INL/MIS-24-79312-Revision-0

DOE ART Graphite R&D Introduction

July 2024

Changing the World's Energy Future

William E Windes

Idaho National Laboratory

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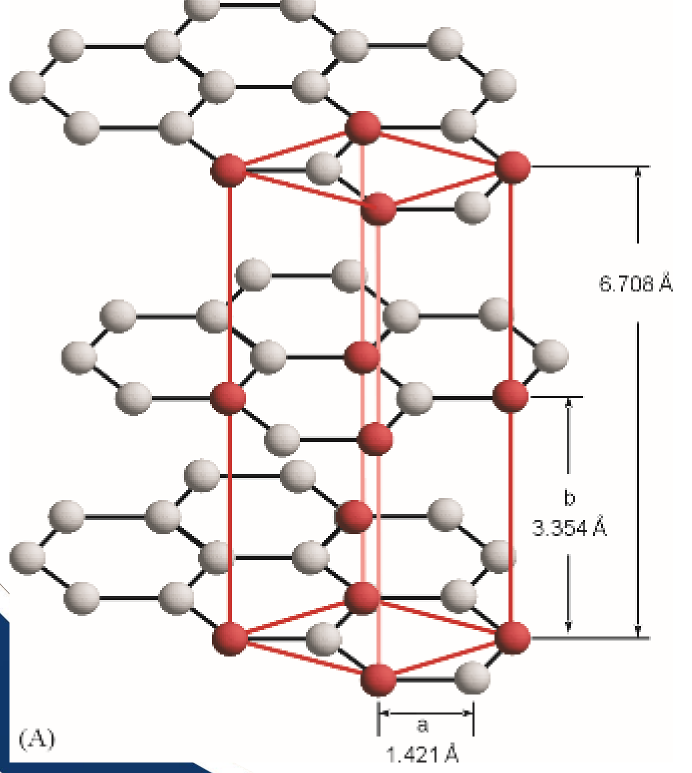
GAS-COOLED REACTOR
ADVANCED REACTOR TECHNOLOGIES PROGRAM



17-July-2024

DOE ART Graphite R&D Program

Will Windes

Graphite Technical Lead - INL

DOE ART GCR Review Meeting

Hybrid Meeting at INL

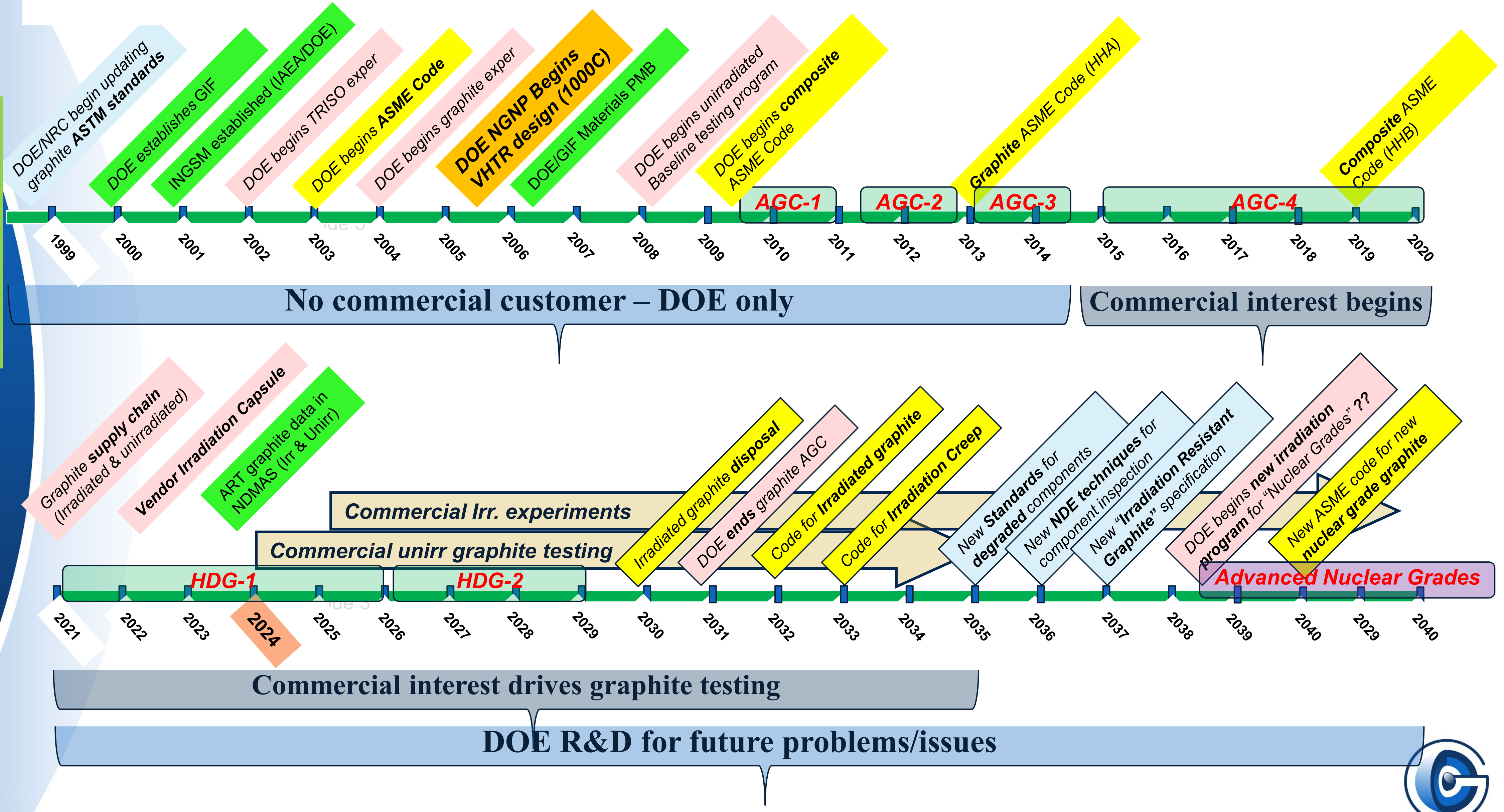
July 16–18, 2024

Graphite topics this FY24

Introduction	Will Windes
Oxidation Activities	Rebecca Smith
Oxidation resistant graphite	Tim Bragg/Michael Barkdull
Model Development	Veerappan Prithivirajan
Break (25 minutes)	
ASME Component failure	(Remote) Martin Metcalfe
ASME Code Development (Design rules)	Andrea Mack
Ceramic Composites	Wilna Geringer
Lunch (Graphite NEUP presentations) • *Multiscale Effects of Irradiation Damage on Nuclear Graphite Properties* • *Quantifying the Dynamic and Static Porosity/Microstructure Characteristics of Irradiated Graphite through Multi-technique*	• *Gongyuan (Patrick) Liu, Penn State University* • *Jacob Eapen, North Carolina State University*
AGC Update	Will Windes
Molten salt intrusion	Nidia Gallego
Split-disk Studies	Arvin Cunningham & Lianshan Lin
Wear testing	Tomas Grejtak
Concluding remarks	Will Windes

Some history and perspective on graphite component development

- *Magnox*
- *AGR (U.K.)*
- *THTR*
- *Ft. St. Vrain*
- *MHTGR*
- *NPR*
- *DOE Blue Ribbon Commission (1998)*



Five different graphite research areas

Licensig & 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

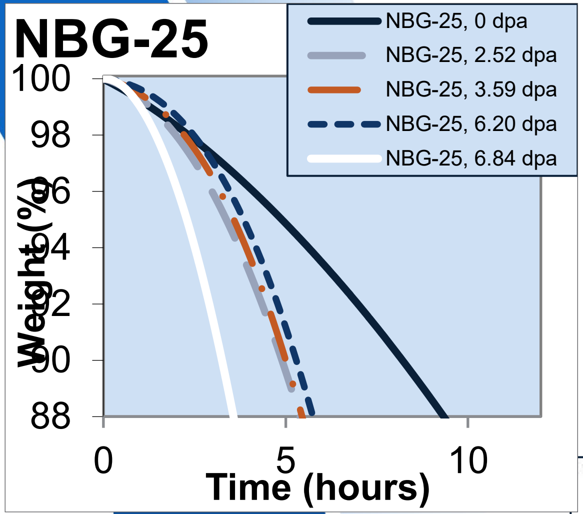
50% to 65% of program funding

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

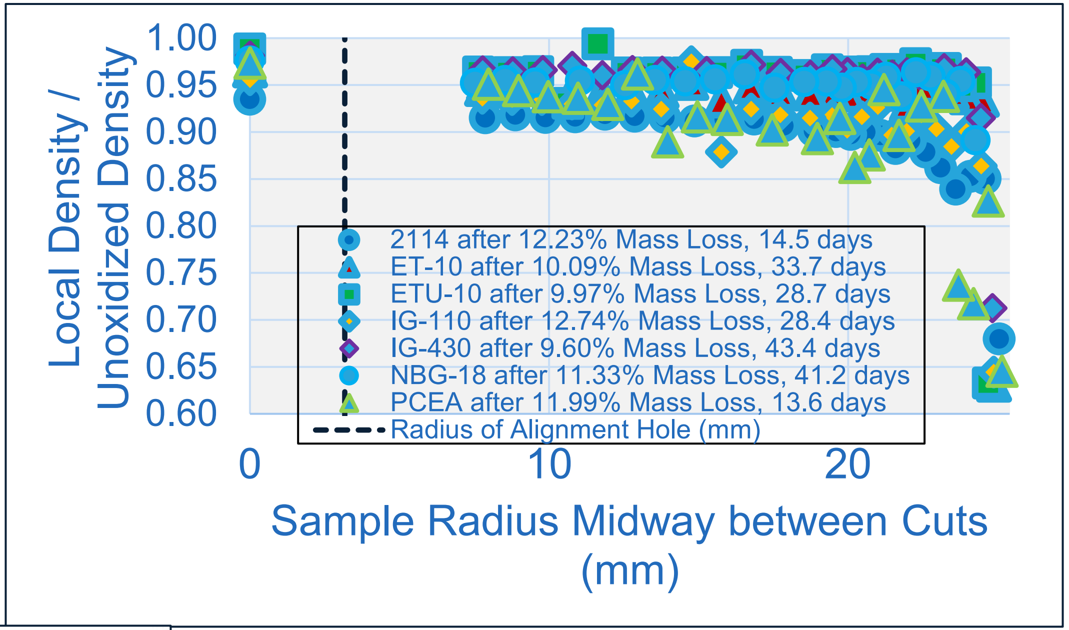
Data
- NDMAS
- Graphite Analysis Tool
- University Collaborations
- Vendor Collaboration
- IAEA/EDF Collaboration
- N. Graphite Specification
- Supply Chain

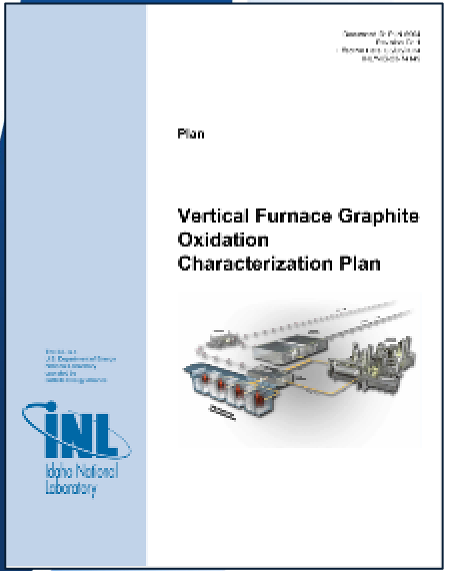
ASME
- Irrdiation Response
- Design Rules
- Molten Salt
- Oxidation
- Definition of Failure
- RIM
- Composites

Graphite Oxidation *(Rebecca Smith)*

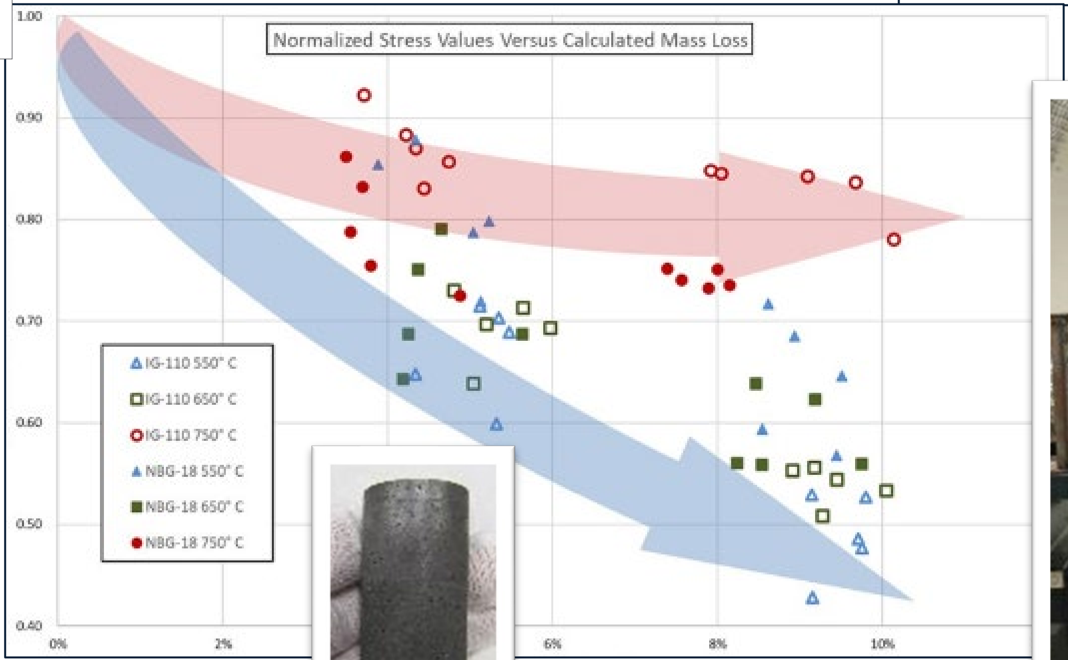


- ***Irr. graphite oxidation rate***
- ***Penetration depth studies***
- ***Strength after oxidation***
- ***Commercial HTR vendors***



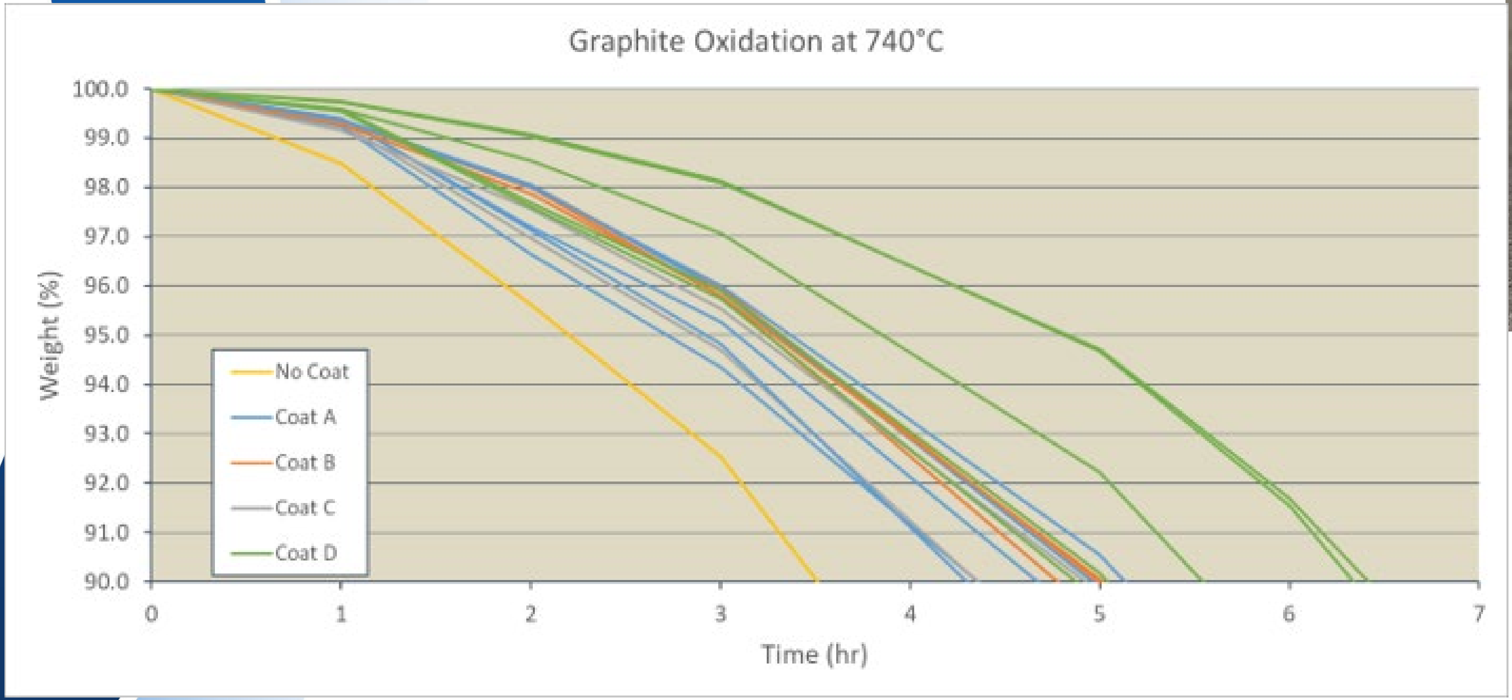

Plan

Vertical Furnace Graphite Oxidation Characterization Plan

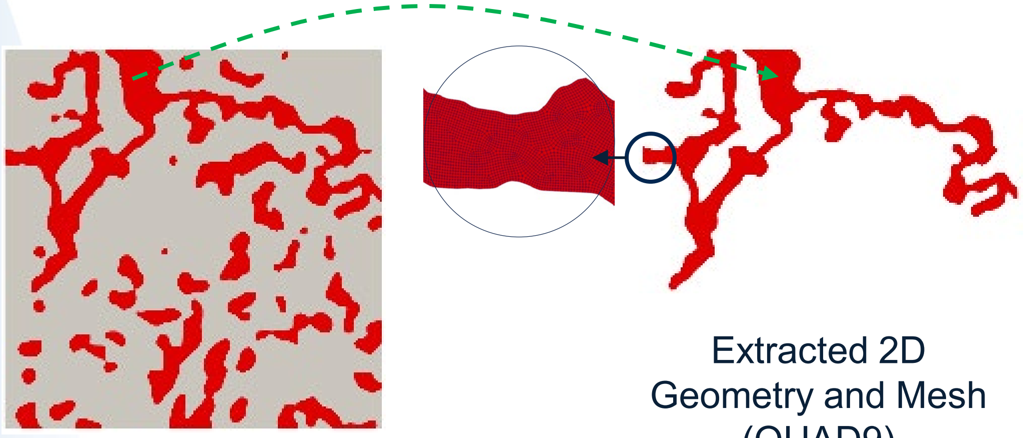


Graphite Oxidation Resistance *(Bragg/Barkdull)*

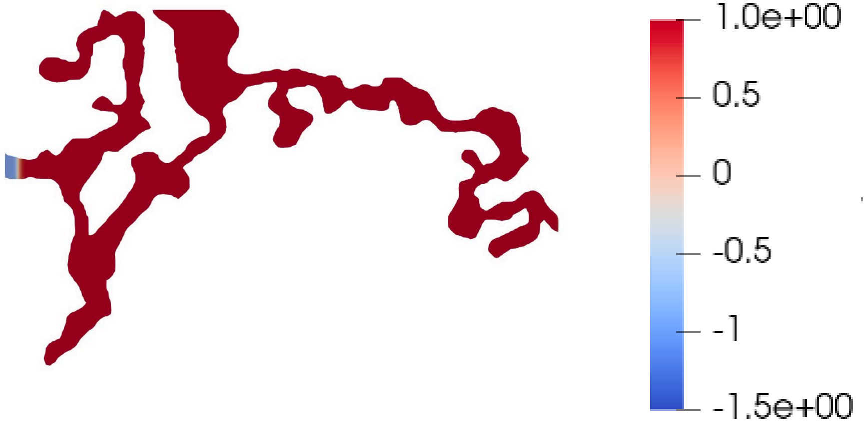
- Increasing the resistance of graphite to oxidation protects graphite from air-ingress accident scenario
- This is done through the introduction of Boron



Graphite Model Development *(Veerappan Prithivirajan)*



Extracted 2D Geometry and Mesh (QUAD9)



- Interactions across nearly all parts of Graphite program
  - Oxidation
  - Microstructure effects
  - Irradiation behavior
- Collaboration with NRC: Molten salt

Fluid Equations

$$\frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u}\cdot\nabla)\mathbf{u} + \nabla P - \nabla\cdot\tau - \frac{\nu}{\epsilon^2}\psi\nabla\phi = 0$$

Phase Field

$$\frac{\partial\phi}{\partial t} + \mathbf{u}\cdot\nabla\phi - \frac{\nu\lambda}{\epsilon^2}\nabla^2\psi = 0$$

$$\psi + \epsilon^2\nabla^2\psi - \phi(\phi^2-1) = 0$$

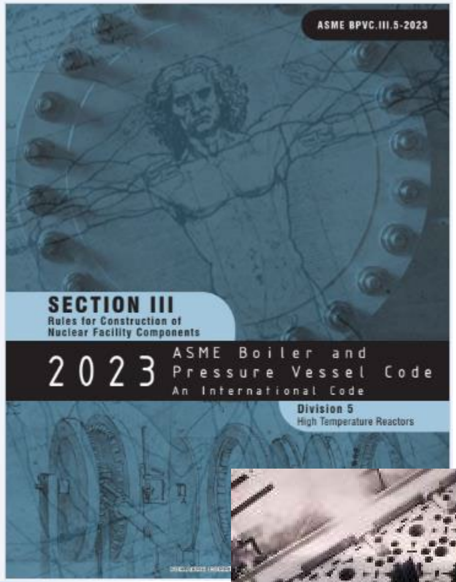
where ϕ is the order parameter and ψ is the auxiliary variable.

Boundary Conditions

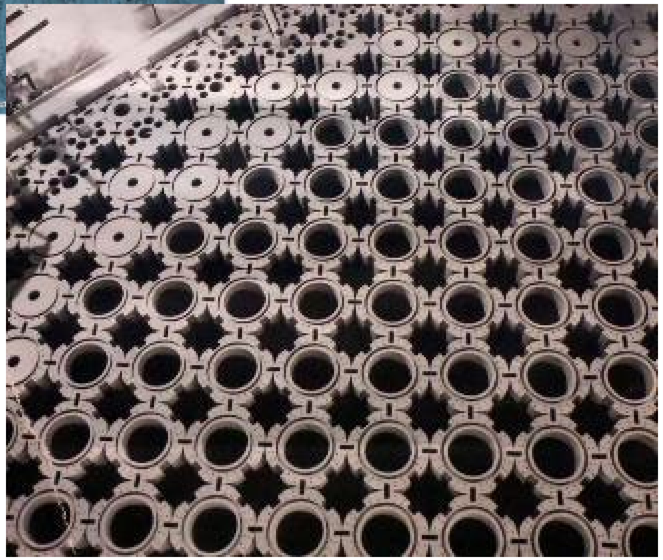
$$\mathbf{u} = 0 \quad \text{on} \quad \partial\Omega$$

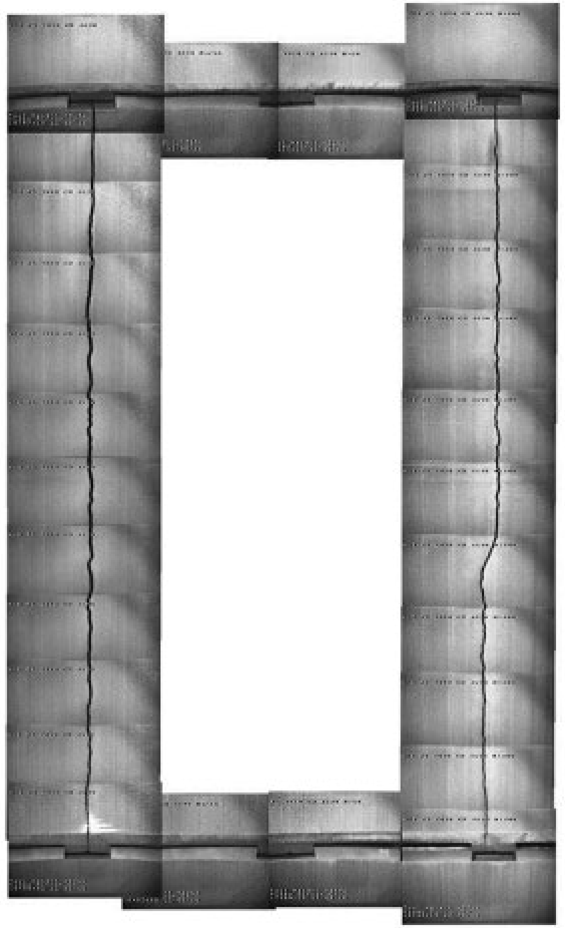
$$\nabla\phi\cdot\mathbf{n} = \frac{1}{\lambda}\frac{3\sigma}{4}\cos(\theta_s)(1-\phi^2)$$

ASME – Grappling with the Concept of Component Failure (Martin Metcalfe)



- Tackling some of the most difficult and pertinent operational questions:
  - ***What is failure in a graphite component?***
  - ***How do you detect failure in core?***
  - ***How can you predict failure?***
- Dr. Metcalfe provides real operational experience





ASME Code Development (Design rules) *(Andrea Mack)*

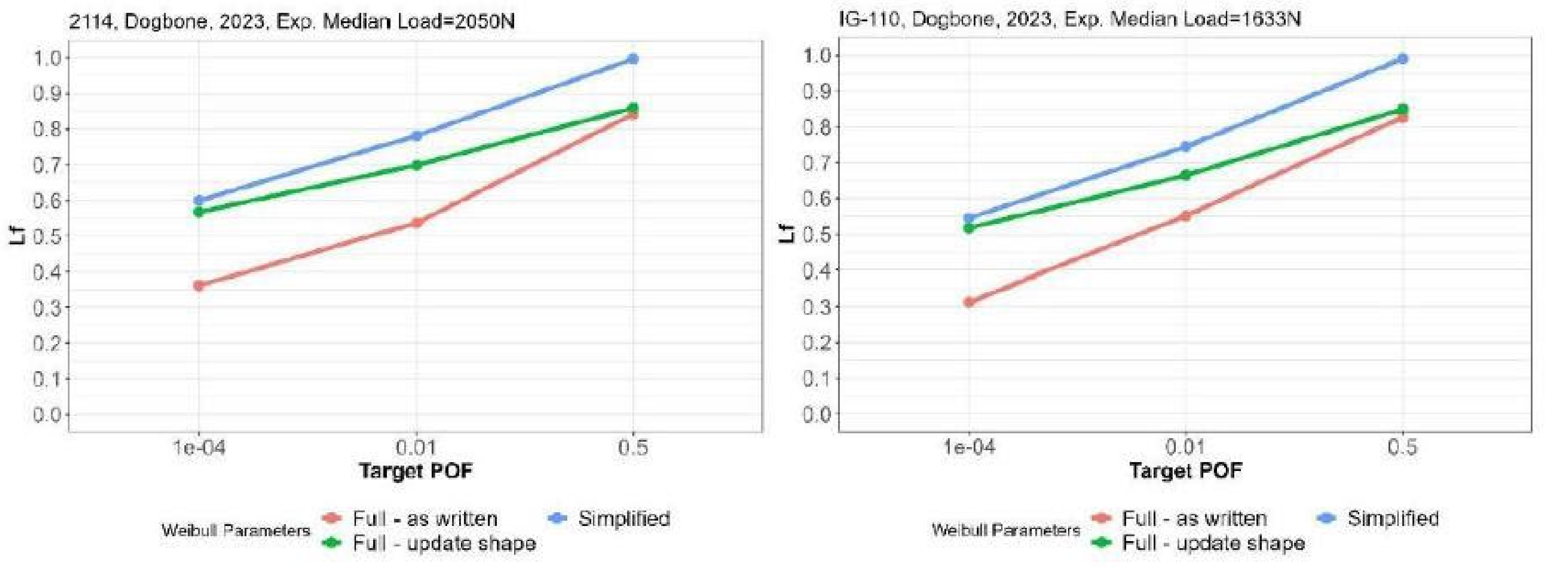


Figure 2: Lf for 2114 dogbones, BPVC 2023

Figure 3: Lf for IG-110 dogbones, BPVC 2023

- Design rules within ASME BPVC are of keen interest (obviously)
- Tremendous amount of work performed in last 2-3 years understanding, improving, and even correcting Design code rules (HHA-3000)
- We have a much better understanding of what code does (and doesn't do now).

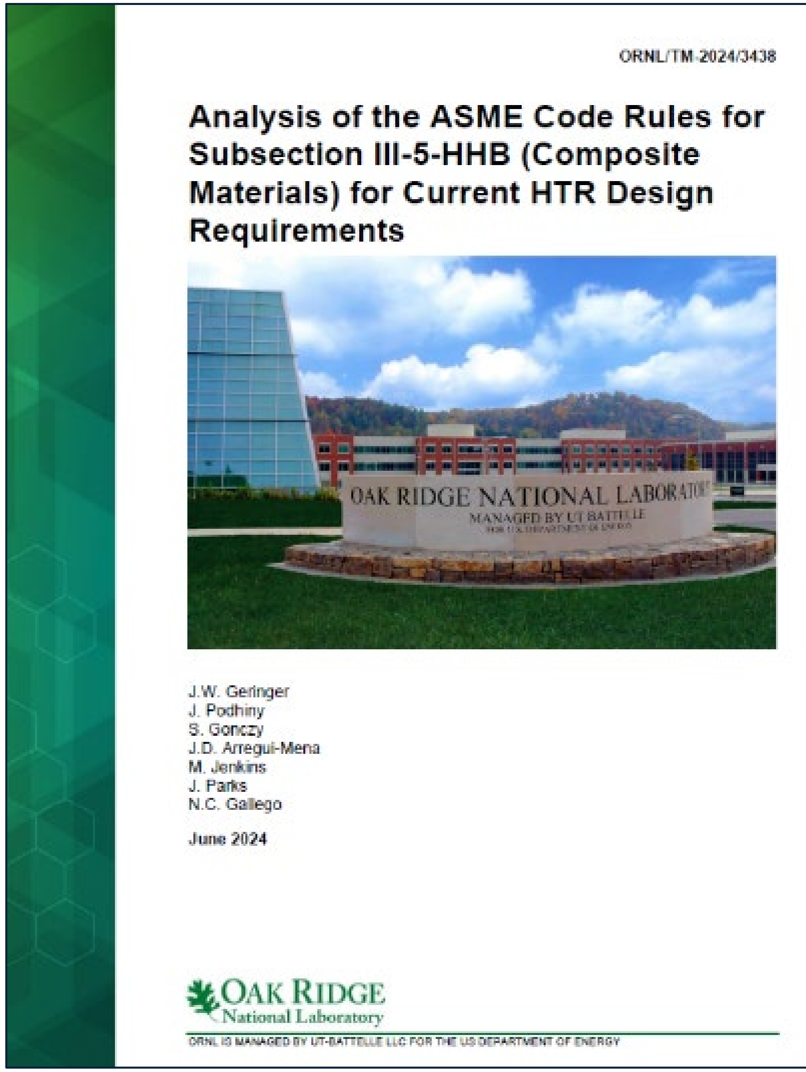
ASME Ceramic Composites *(Josina W. Geringer)*

Previous Status

- Code rules established within the ASME design framework
- Allows the use of fiber reinforced CMCs for structural core components in HTRs.
- Provides a method to qualify new CMCs, acceptable for use of nuclear application (NQA-1)

Recent Achievements

- Completed critical analysis review
- Initiated optimization and refinement efforts (e.g. design by test, maximum failure mode, material qual.)



ORNL/TM-2024/3438

Analysis of the ASME Code Rules for Subsection III-5-HHB (Composite Materials) for Current HTR Design Requirements

J.W. Geringer
J. Podhiny
S. Gonczy
J.D. Arregui-Mena
M. Jenkins
J. Parks
N.C. Gallego

June 2024

OAK RIDGE National Laboratory

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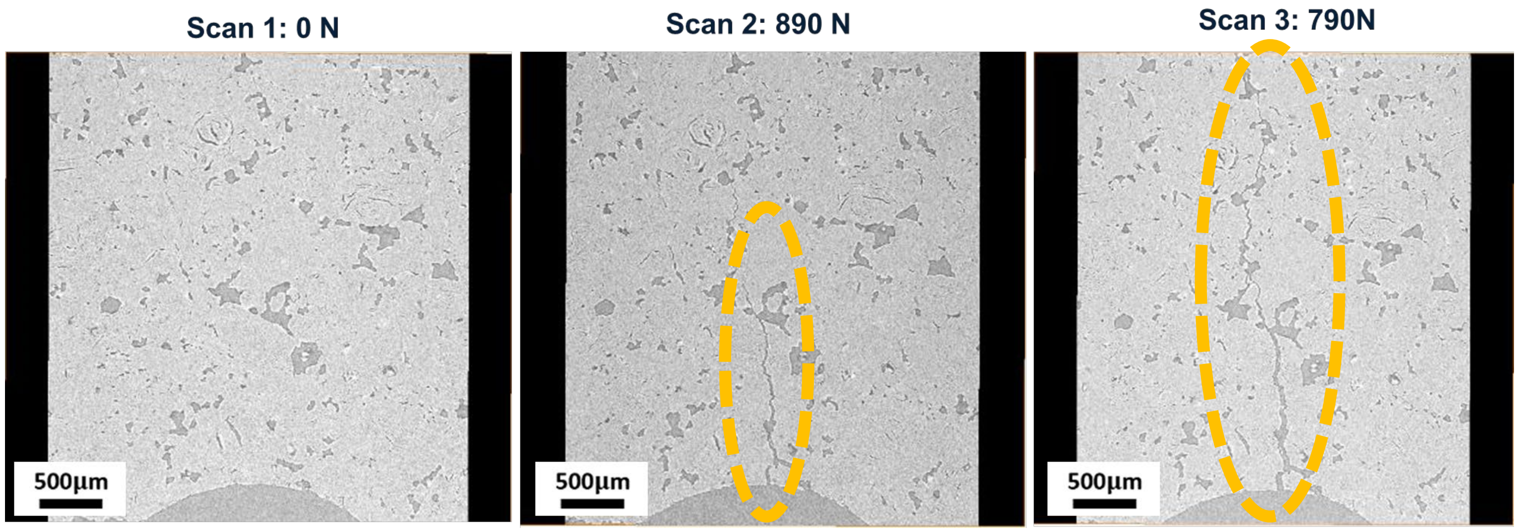
Josina W. Geringer

NEUP: *In-situ* micro-CT fracture test *(Gongyuan Liu and Jacob Eapen)*

- NEUP grants to address the lack of information on mesoscale behavior
- Need to determine effect of graphite microstructure at the mesoscale level
  - ***We understand atomic length-scale and are measuring macroscale response but what is going on at mesoscale?***
- Will be needed in order to develop better "nuclear" graphite components

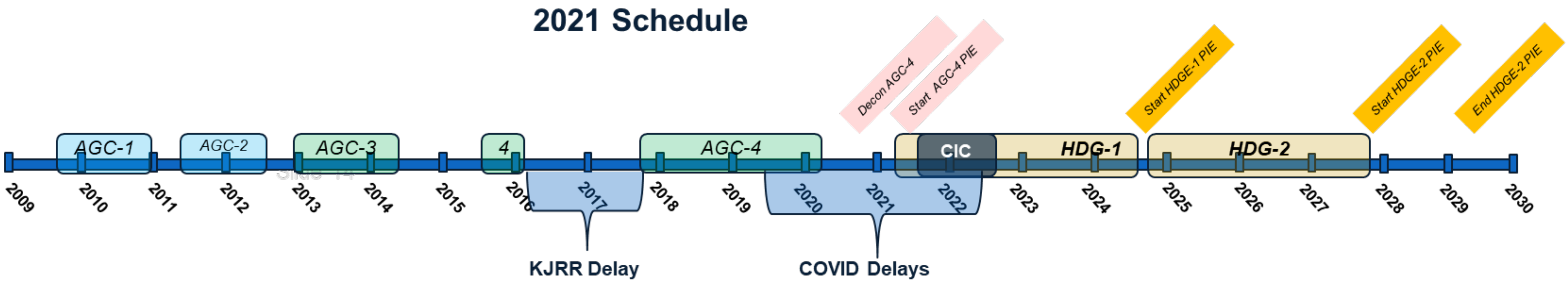
The NBG-17 graphite was scanned three times under different loads.

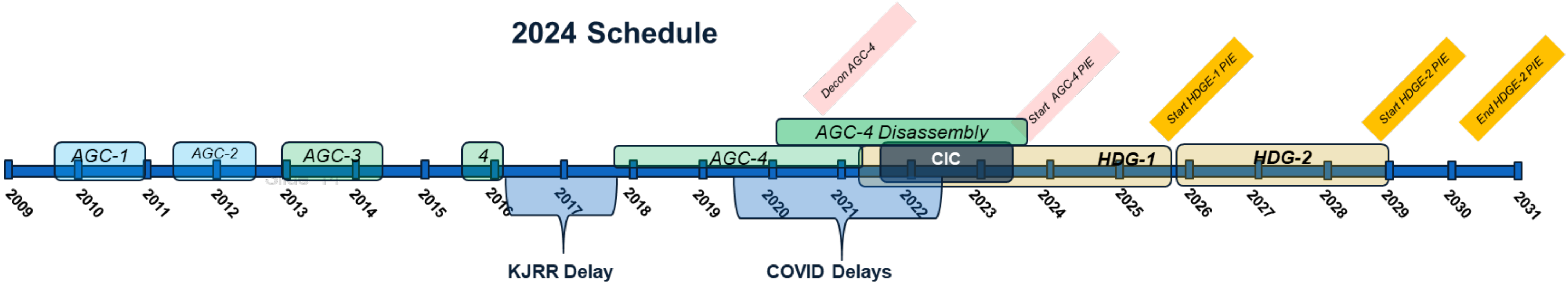


Gongyuan (Patrick) Liu
Department of Mechanical Engineering, The Pennsylvania State University

Prof. Jacob Eapen
Department of Nuclear Engineering, North Carolina State University

AGC Update *(Will Windes)*



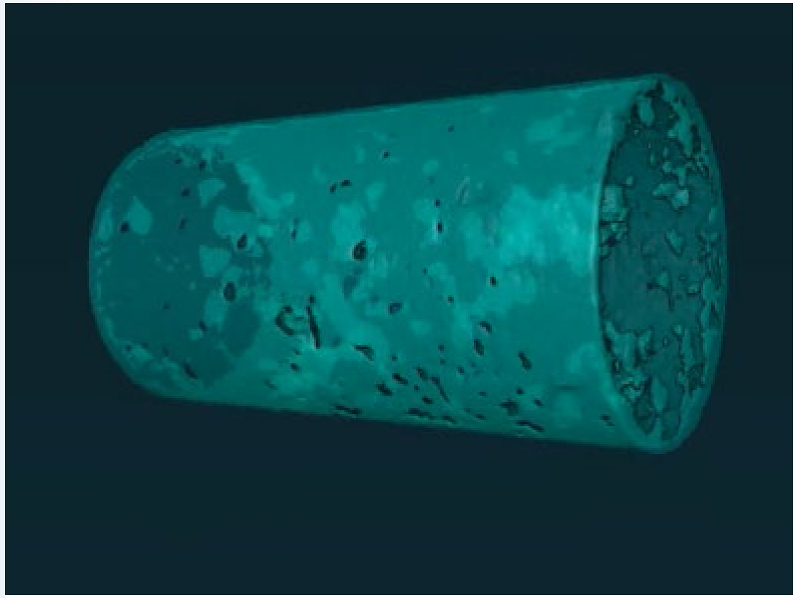


Studies of Molten Salt Intrusion and salt wettability in Graphite

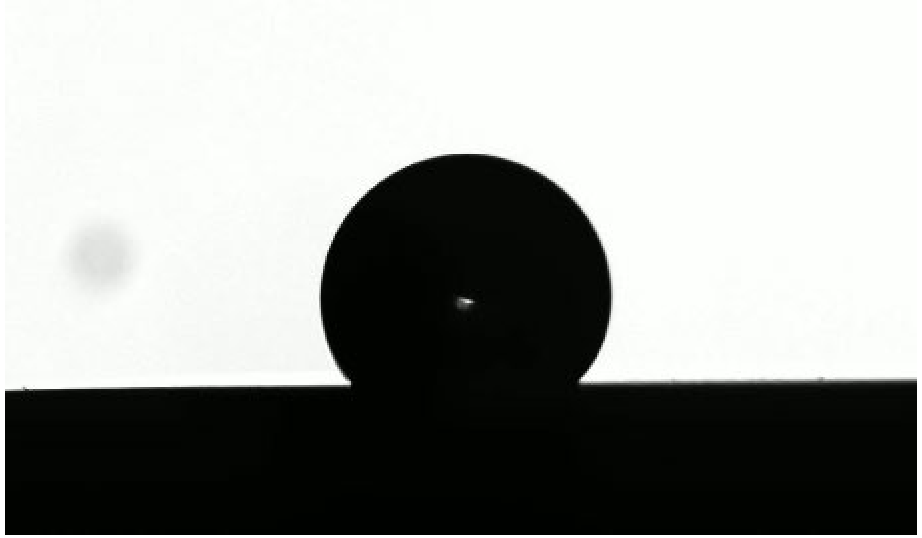
(Nidia C. Gallego, Jisue Braatz, et al.)

Focus on:

- Understanding salt intrusion (penetration depth and salt distribution) in a wide range of graphite grades (various microstructures) as a function of temperature, pressure and time.
- Studying wetting behavior of salt on graphite surfaces to develop predictive models for salt intrusion



Tomography of NBG-18 sample exposed to molten FLiNaK, 3 bar, 750°C, 336 hours



Drop of molten FLiNaK on a graphite surface

Effect of Sample Thickness on the Tensile Strength of Small Graphite Discs

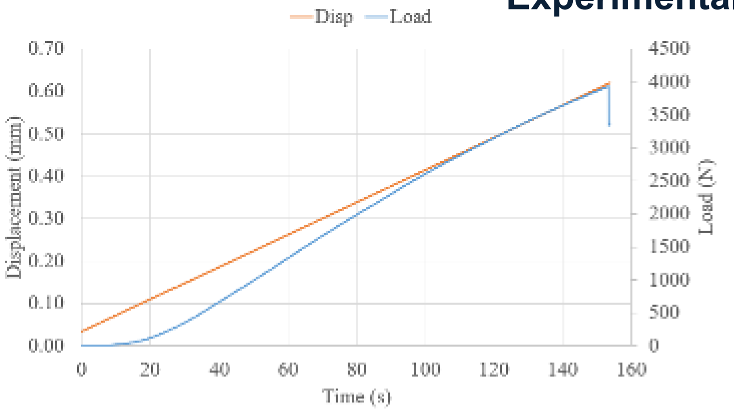
(Lianshan Lin, Nidia C. Gallego)

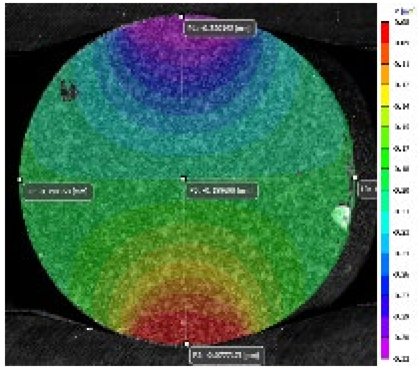
Objective: complete the Advanced Reactor Technologies (ART) Level 3 Milestone (M3TG-24OR0501054), "Continue activities related to Split Disc-DIC - complete analysis of effect of sample thickness on one fine grain graphite."

Approach: Apply the ASTM D8289 Standard test on graphite samples to investigate the effect of sample thickness on splitting tensile strength. The tests involved Ø12.7 mm samples of fine-grain graphites 2114 and IG 110 of different thicknesses (6.35, 5, 4, and 3 mm). The digital image correlation (DIC) method was applied to the samples, along with the ASTM D8289 Standard, to help interpret the measured results.

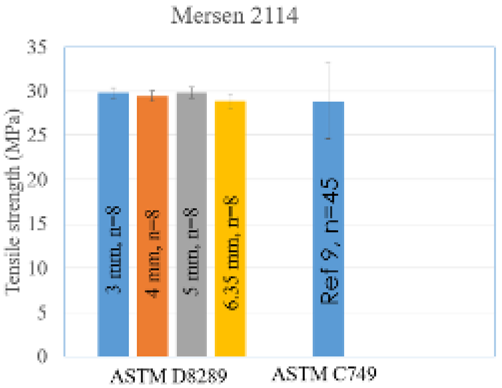
Test Facility & Experimental Setup

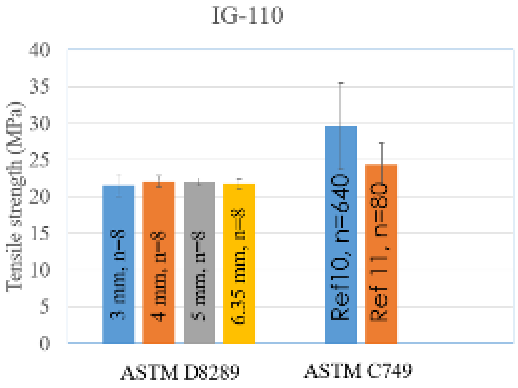
Experimental Results





Thickness Effect on Tensile Strength



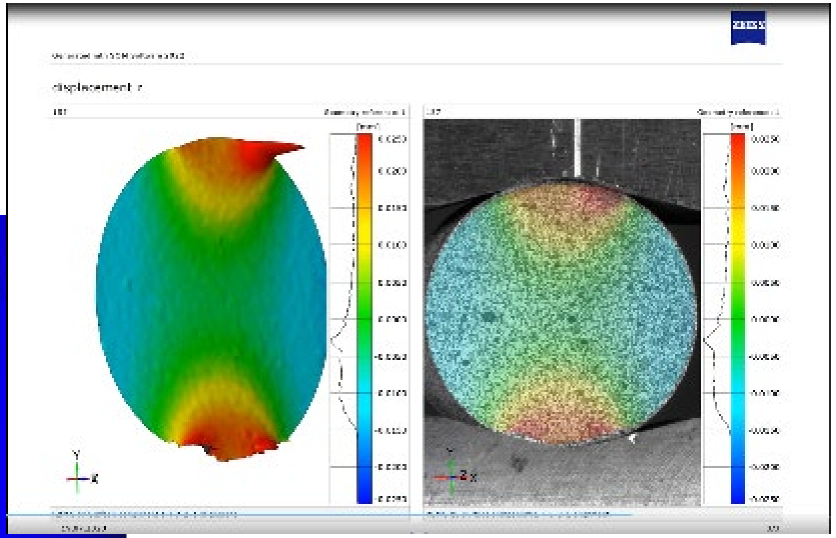


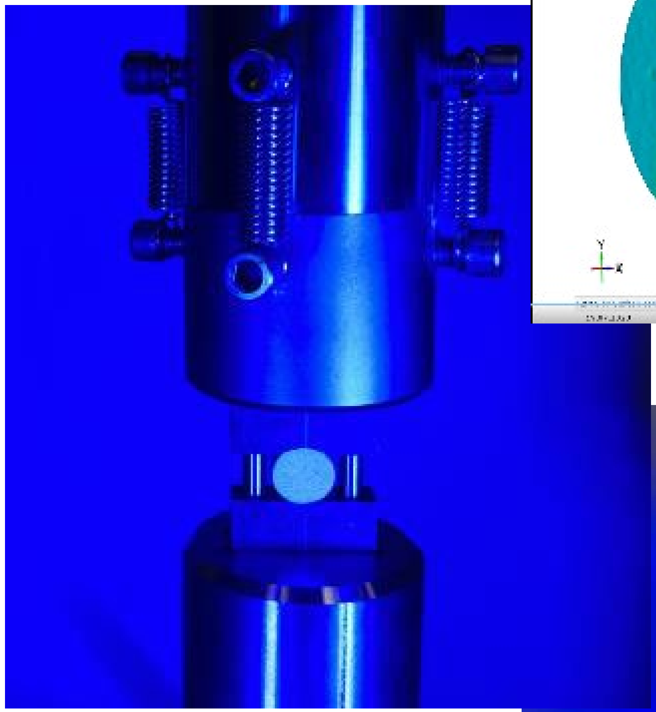
Milestone Report: Lianshan Lin, Nidia C. Gallego, Effect of Sample Thickness on the Tensile Strength of Small Graphite Discs, ORNL/TM-2024/3403. Oak Ridge National Laboratory, 2024

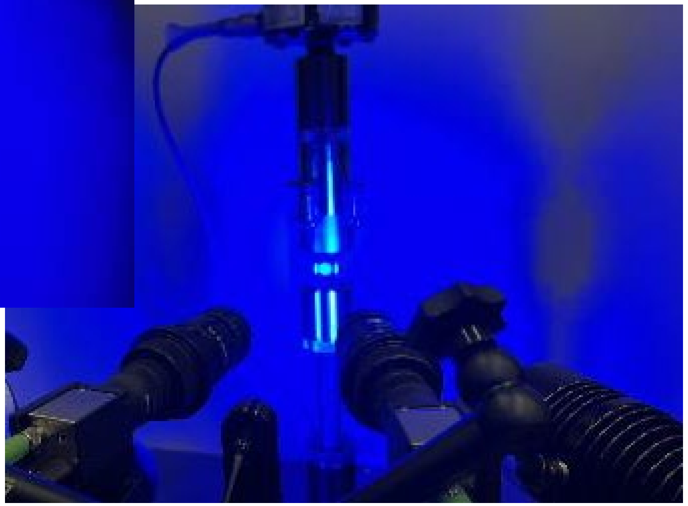
Split-disc studies utilizing Digital Image Correlation (DIC)

(Arvin Cunningham)

- We have a problem measuring mechanical strength of irradiated graphite
  - We can't use traditional ASTM sized tensile specimen
- ASTM D8289 "Split-disc tensile strength estimate" allows us to use miniature sample sizes
  - But it's an estimate of tensile strength, not true measure of tensile strength
- This must be corrected
  - ASME design code will require it







Tribological characterization of graphite in dry argon and molten salt environments

Tomas Grejtak, James R. Keiser, Jun Qu, Nidia C. Gallego

AIM

Objective: investigate the tribological (wear and friction) behavior of graphite pebbles in High Temperature Gas-cooled Reactor (HTGR) and Molten Salt-cooled Reactor (MSR) environments. Complete the (ART) Level 2 Milestone M2TG-24OR0501081: "*Complete report on initial tribological studies within molten salt environment*".

Approach: 1) determine tribologically relevant conditions such as pebble-pebble and pebble-wall contact loads, pebble sliding and rolling speeds; 2) conduct wear and friction experiments on graphite in dry argon and molten FLiNaK salt environments.

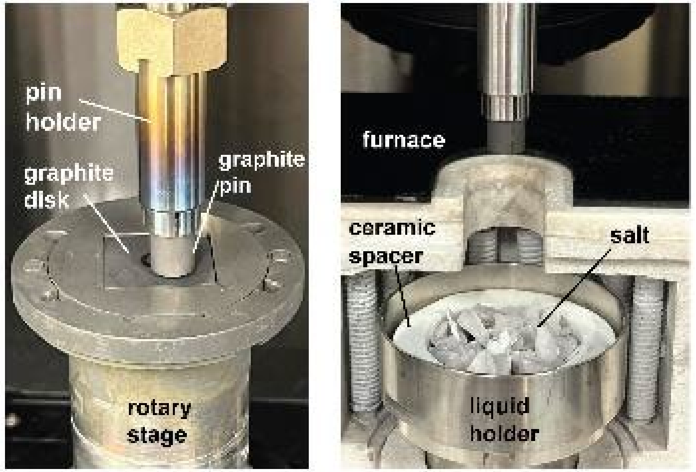
Results

Key input parameters of pebbles

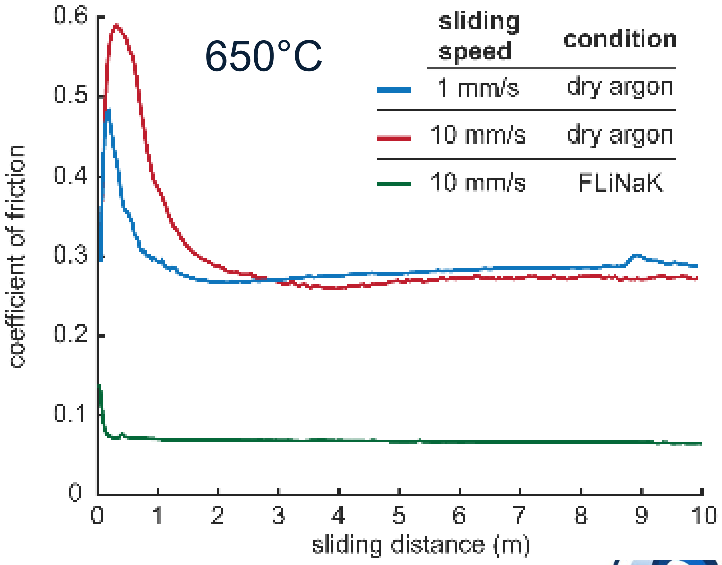
	HTGR	MSR
Contact load (N)	~28	<100
Sliding speed (mm/s)	$<1.2\times10^{-3}$	$\sim4.0\times10^{-4}$
Rolling speed (mm/s)	$<1.1\times10^{-4}$	N/A

Experimental setup

dry argon FLiNaK salt



Frictional behavior



Milestone report

Grejtak, T., Qu, J., Gallego, N.C., Keiser, J.R., Report on Initial Tribological Studies of Graphite in Dry Argon and Molten Salt Environment. ORNL/TM-20024/3253. Oak Ridge National Laboratory, 2024

Concluding remarks

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