July 14, 2022 – Session 3

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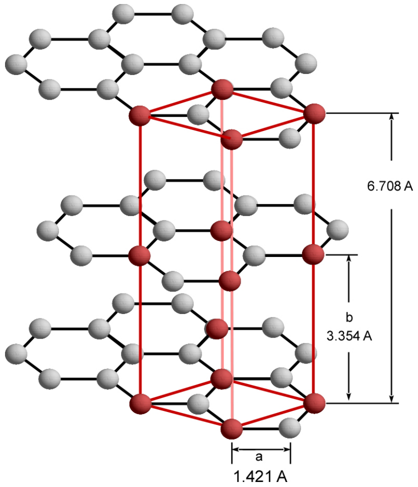
DOE ART Graphite R&D Technical Lead

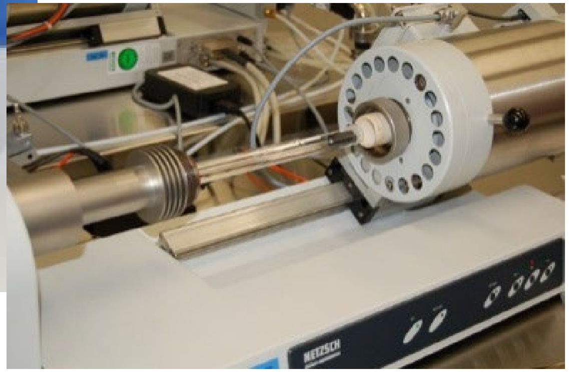
ART Graphite R&D Introduction

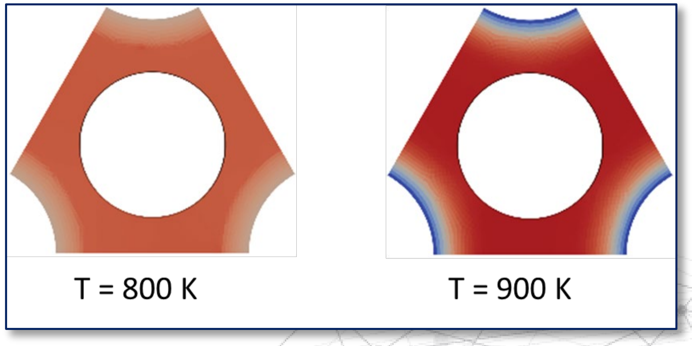
ART
Advanced Reactor Technologies

Topics of discussion

- The DOE ART Program
  1. As-fabricated material properties
  2. Oxidation degradation
     - ***Pebble matrix oxidation studies***
  3. Model Development
  4. AGC irradiation
     - ***AGC-4 Status***
  5. Fundamental Work
     - ***Microstructure of graphite***
     - ***Irradiation damage***
     - ***Collaborations***
  6. Licensing







Contributors to this discussion

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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

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

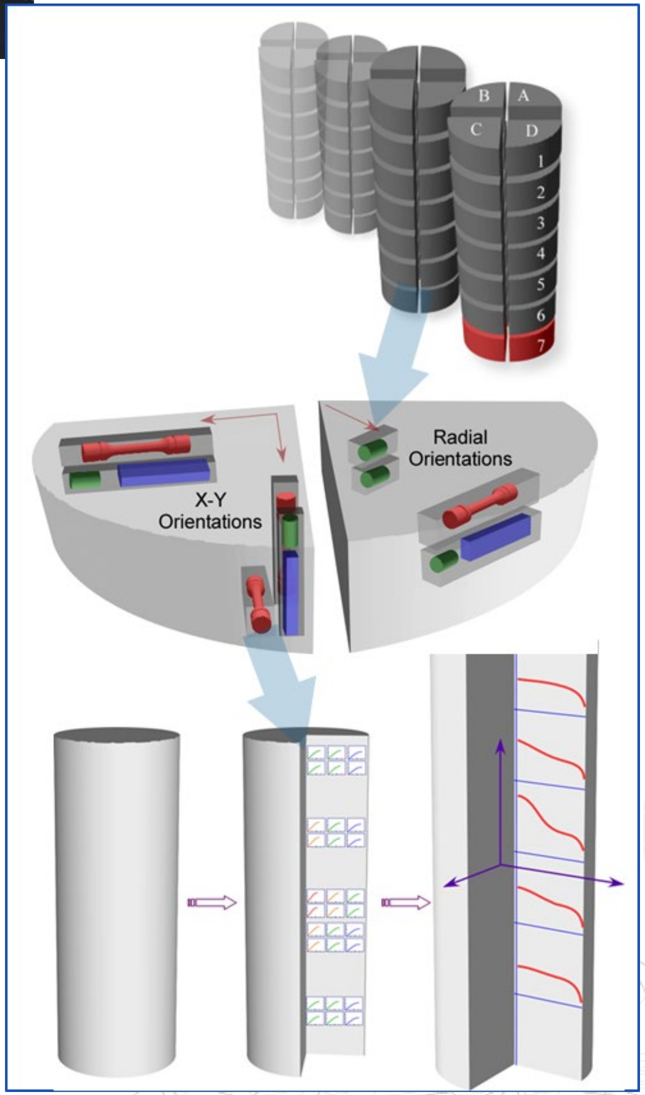
As-Fabricated Properties (Baseline) *(Matthews)*

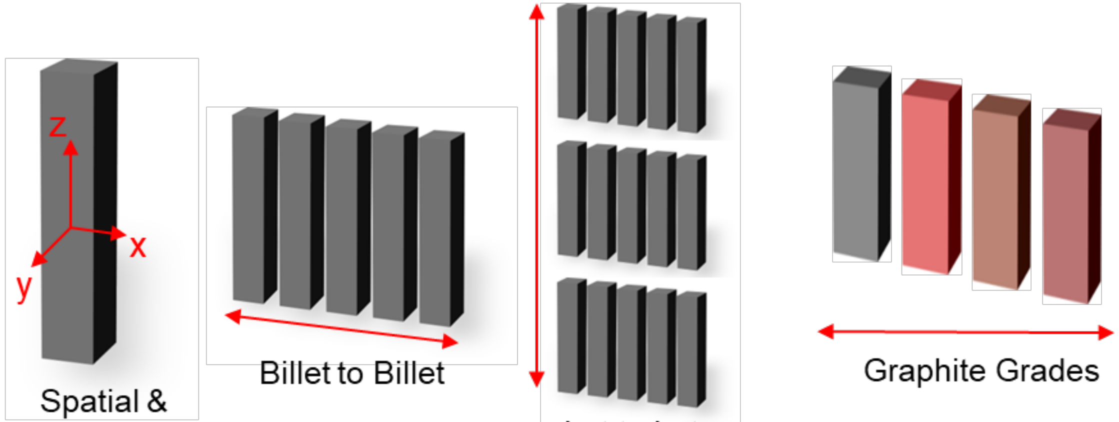
Unirradiated Baseline for irradiation changes

- 1000s of data points, rather than 10s
- Statistically established as-fabricated material property measurements
  - *Irradiated (AGC) data will be superimposed on Baseline data*
- Determine Intra-, Inter-, and Lot-to-Lot variability of material properties

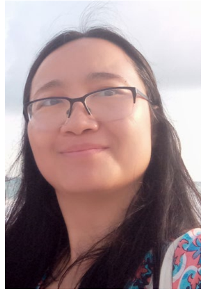
Data for ASME code development

- Largest material property database of current nuclear graphite grades
- Using data to determine accuracy, consistency, and viability of code rules
  - *Determine minimum sample population needed to qualify a graphite grade*
  - *Assess the probability of failure method using Baseline data*



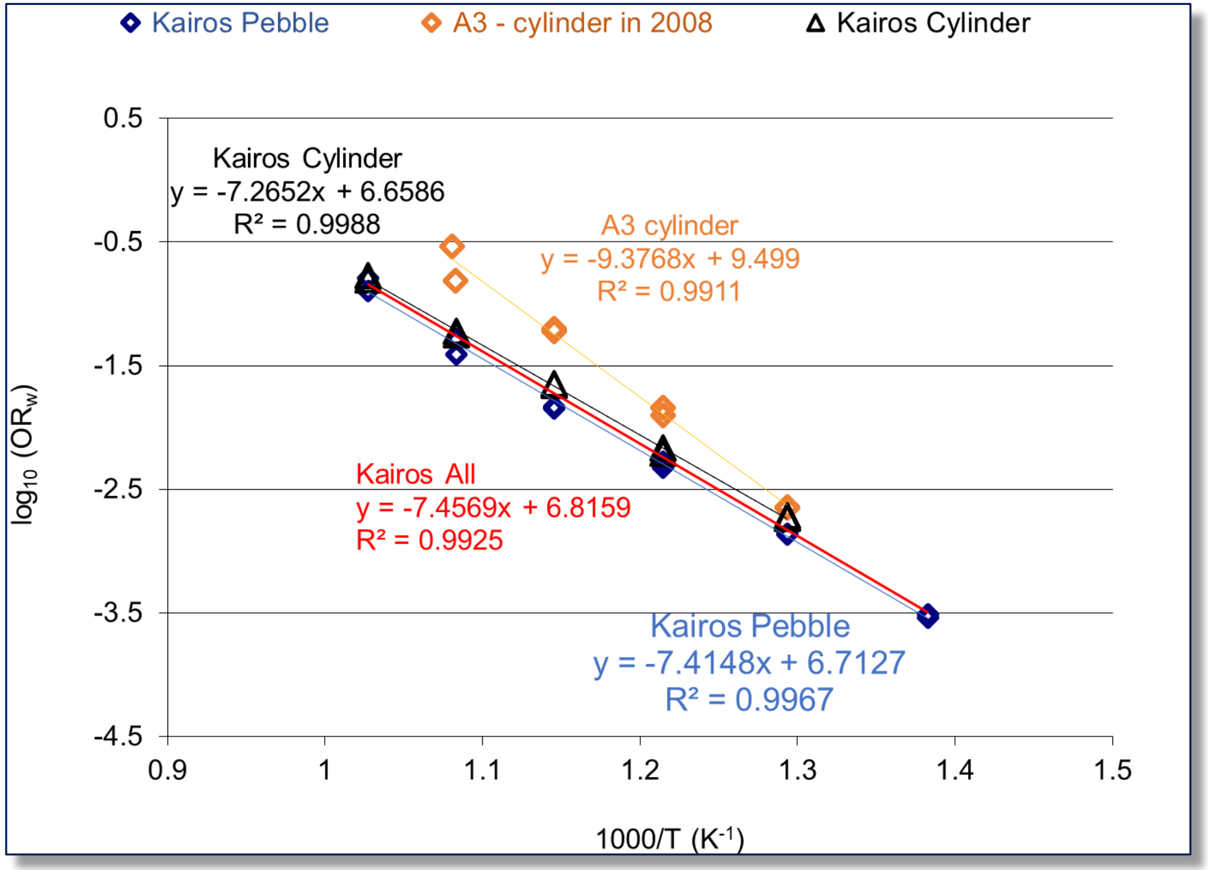


Oxidation testing *(Cai)*

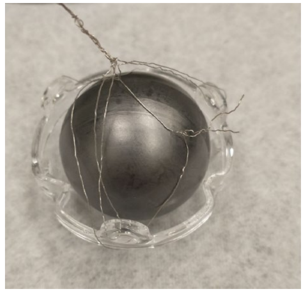


Pebble Matrix Oxidation (unirradiated)

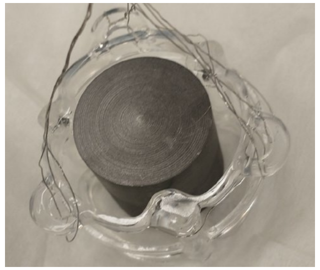
- Collaboration with Kairos Power, Inc.
- Temperature range 450°C – 700°C
- Excellent response in Kinetic-Controlled regime



Pebble: D=40 mm

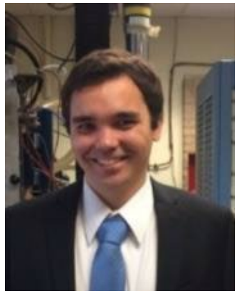


Cylinder: D=H=25.4 mm



Quadrant of a disk (D~12 mm, H~6mm)

Behavior Models *(Bass)*



Model development:

- Baseline material properties:
  - Strength, modulus, density, etc.
- Degradation behavior
  - Penetration/profile into components
  - Changes to material properties
    - *Increase or decrease of properties*
  - Material loss (oxidation, abrasion, etc.)
- Level of degradation
  - Strength vs. Oxidation mass loss
  - Irradiated material property changes
    - *Temperature dependency*

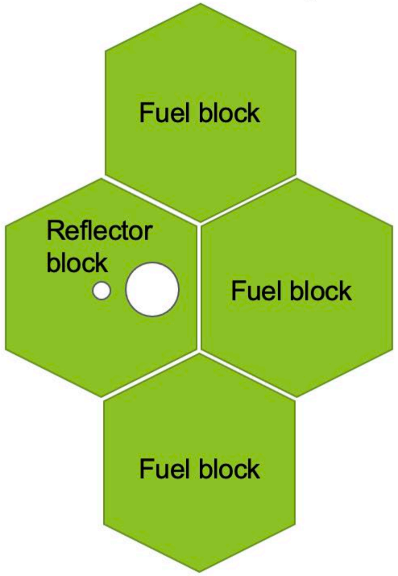
Setup

• Application of Model

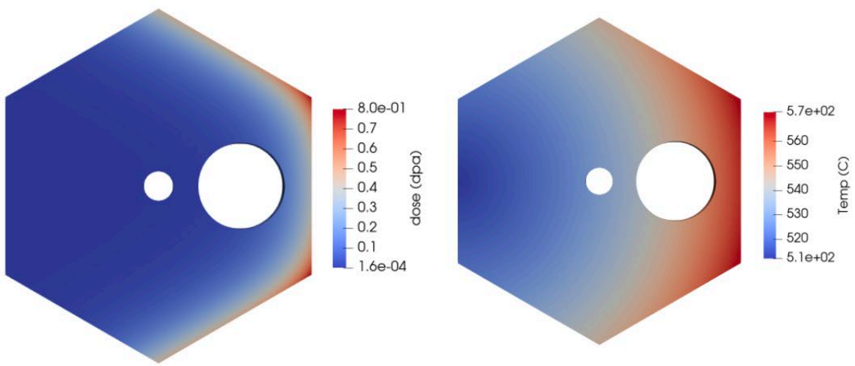
- Development of FEM mesh
- Application of changes
- Application of ASME Probability of Failure (POF)
  - ASME code rules tested
  - POF calculations proven
  - Accuracy of ASME rules for graphite components

Results

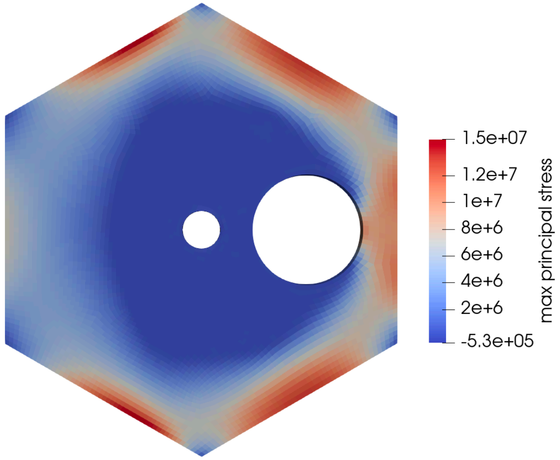
Core Geometry



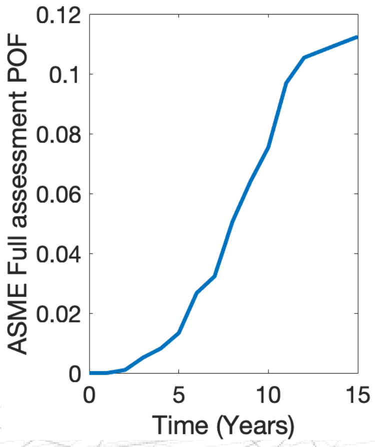
Dose and Temperature Distributions



Principal Stress

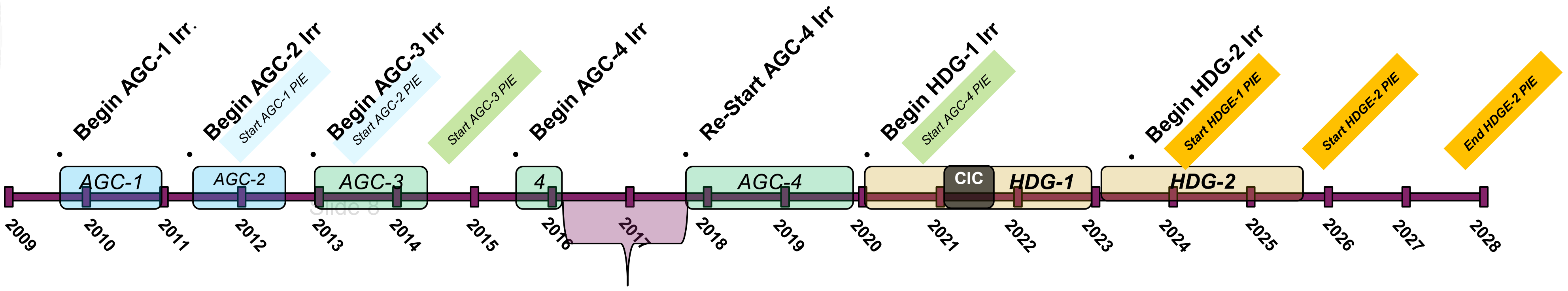


ASME POF

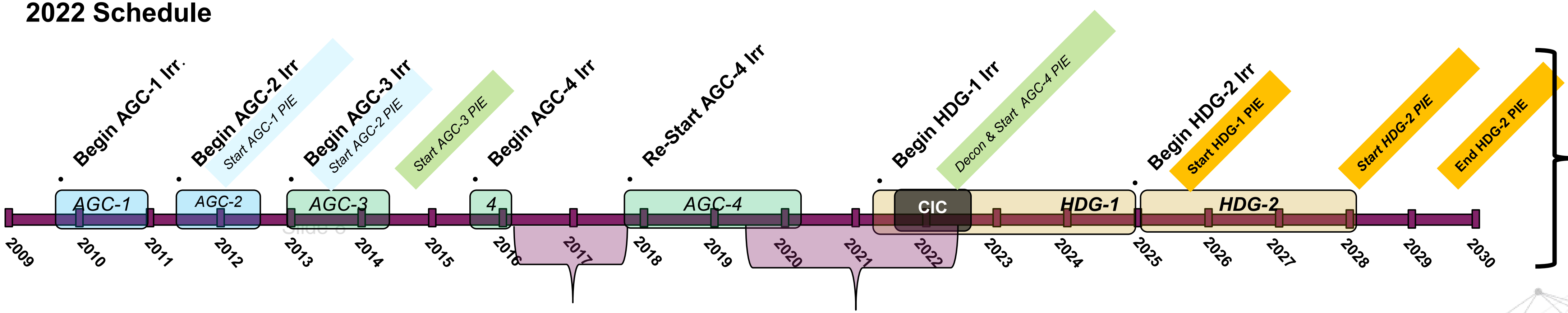


AGC Experiment Status *(Windes)*

2018 Schedule



2022 Schedule



COVID & CIC added about 18 months to AGC schedule

Microstructure of graphite *(Arregui-Mena)*

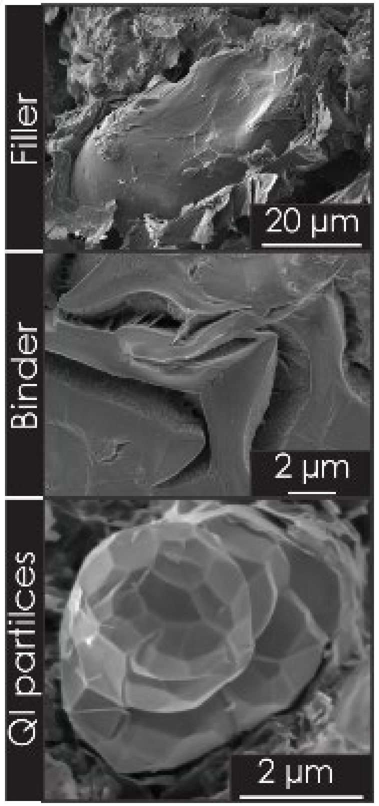
Microstructural characterization

- Understand the microstructure of historical and modern graphite grades
- Investigate the irradiation and environmental effects over multiple length-scales

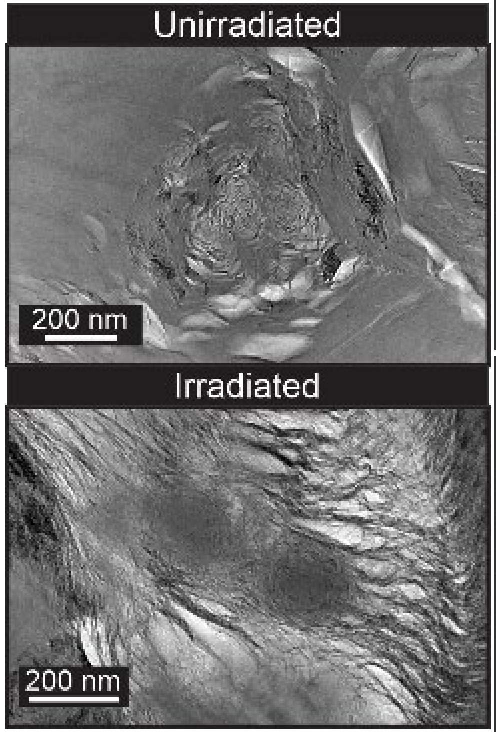
Multiscale characterization

- Use microstructural based models to support and improve behavioral models
  - Implementing two strategies: Image-based models and artificial microstructures

Phases



Irradiation effects



Porosity

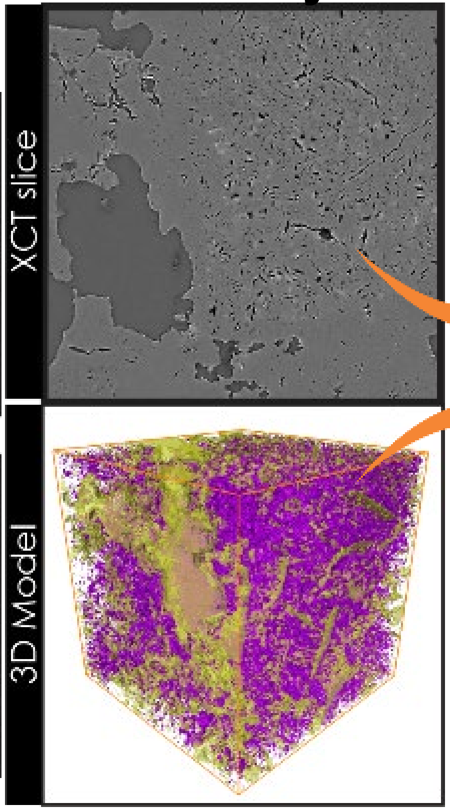
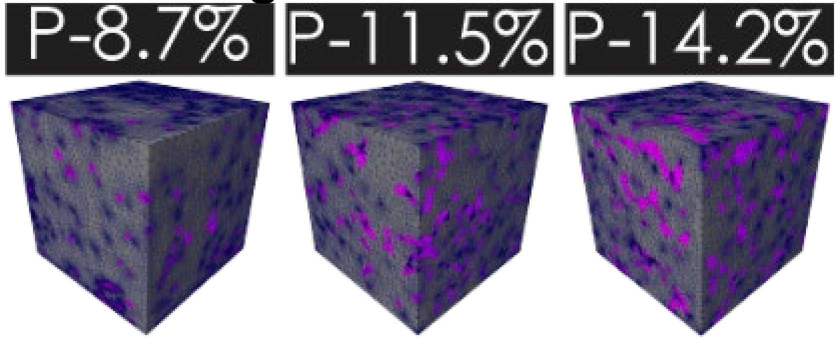


Image-based models



Random field models

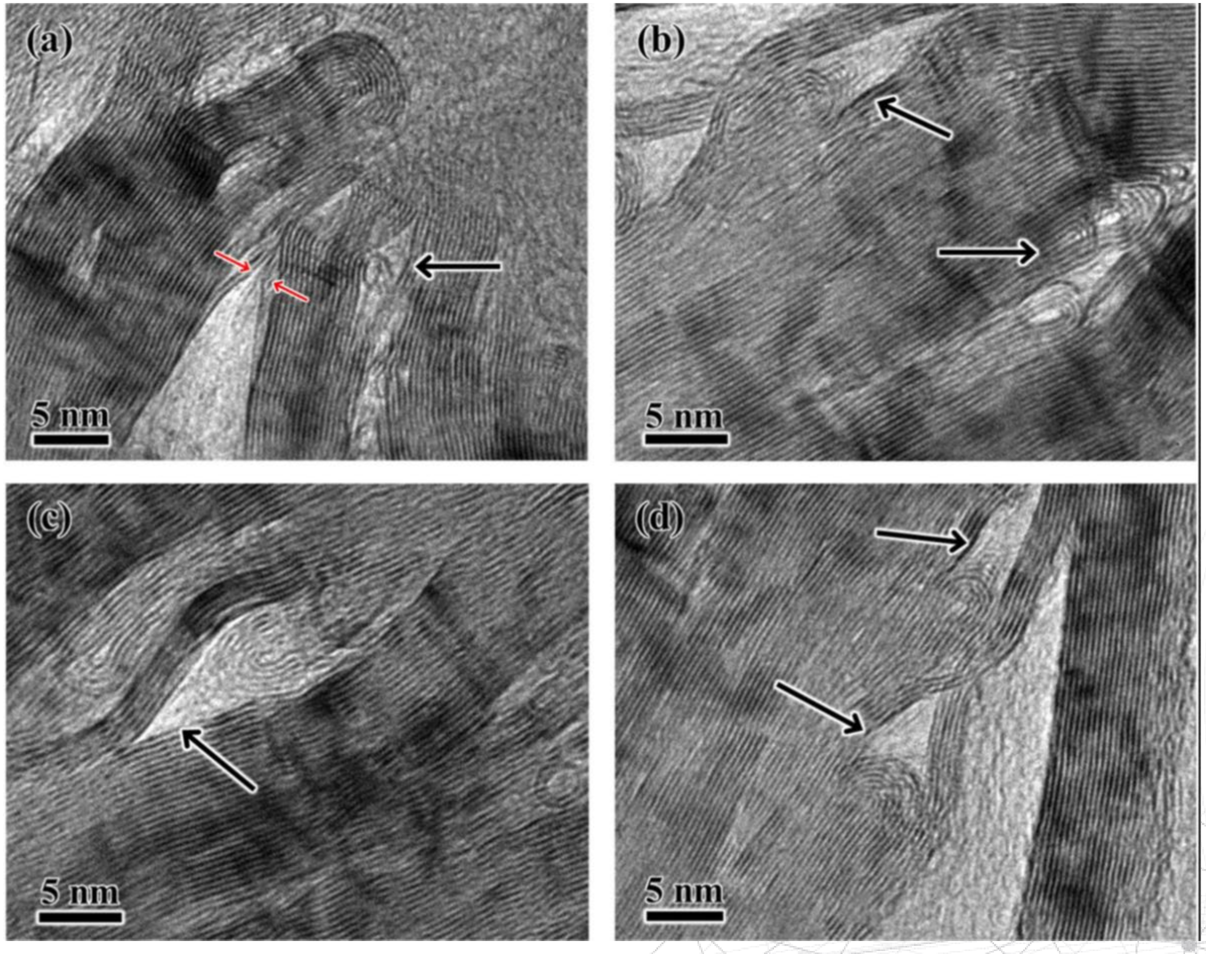
Irradiation damage and collaborations *(Johns)*

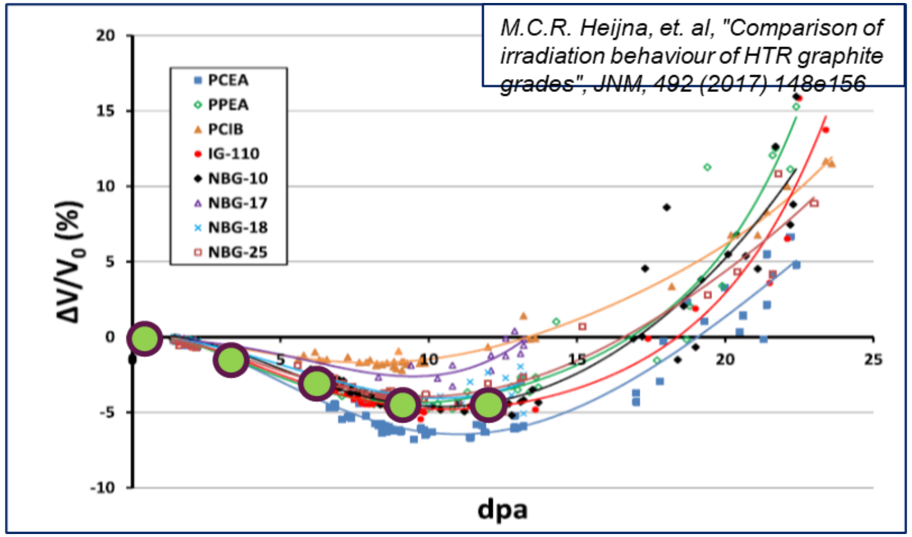
Irradiation damage mechanisms:

- Why does graphite behave the way it does?
- Underlying mechanisms to predict behavior
  - Material property changes, degradation behavior
  - Turnaround behavior – what does it mean?
- Needed to develop ASME rules for irradiated behavior

Collaborations

- NEUP, IRP, DOE intra-lab, and international collaborations
- Need consensus of mechanisms (Code Rules)





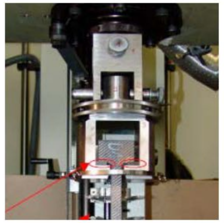
M.C.R. Heijna, et. al, "Comparison of irradiation behaviour of HTR graphite grades", JNM, 492 (2017) 148e156

ASME Code Development *(Geringer)*

Anticipated applications for composites in HT reactor systems.

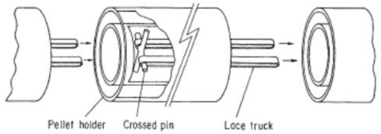
Reactor Unit

Tie Rods



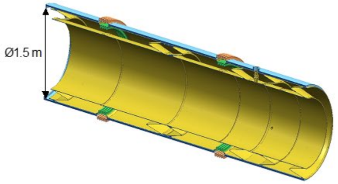
Restraint Straps

Control Rods
Example HTTR
CFRC Control Rod



Interconnecting Duct

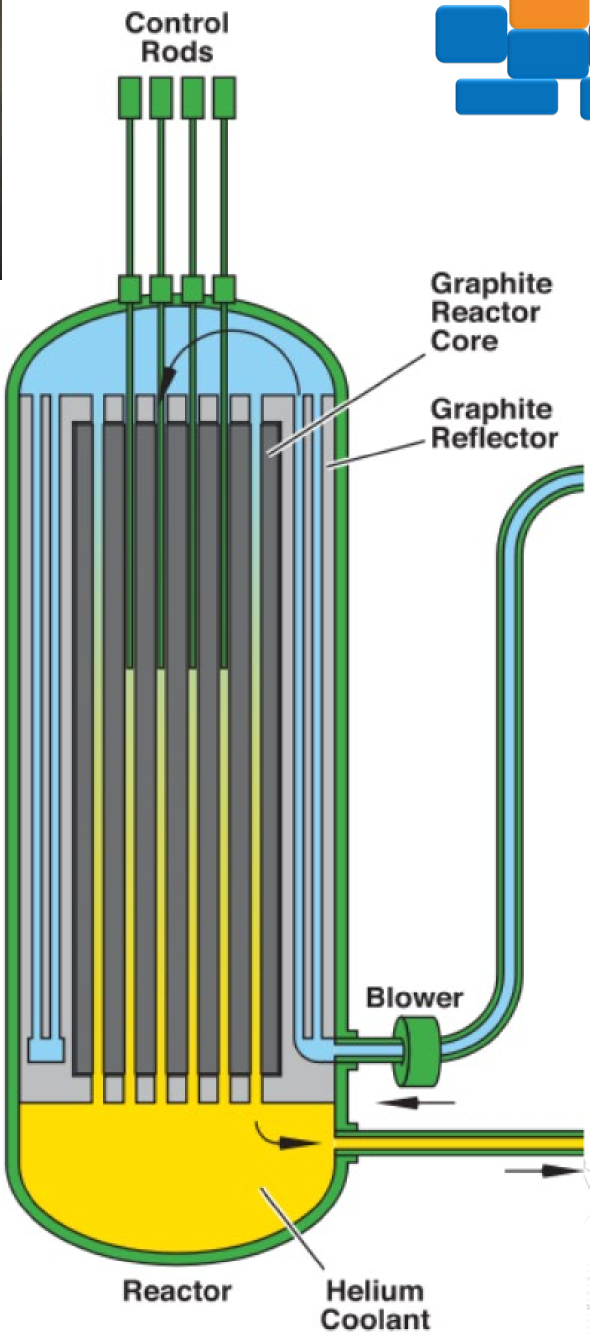
Hot Gas Duct



Power Conversion

HP Turbine Blisk

Heat Exchangers



Subsection HHA (Graphite): Code changes and areas of development

- New definition of failure in graphite components
- Oxidation code rule changes – oxidize at lowest temp

Subsection HHB (Composites): New areas of development

- New Task Group to review composite code for optimization areas
- New non-mandatory articles in development to expands code into C-C CMCs

Collaborations (non intra-Laboratory)

University research on graphite:

- FY 2022 - Started back up this year!
  - Two new NEUP activities researching underlying mechanisms for mechanical property changes
    - *Penn State: Multi-scale Effects of Irradiation Damage on Nuclear Graphite Properties.*
    - *North Carolina State University: Quantifying the Dynamic and Static Porosity/Microstructure Characteristics of Irradiated Graphite through Multi-technique Experiments and Mesoscale Modeling.*
- FY 2023 – Both a NEUP and an IRP research calls
  - NEUP: Development of test standards for fuel matrix material
  - IRP: Initial assessment and development of waste practices for structural graphite

International research collaborations:

- Generation IV International Forum (GIF)
  - Split-disk testing: Combining data from multiple laboratories
  - Development of small sample testing protocols
- IAEA Coordinated Research Projects (CRPs)
  - Development of international definition of failure in graphite core components
  - To be used for development of ASME code rule and define the operational lifetimes of graphite components

Idaho National Laboratory