July 26, 2023

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DOE ART Graphite Program

Status 2023

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

ART
Advanced Reactor Technologies

Graphite Program Contributors to this discussion

Researcher	Expertise
Andrea L. Mack andrea.mack@inl.gov	ASME Code
Anne Campbell campbellaa@ornl.gov	PIE, Irradiation damage, Irradiation behavior
Arvin Cunningham arvin.cunningham@inl.gov	Oxidation, Split-disk testing
Austin C. Matthews austin.matthews@inl.gov	Material property testing, PIE, Oxidation
David T. Rohrbaugh david.rohrbaugh@inl.gov	Unirradiated and Irradiated material properties
Jose' D. Arregui-Mena arreguimenjd@ornl.gov	Microstructure, irradiation damage
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Researcher	Expertise
Mary Kaye Aimes marykaye.ames@inl.gov	Oxidation, Material testing
Michael E. Davenport michael.davenport@inl.gov	Irradiation experiments
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Philip L. Winston philip.winston@inl.gov	Irradiation experiments
Rebecca E. Smith rebecca.smith@inl.gov	Graphite oxidation (irr. and unirr)
Steve Johns Steve.johns@inl .gov	Irradiation damage, Characterization, Split-disk
William Windes william.windes@inl.gov	Irradiation behavior, ASME
Wilna Geringer geringerjw@ornl.gov	ASME, Composites, Graphite

Five different research areas

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

As-Fab'd 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

FY23 Graphite Activities

Capsule Irradiation

- HDG-1 Irr
- HDG-2 Design
- HDG-2 Sample order

PIE

- AGC-4 Disassembly
- Sample Transport
- AGC-4 PIE
- Irradiation Behavior

50% to 65% of program funding

Characterization

- Baseline
- Licensing ASME
- ASTM Dev
- Oxidation
- Oxidation Properties
- Oxidation Resistance
- Thermal Creep
- HT Mech Testing
- Modeling
- Matrix Oxidation
- Irradiation Damage
- Graphite Microstructur
- Carbon Lab Upgrade
- Split Disc

Data

- NDMAS
- Graphite Analysis Tool
- University Collaborations
- Vendor Collaboration
- IAEA/EDF Collaboration
- N. Graphite Specification
- DOE/EPRI Graphite Rpt
- Supply Chain

ASME

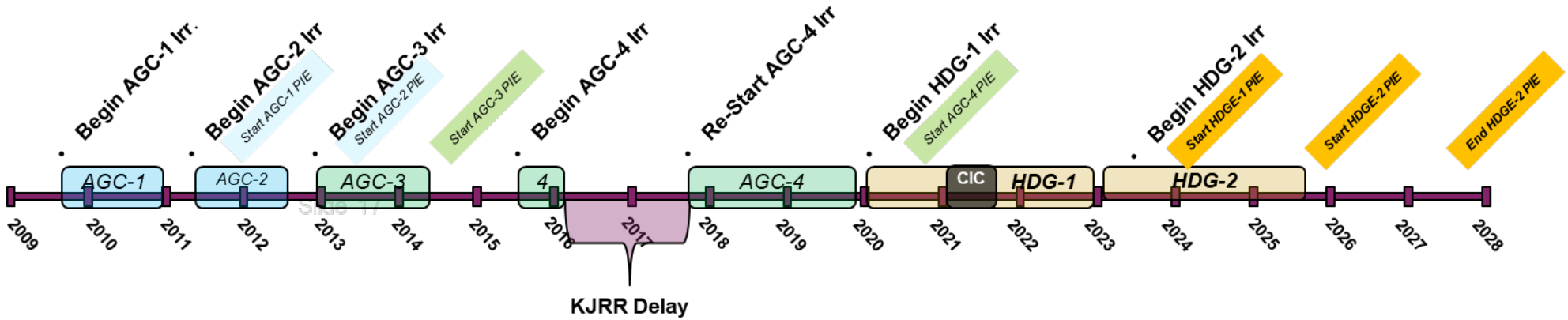
- Irrdiation Response
- Design Rules
- Molten Salt
- Oxidation
- Definition of Failure
- RIM
- Composites

What are we discussing this year?

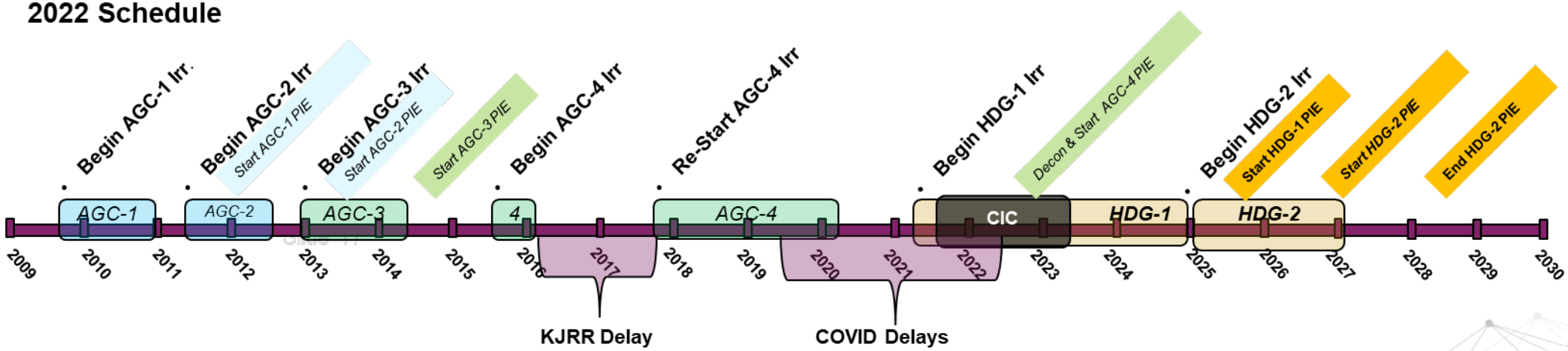
- **AGC Update**
- **Oxidation Activities**
  - *Oxidation rate, penetration/lathing, strength after oxidation*
- **Baseline Status**
  - *Data use in ASME and improved split-disc studies*
- **ASME Code Development:**
  - *Irradiation model*
  - *Ceramic Composites*
  - *Design task group*
  - *Component failure*
- **VIC Project Update**
- **Molten salt studies**
  - *We are initiating material interactions now*

Advanced Graphite Creep (AGC) Experiment *(Will Windes)*

2018 Schedule

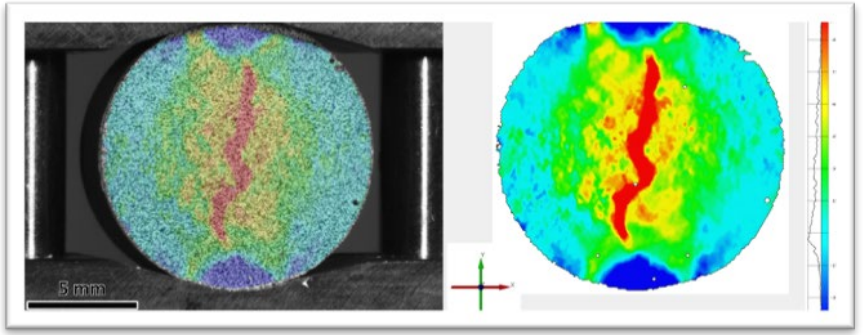


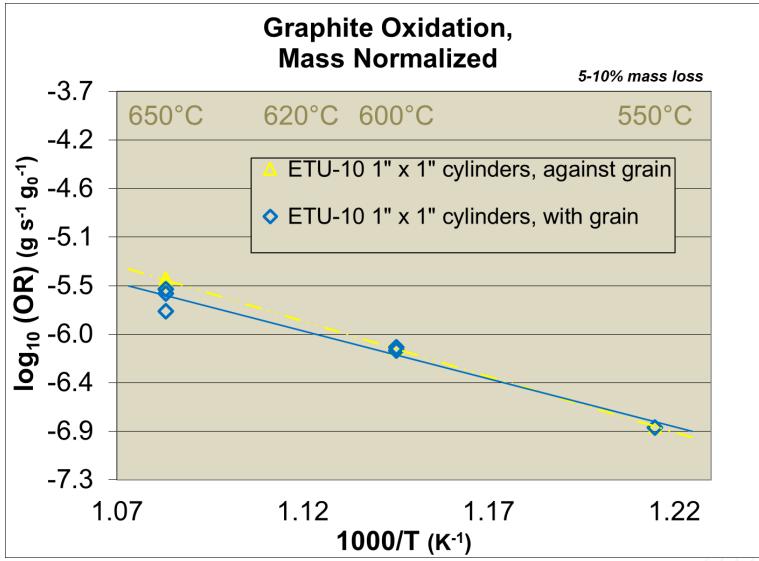
2022 Schedule

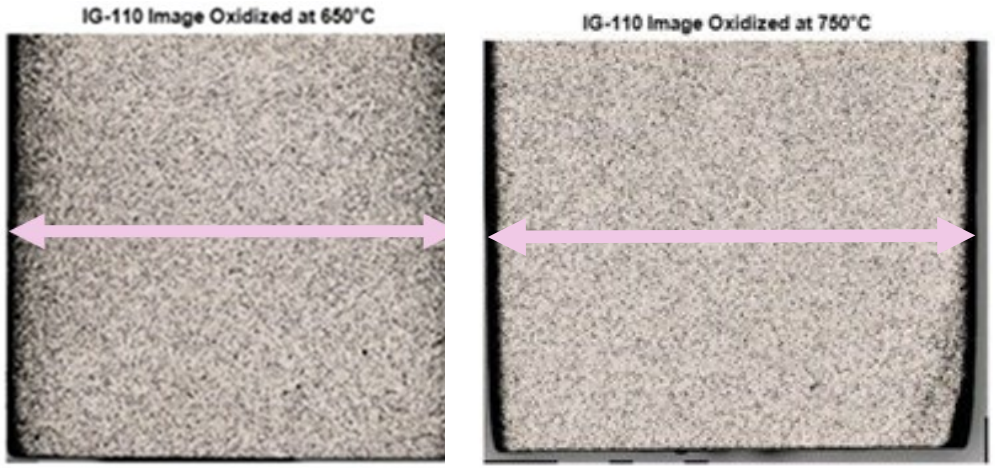


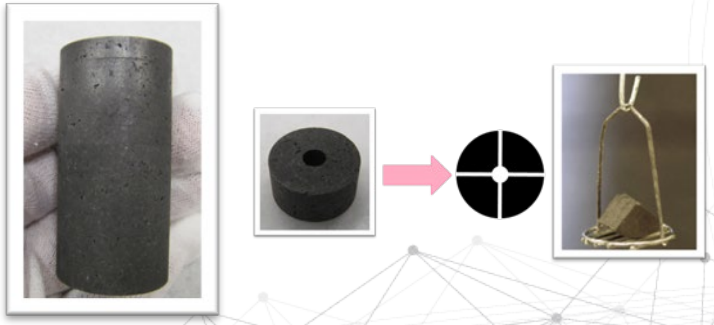
Oxidation Studies *(Rebecca Smith)*

- Large amount of work being performed
  - Oxidation rate work is minimal
  - Mostly ASME and ASTM involved work
    - Strength after oxidation
    - Oxygen penetration depth
    - Oxidation of MS grades
- Oxidation of irradiated graphite



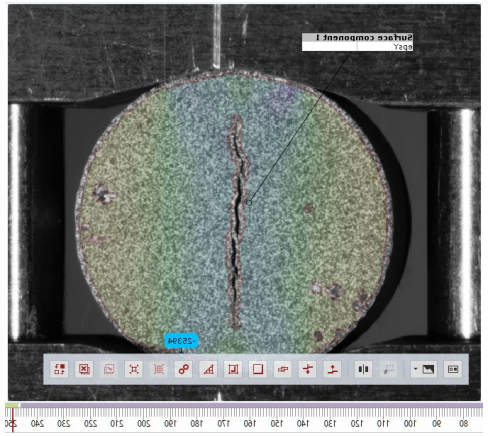






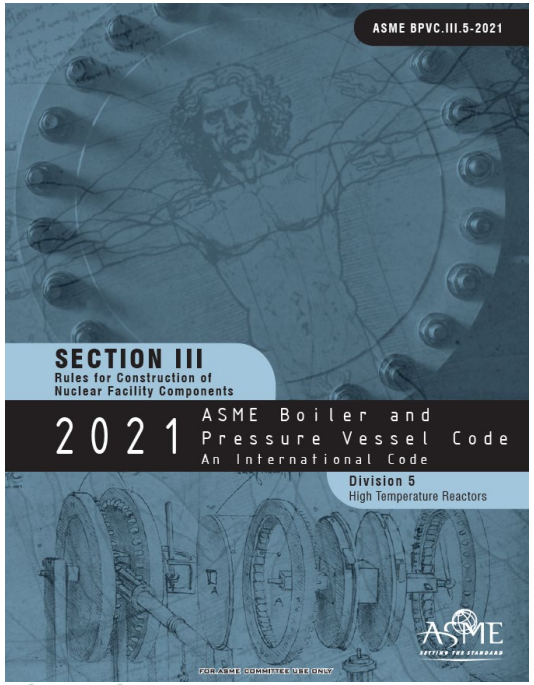
Baseline *(Arvin Cunningham)*

- Over 23,800 NQA-1 qualified measurements thus far
- 5 major graphite grades
- Focus is supporting other areas:
  - ***Irradiation: AGC***
  - ***ASTM: Split-disc testing (D8289)***
  - ***ASTM: High Temperature tests***
  - ***ASME code rule development***
  - ***Molten salt interactions***

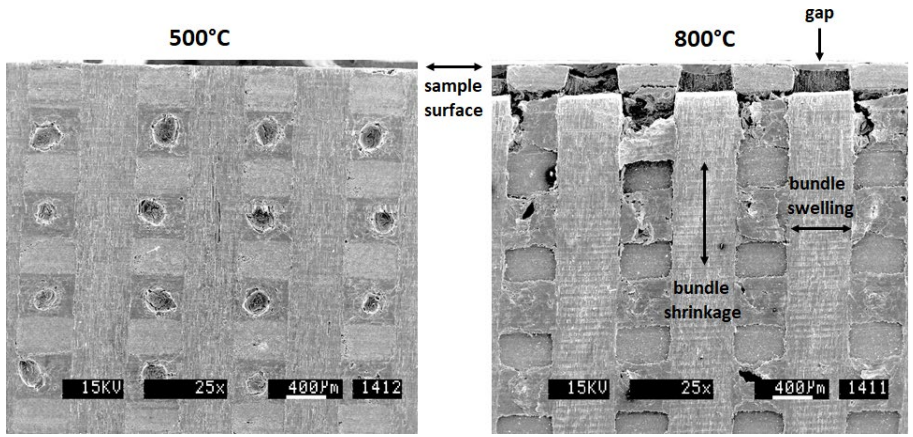


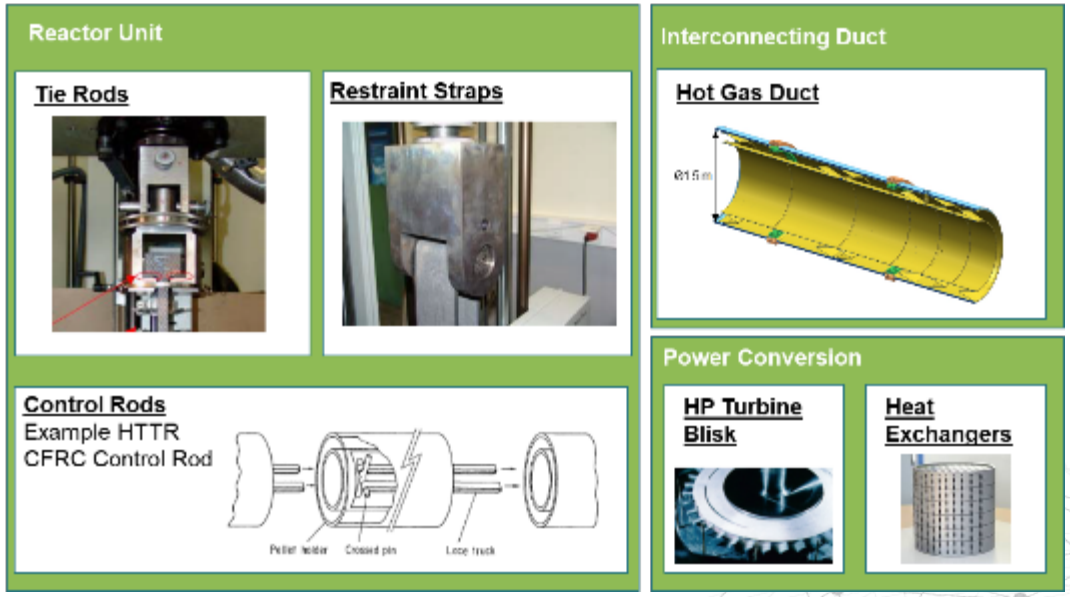
Graphite	Laboratory	Billet #	Percent Complete					Data Report	Analysis Reports	Data In NDMAS?
			Machining	Mass and Density	Elastic Testing	Mechanical Testing	Thermal Testing			
PCEA	ORNL	XPC01S8-11	100%	100%	100%	100%	100%	ORNL/TM-2015/765	ORNL/TM-2015/765	NO
PCEA	INL	XPC02S8-7	100%	100%	100%	100%	100%	ECAR-3725	INL/EXT-13-30011	YES
PCEA	INL	XPC01S8-9	100%	100%	100%	100%	100%	ECAR-6111	INL/MIS-23-70949	NO
PCEA	INL	XPC02S8-5	100%	100%	100%	100%	100%	ECAR-6110	INL/MIS-23-70951	NO
PCEA	INL	XPC01D3-35	66%							NO
PCEA	INL	XPC01D3-36	100%	100%	100%	100%	100%	ECAR-3677	INL/EXT-16-39604	YES
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	YES
NBG-18	INL	635-14	100%	100%	100%	100%	100%	ECAR-1930	INL/EXT-10-19910, INL/EXT-13-30011	YES
NBG-18	ORNL	635-6	100%	100%	100%	100%	100%	ORNL/TM-2010/219	ORNL/TM-2010/219	NO
NBG-18		Multiple Other Billets Available								
2114	INL	A20568	100%	100%	100%	100%	100%	ECAR-5798	INL/MIS-22-66680	NO
2114	INL	A20570	100%	100%	100%	100%	100%	ECAR-4322	INL/EXT-14-33120	YES
2114	ORNL	116310	100%	100%	100%	100%	100%	2018/1038, 2019/1256	ORNL/TM-2018/1038, ORNL/TM 2019/1256	YES*
2114		Multiple Other Billets Available								
NBG-17	INL	830-3	100%	100%	100%	100%	100%	ECAR-3727	INL/EXT-14-33120	YES
NBG-17	INL	V104	100%			33%				NO
IG-110	INL	089052-7	100%	100%	100%	100%	100%	ECAR-3621	INL/EXT-14-33120	YES
IG-110	INL	10X69	100%	100%	100%	100%	100%	ECAR-4182	ECAR-4182	NO

ASME: Component Failure *(Martin Metcalfe)*

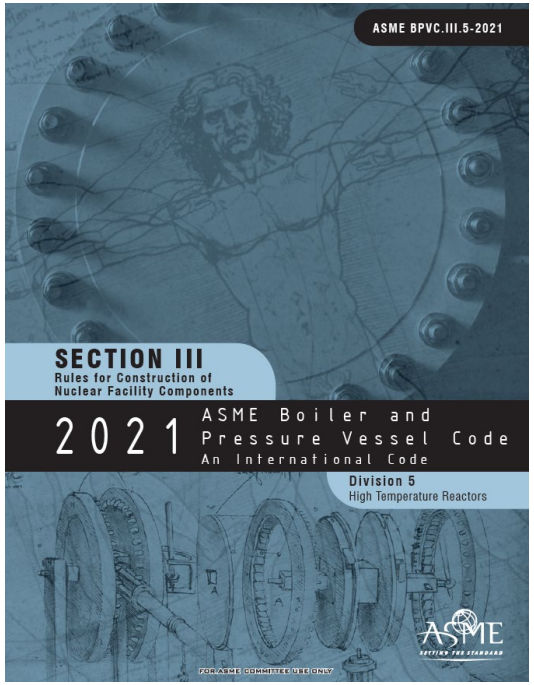


- Composite code development within ASME Section III Division 5 (HHB).
  - Approved in 2019 PBVC version
  - A nonmetallic but wholly different from graphite
    - *Highly directional (fiber orientation)*
    - *Specifically fabricated to design*
    - *Different failure behavior*
  - Initial rules require some modification





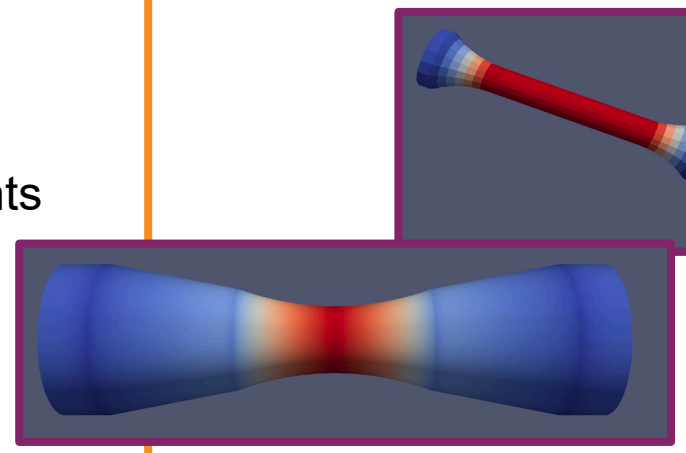
ASME: Design Rules *(Andrea Mack)*

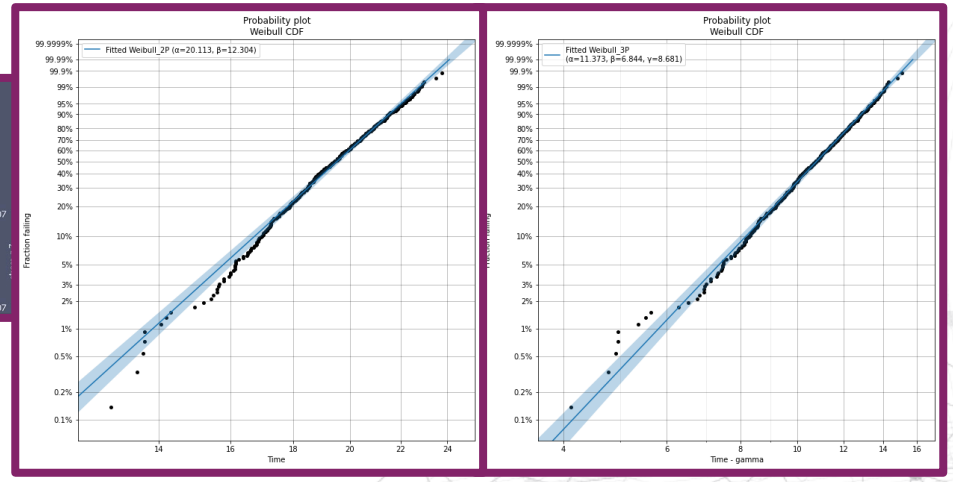


- Lead Task Group in Nonmetallics Working Group (NWG)
  - *Largest commercial vendor participation*
- Priority activity in ASME Section III
  - *Sec III-5 has designated NWG Design rule changes as a priority activity*
  - *Striving to get changes into **2025 ed. BPVC***
- Heavy use of Baseline data

Full Assessment
- Disparate flaw distribution
- Tuning V_m and Δ
- Mesh refinement
- Location
- Sample size requirements
- Margin

Simplified Assessment
- Stress terminology
- R_{tf}

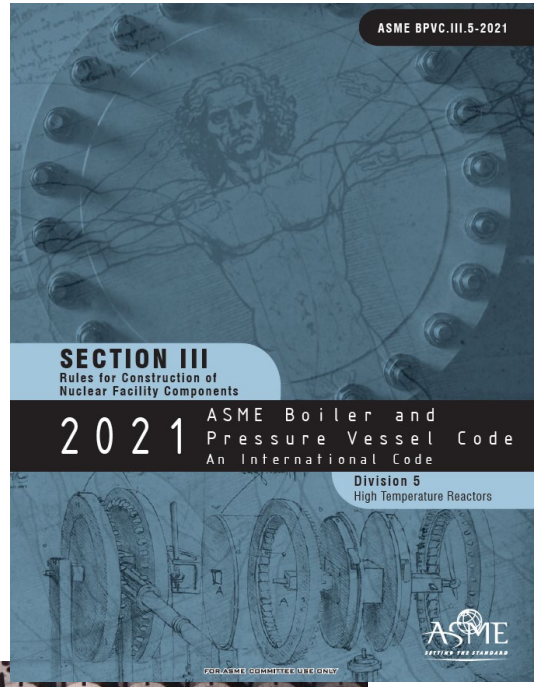


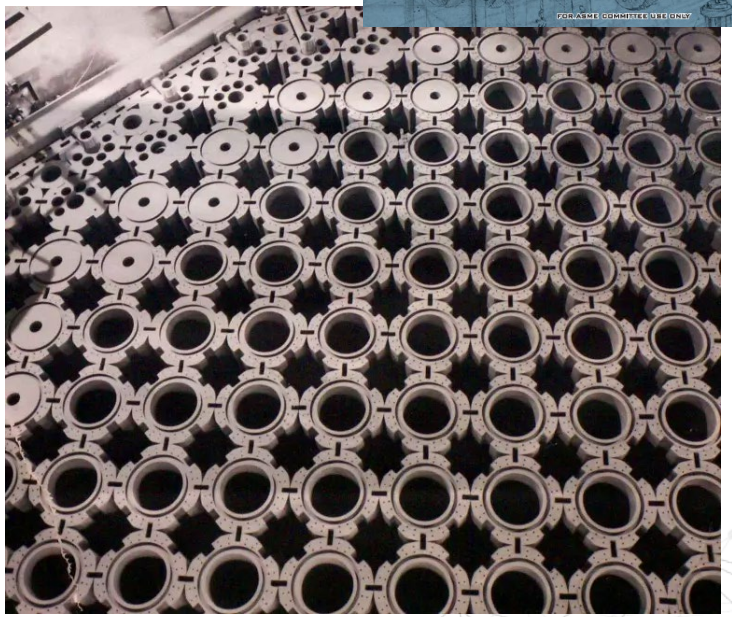


ASME: Component Failure *(Martin Metcalfe)*

- ASME Section III Division 5: Rules for Construction of Nuclear Facility Components (High Temperature Reactors)
  - Damage tolerance and component functionality
  - Review of damage tolerance in the graphite cores of UK power reactors
  - Clarification of terminology associated with component assessment methodologies

- ASME Section XI Division 2: Rules for Inservice Inspection of Nuclear Power Plant Components (Reliability and integrity management)
  - A new supplement covering graphite components in high temperature gas reactors

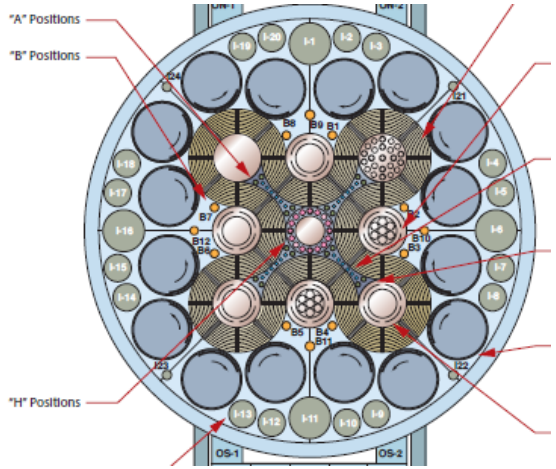




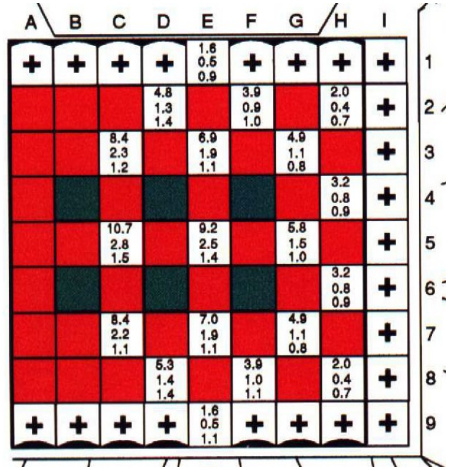
Vender Irradiation Capsule *(Will Windes)*

- What is the general idea
- Why is it needed?
- What are our options?
- What do the commercial vendors think?
- What is the next step

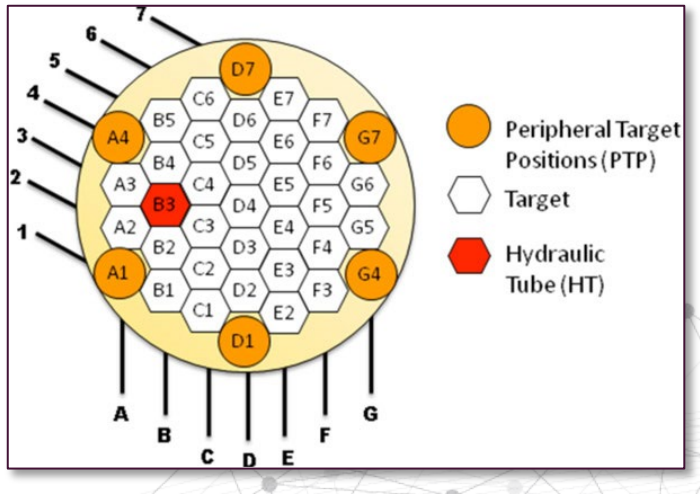
ATR



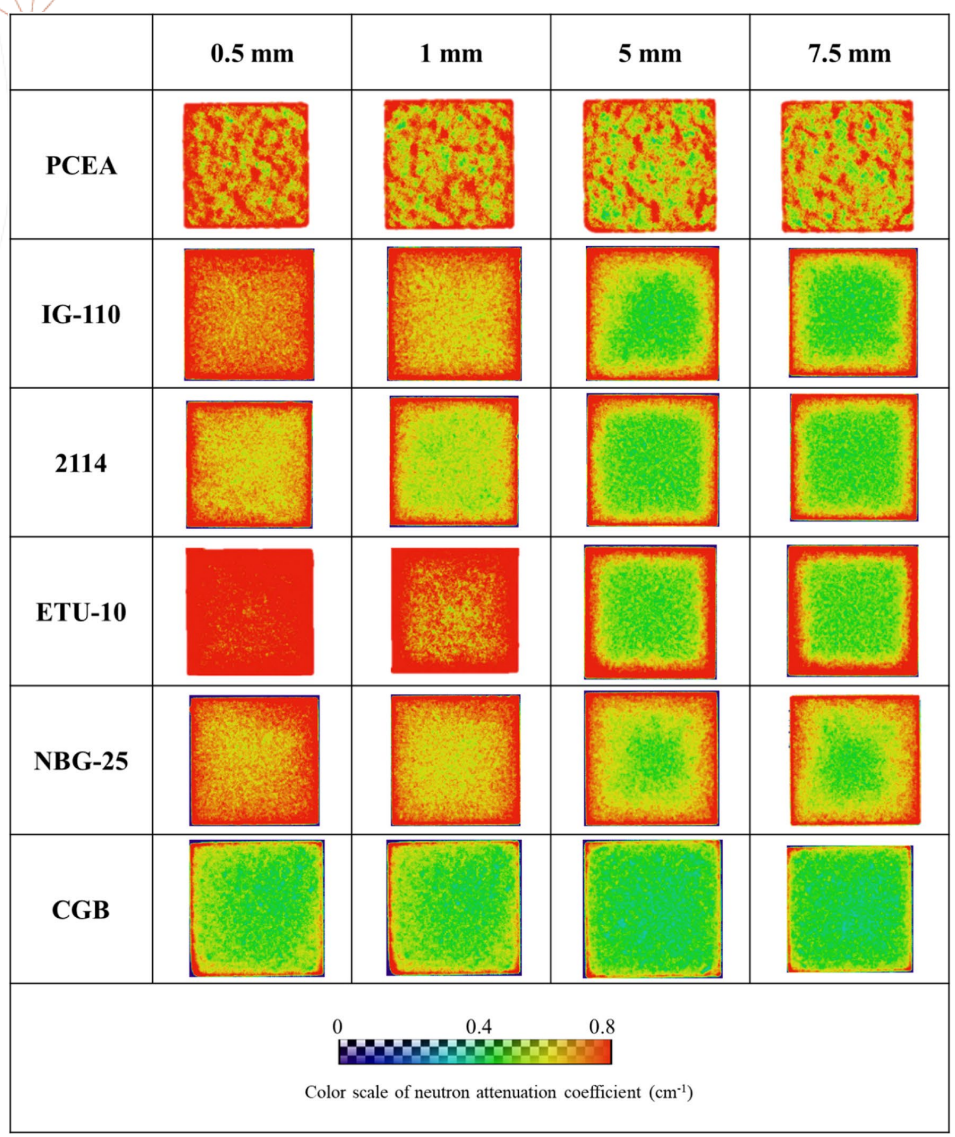
HFR (Petten)



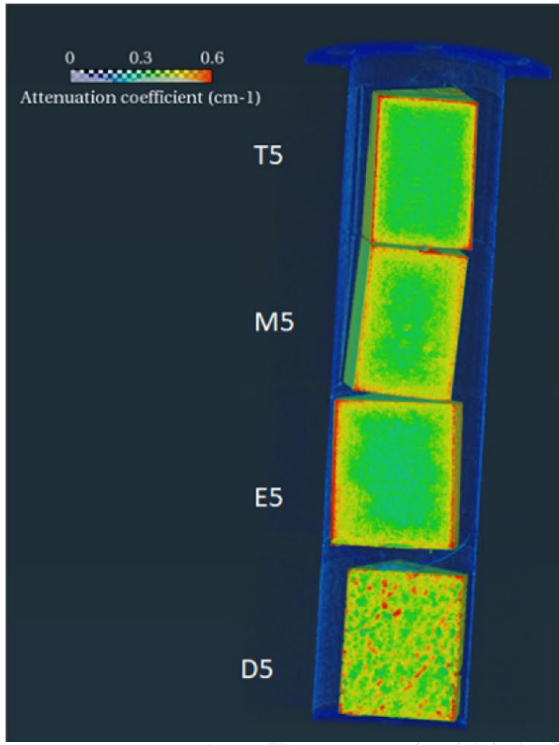
HFIR



Molten Salt – Graphite Interactions *(Nidia Gallego)*



- Molten salt is just another degradation mechanism for nuclear graphite
  - *Unirradiated and irradiated material behavior still occur*
- A status on initial molten-salt interaction studies
  - *MS penetration into graphite microstructure*
  - *Erosion/Abrasion*
- New funding molten salt – graphite interaction studies (no results yet)
  - *Enhance and complete results from these initial studies*



NEUP: New graphite research (Thursday, July 27th, 2023)

Advanced Reactor Component Materials Topics for FY21 NEUP Call

- RC X-Y. Effects of Irradiation Induced Microstructure Change in Graphite

1. Multiscale Effects of Irradiation Damage on Nuclear Graphite Properties
   - ***Aman Haque, Pennsylvania State University***

2. Quantifying the Dynamic and Static Porosity/Microstructure Characteristics of Irradiated Graphite through Multi-technique Experiments and Mesoscale Modeling
   - ***Jacob Eapen, North Carolina State University***