  - Design of irradiation capsule initiated
  - Irradiation begins 2024
  - Re-irradiation of AGC-3 & -4 specimens to max. 15 dpa



Dave Rohrbaugh, Will Windes, and W. David Swank, "HDG-1 Graphite Pre-Irradiation Data Package Report", August 2020

Degradation of Graphite

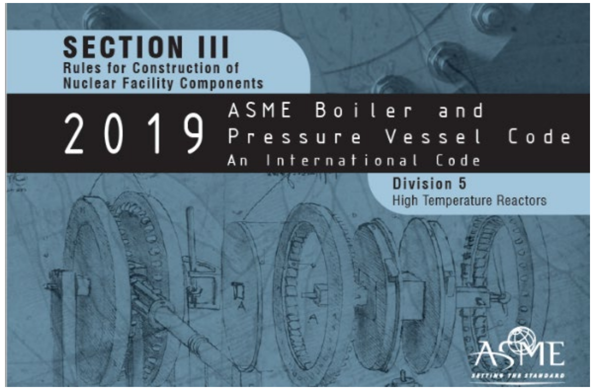




Degradation studies

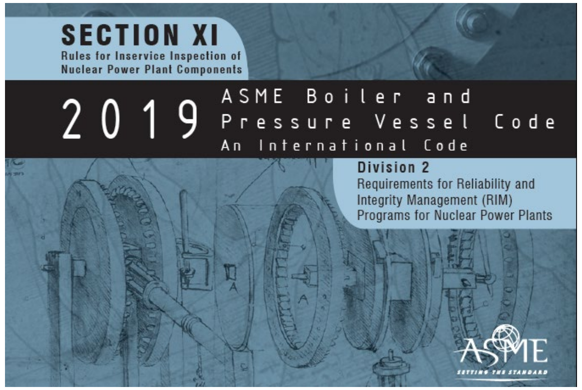
- Oxidation rate of irradiated graphite
  - ***2 to 3 times faster rate for 6 dpa.***
  - Draft peer-reviewed paper by end of 2022.
- Oxidation material property degradation
  - Results published and used for ASME code rule changes
  - Material property changes from oxidation
    - ***Initial studies complete. Report end of 2022***
- Oxidation of pebble fuel matrix (Kairos collaboration)
  - Pebble oxidation rate studies
  - Pebble oxidation penetration studies
  - Pebble/fuel matrix strength reduction
- GIF High Level Deliverable (HLD)
  - Completed summary of all oxidation results for all GIF contributors
    - ***USA, EU, China, Japan, S. Korea***

Graphite Code Rules and Test Standards



- **Progress in ASME Code development**
  - Latest updates on ASME graphite and composite code development
  - Laundry list of new areas of optimization from NRC assessment (Task Groups)
    - Defining failure criteria
      - Clarification of probability of failure (POF) assessment
    - Oxidation rate and effects on structural performance
    - Addition of irradiation data and trends to code rules
    - Addition of molten salt code rules

- **Reliability and Integrity Management (RIM)**
  - Many of these new rules are not applicable for construction rules (Section III)
  - Discussing new rules within Section XI, Division 2 (RIM)
    - Long term degradation rules
    - RIM data required to determine failure
      - RIM data to determine if failure has occurred
  - End-of-life irradiation and oxidation degradation rules



U.S. Baseline and AGC Data: NDMAS Portal

ART
ADVANCED REACTOR TECHNOLOGIES

The DOE-ART Graphite R&D program

The DOE-ART Graphite R&D program is the primary nuclear graphite research program for the USA. This program focuses on research and development activities necessary to qualify and license graphite components for use within nuclear applications, specifically within advanced reactor designs such as High Temperature Reactor designs. The data generated within the ART Graphite program is intended to be used in conjunction with other publicly available nuclear graphite data such as is contained within the IAEA Nuclear Graphite Knowledge Base. The ART Graphite program is divided into 5 primary research areas providing a combination of data, analysis reports, and pertinent references to describe and explain the trends within the data.

- **Unirradiated (Baseline):** Establish as-manufactured (Baseline) values for unirradiated material properties that can be used to determine the quantitative changes during irradiation and degradation during nuclear applications.
- **Irradiation (AGC Experiment):** Establish evolution of material property changes due to irradiation dose and temperature. The AGC Experiment is an irradiation creep experiment which provides creep data for selected graphite grades.
- **Degradation:** Establish effects of irradiation, oxidation, and molten salt interaction on graphite behavior.
- **Behavior models:** Predictive and degradation models for graphite behavior.
- **Licensing and code:** Papers and data supporting ASME code development and NRC license assessment.

Baseline (Unirradiated)

AGC (Irradiated)

Degradation

Behavior Models

Licensing (ASME/NRC)

IAEA

- **New portal to U.S. graphite data – Now ready (maybe)**
  - Front page (shown) is available at: www.ndmas.inl
  - Unirradiated (Baseline) data is complete (data available soon – days?)
  - Irradiated database in 2022 (hopefully)

Questions

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