July 25, 2023

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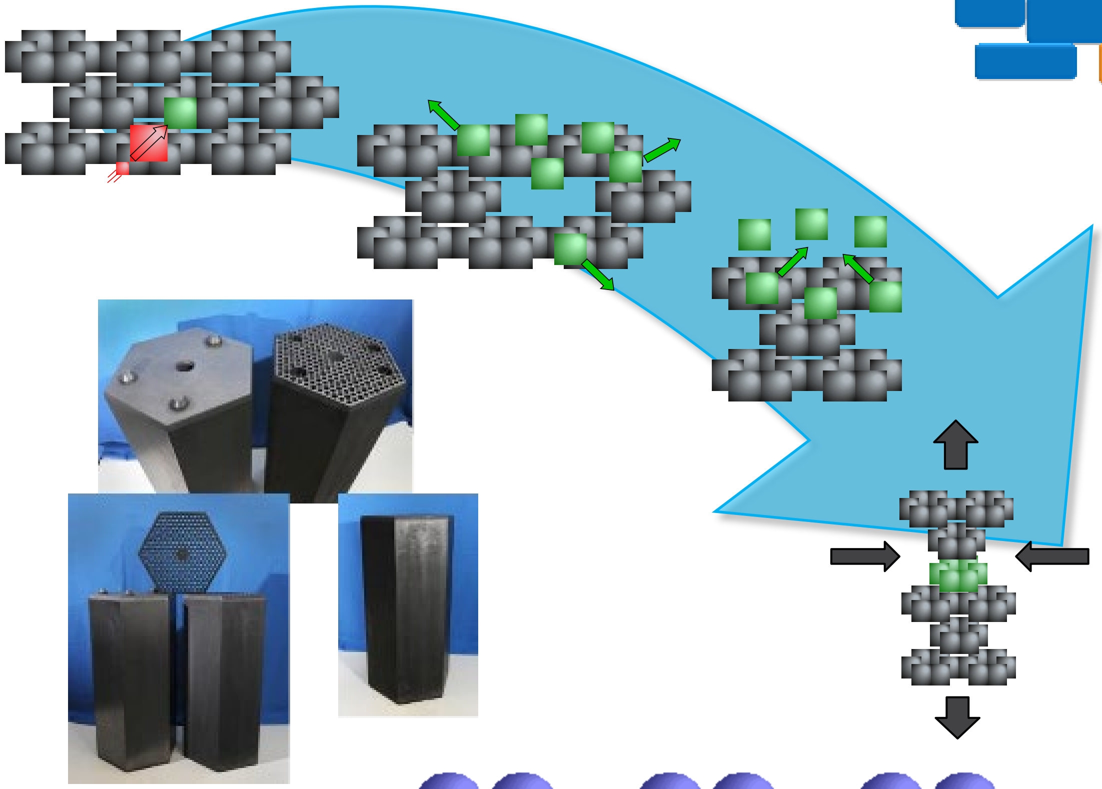
ART Advance Graphite Creep (AGC) Irradiation Experiment

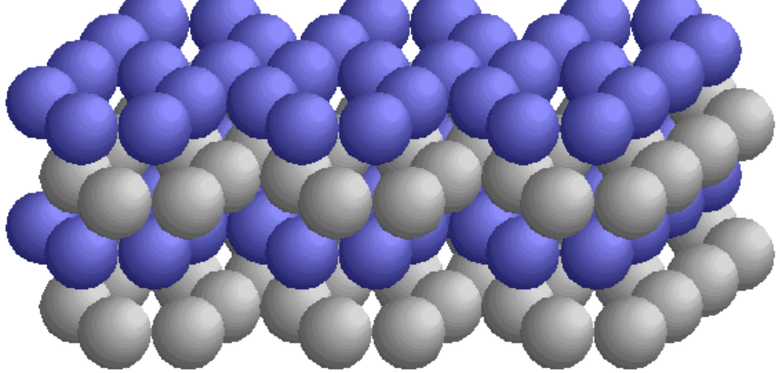
DOE ART Gas-Cooled Reactor (GCR) Review Meeting
Virtual Meeting
July 25 – 27, 2023

ART
Advanced Reactor Technologies

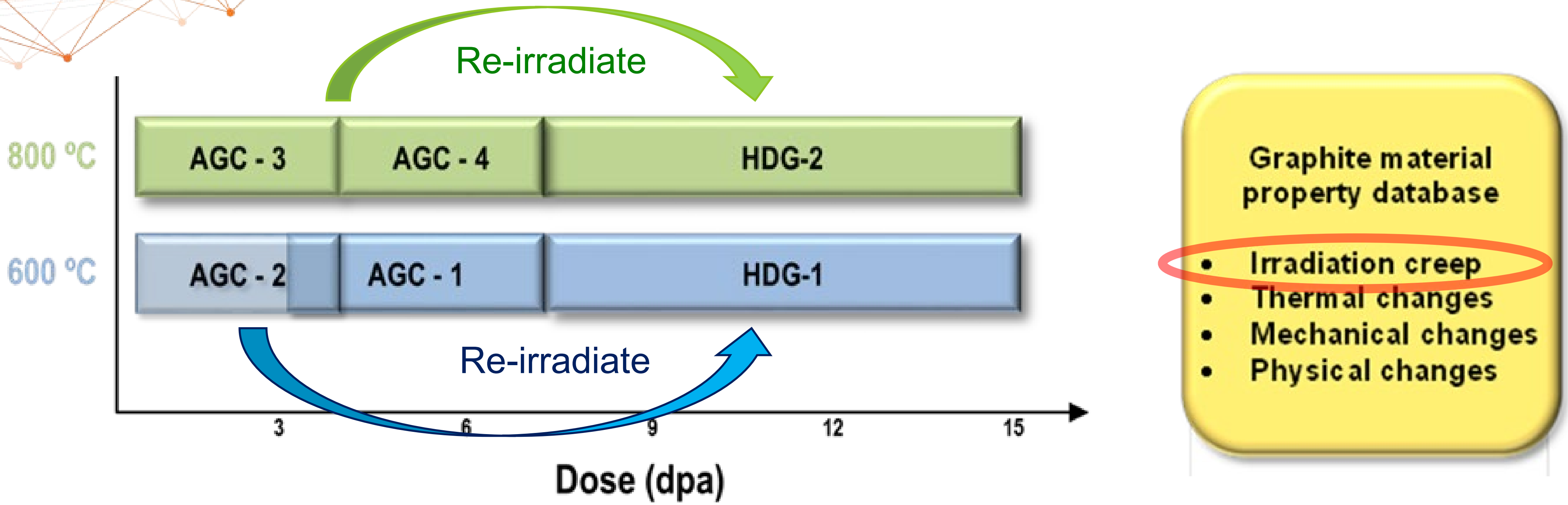
Topics of discussion

1. Schedule
2. AGC Experiment Update
3. AGC-4 Status
   - ***Disassembly and Decon***
   - ***Initial PIE***
4. Anticipated areas data will be used
   - ***ASME code rules for irradiated graphite data***
   - ***Support of HTR designs***
   - ***Collaborations (Commercial vendors, NRC, GIF, IAEA)***
5. Vendor specific irradiation capsule
   - ***Why? Please not another AGC experiment***
   - ***How does it fits with new ASME code rules***





AGC Irradiation Experiment: A review



Initial 600°C and 800°C irradiations

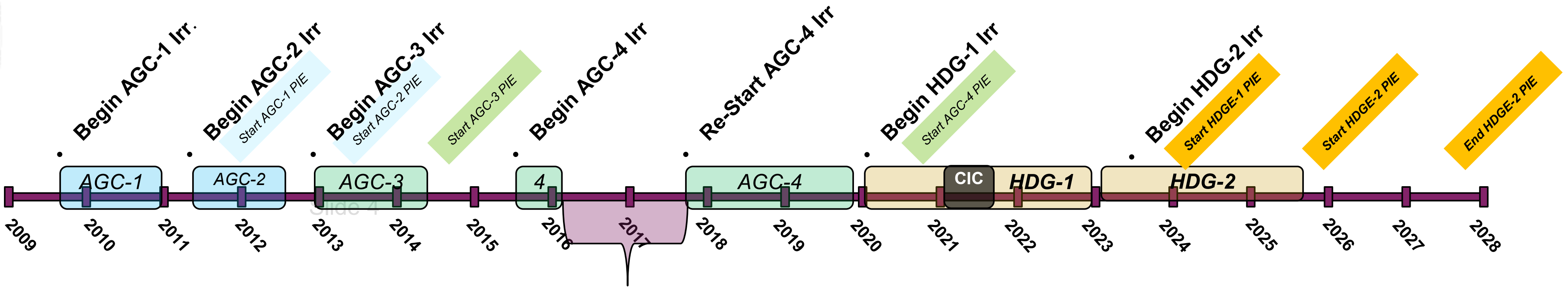
- AGC-1 and AGC-2 (600°C irradiation)
- AGC-3 and AGC-4 (800°C irradiation)
- Dose range ~ 1 to 8 dpa (for both temperatures)
- **Creep data!**

High Dose Graphite (HDG) capsules

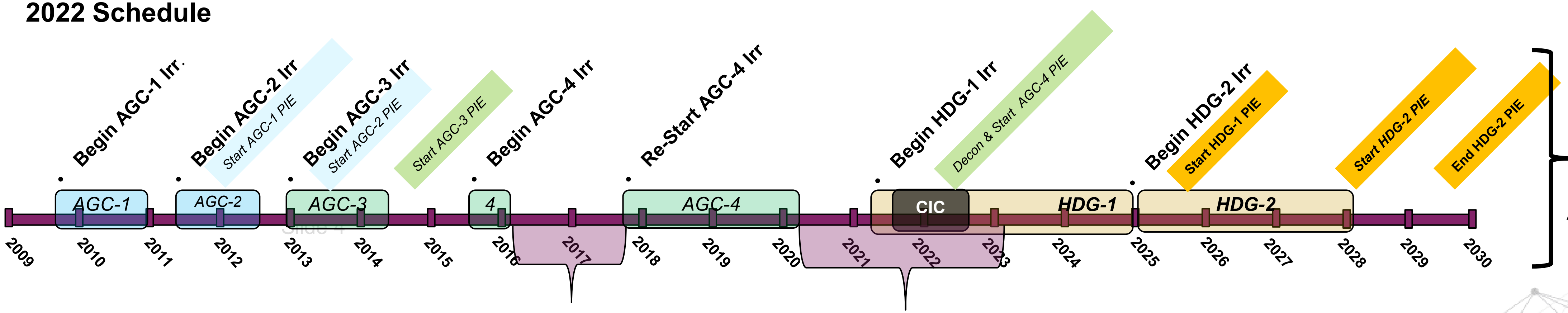
- Re-irradiate previous AGC specimens
- Higher max dose (15 dpa)
- Same Temperatures (600 – 800°C)
- **Higher dose creep data!**

AGC Experiment Status

2018 Schedule



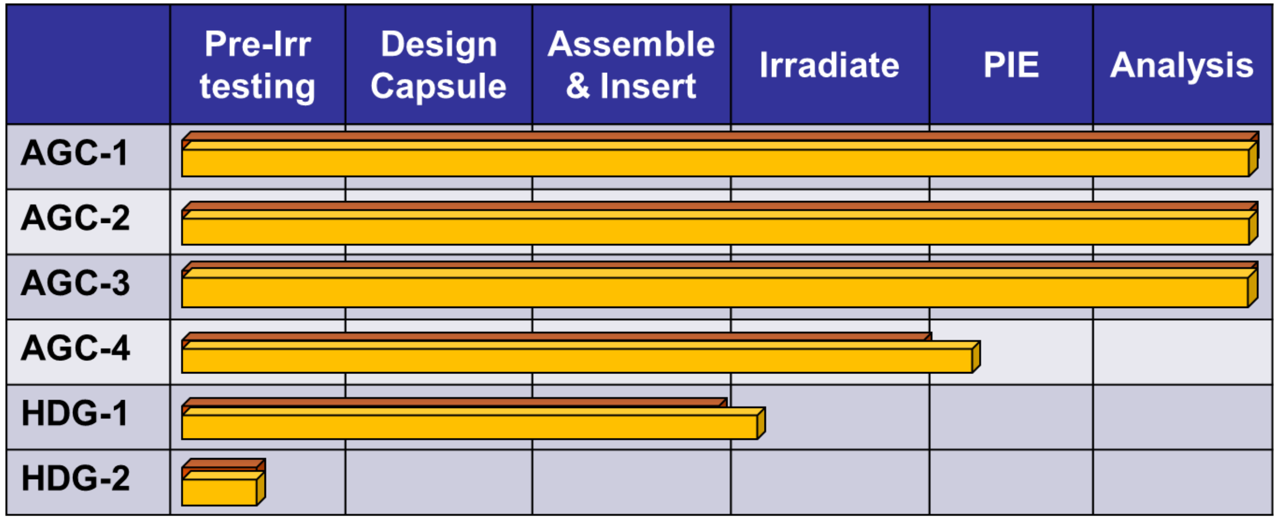
2022 Schedule



COVID & CIC added about 18 months to AGC schedule

Irradiation material properties (AGC Experiment)

- **AGC-1 & AGC-2 :** 600°C (0.5 to 7 dpa)
  - Initial irradiation, PIE, and analysis is complete
- **AGC-3 :** 800°C (0.5 to 3.5 dpa)
  - Initial irradiation, PIE, and analysis is complete
- **AGC-4 :** 800°C (3 to 8.5 dpa)
  - Irradiation complete (February 2020)
  - ***Specimen disassembly complete***
  - ***We have some specimens with high rad levels***
  - PIE (2022 – 2023)
- **HDG-1 :** 600°C (7 to 15 dpa)
  - Back in ATR – ready for irr: 2 more years to max. 15 dpa
  - **Re-irradiation of AGC-2 specimens**
    - *Added super-fine grain sized grades => of interest for MSR designs*
- **HDG-2 :** 800°C (7 to 15 dpa)
  - Irradiation begins 2023
  - Re-irradiation of AGC-3 & -4 specimens to max. 15 dpa

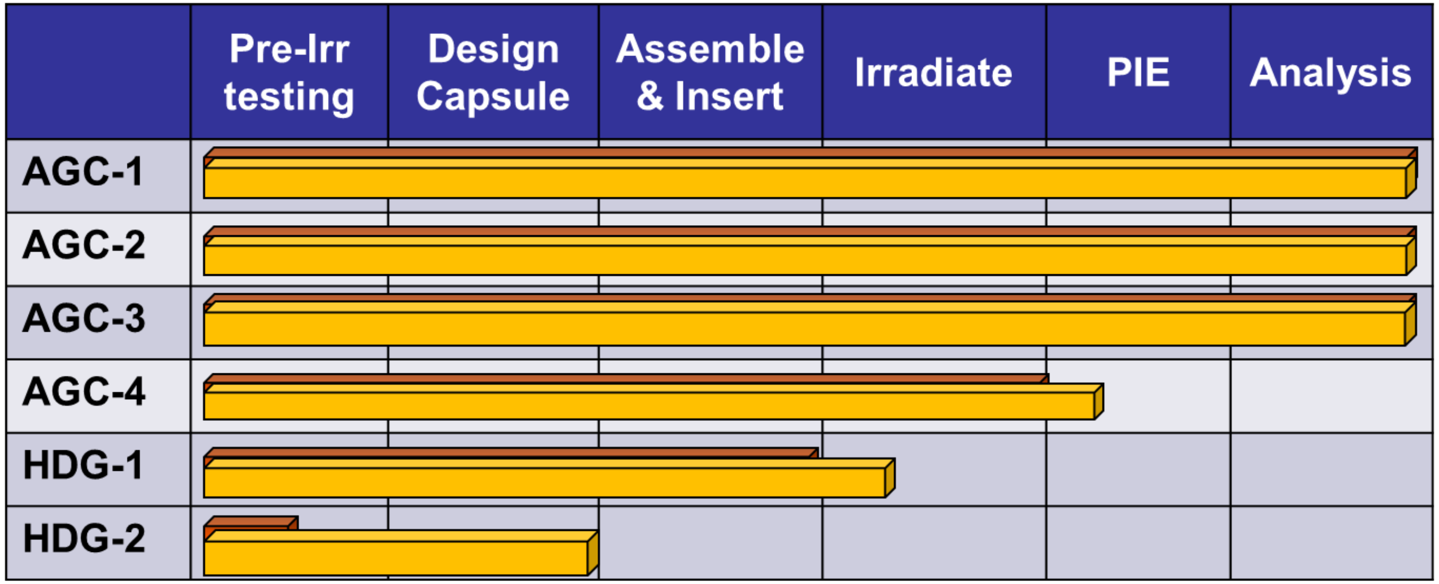


Pertinent Irradiated Graphite Reports
ECAR-5345, As-Run Physics Analysis for the AGC-4 Experiment Irradiated in the ATR, January 2021
ECAR-5414, As-Run Thermal Analysis for the AGC-4 Experiment Irradiated in the ATR, April 2021
INL/EXT-21-63591, AGC-4 Disassembly Report, July 2021

AGC Experiment Status

AGC Experiment Status:

- **AGC-1 & AGC-2 :** 600°C (0.5 to 7 dpa)
  - Initial irradiation, PIE, and analysis is complete
- **AGC-3 :** 800°C (0.5 to 3.5 dpa)
  - Initial irradiation, PIE, and analysis is complete
- **AGC-4 :** 800°C (3 to 8.5 dpa)
  - Irradiation complete (February 2020)
  - Disassembled July 2021
  - ***PIE has begun*** (2023 - 2024)
  - Complete PIE and issue reports (2024)
- **HDG-1 :** 600°C (7 to 15 dpa)
  - ***Back in reactor***: Start-up has been delayed
  - Two (2) more years until 15 dpa
  - Re-irradiation of AGC-2 specimens
- **HDG-2 :** 800°C (7 to 15 dpa)
  - Design of irradiation capsule initiated
  - Irradiation begins 2025
  - Re-irradiation of AGC-3 & -4 specimens to max. 15 dpa



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ECAR-5414, As-Run Thermal Analysis for the AGC-4 Experiment Irradiated in the ATR, April 2021
INL/EXT-21-63591, AGC-4 Disassembly Report, July 2021 ***To be re-issued 2023 (Rev 1) to add the decontamination activities***

Extracting piggyback samples
from machined Graphite Body

High activity levels detected

- A few specimens have high rad levels
- Special decon glovebox set-up
- Decontamination of all specimens
  - *Activity levels measured for individual specimens*
- Appears to be nickel contamination that cannot be wiped clean

PIE options based on activity levels

- AGC-4 PIE has begun on low rad level specimens
  - ***Approximately ½ of specimens have arrived at CCL***
  - ***Remaining samples expected by end of August***
- If activity levels are too high ➔ Limited PIE on the desert
  - Mass, density, and elastic/ shear modulus measurements

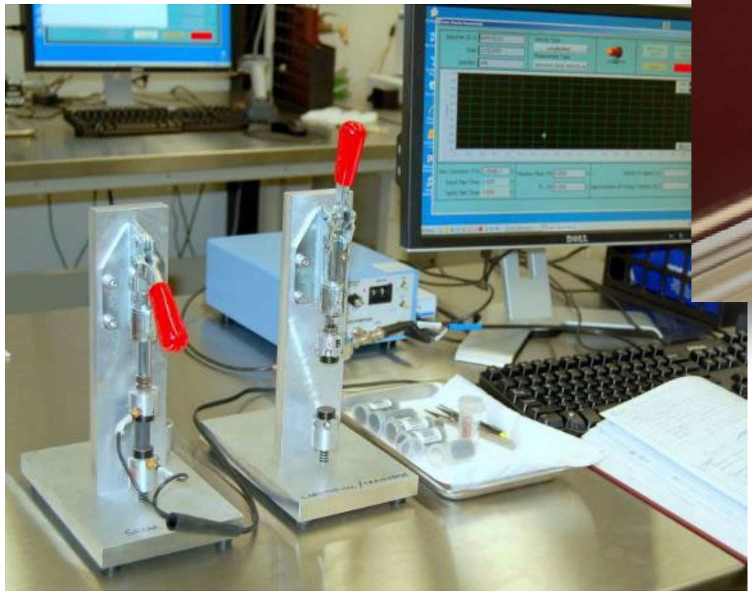
Typical lead lined shipping drum assembly (~5000 lbs) and new small quantity shipping drums (~50 lbs)

AGC-4 PIE Status

Split-Disk Strength

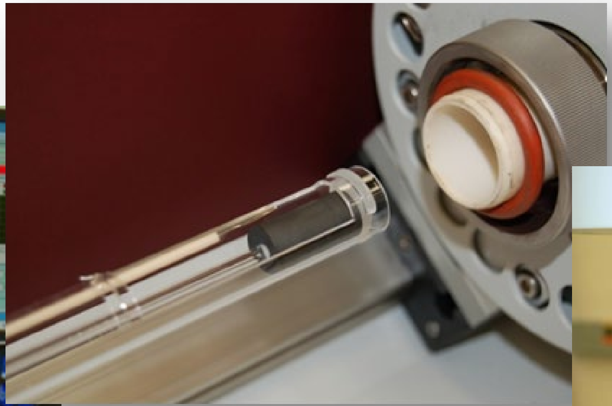
ASTM D8982

Stiffness modulus

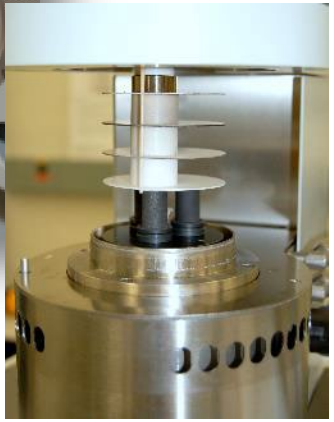


ASTM C 769

CTE



ASTM E 228-06



Physical & Thermal Properties Testing

- *Density*
- *Coefficient of Thermal Expansion*
- *Thermal Conductivity*
- *Resistivity*
- *Resonant Frequency (E_{DYN})*
- *Torsional Frequency (G_{DYN})*
- *Sonic Velocity*
- *Fracture Character**

Tested ~1/4 of specimens so far …

- HEPA system maintenance delays

Due to decontamination activities specimens will be shipped in small batches

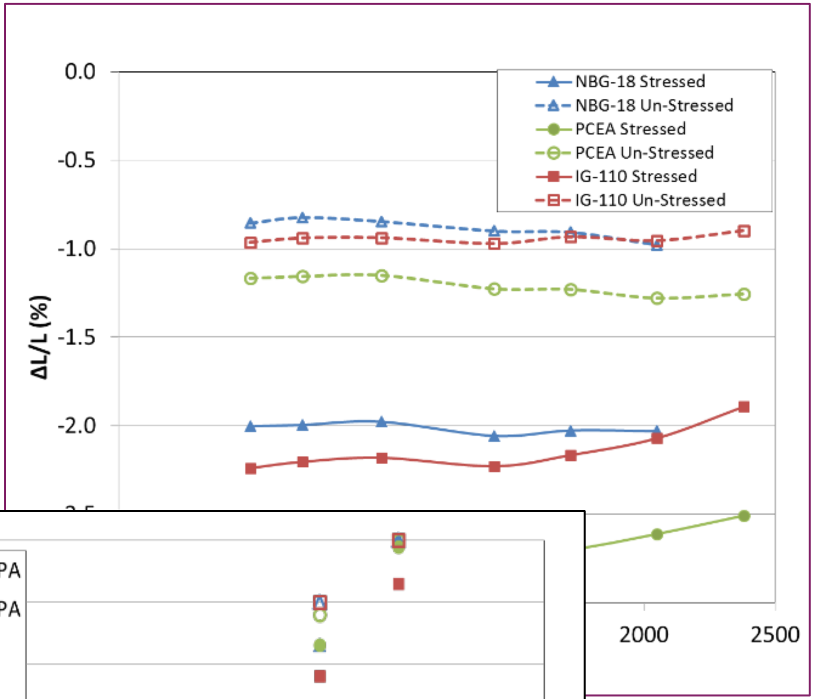
- Several small batches of specimens
- Much longer time to test
- Much easier to handle, no special equipment or training.

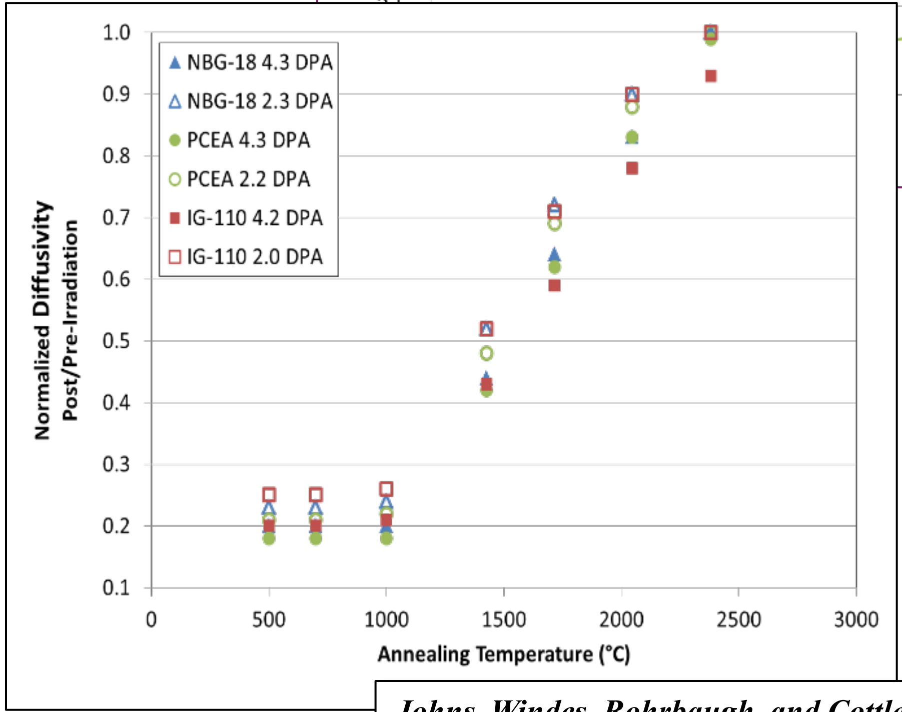
**Not a non-destructive evaluation*

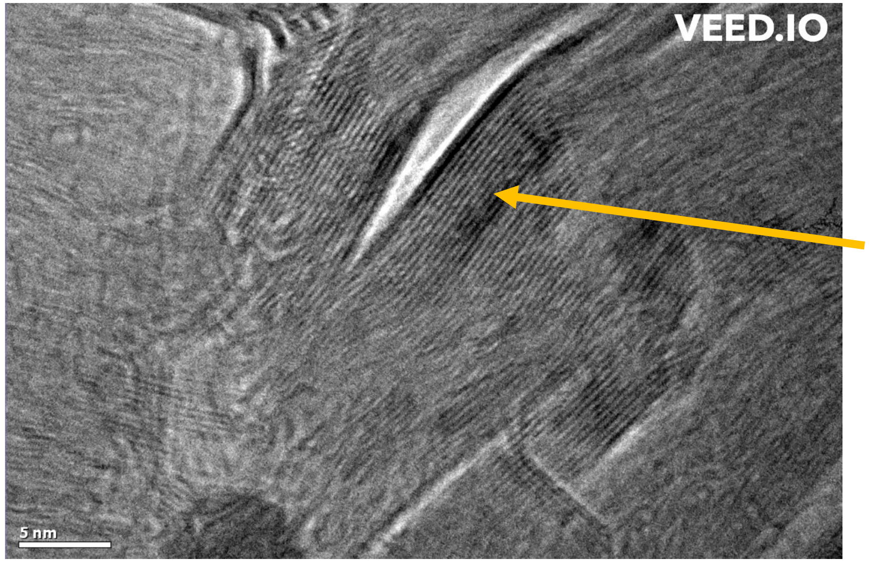
Irradiation data: Understanding graphite behavior

Irradiation damage mechanisms:

- New annealing studies
  - Changes to material properties after heat treatment
  - No dimensional change recovery until after graphitization temperatures
  - 100% recovery of thermal diffusivity > 2400C
- Underlying mechanisms to predict behavior
  - Material property changes, degradation behavior
  - Assist develop ASME rules for irradiated behavior







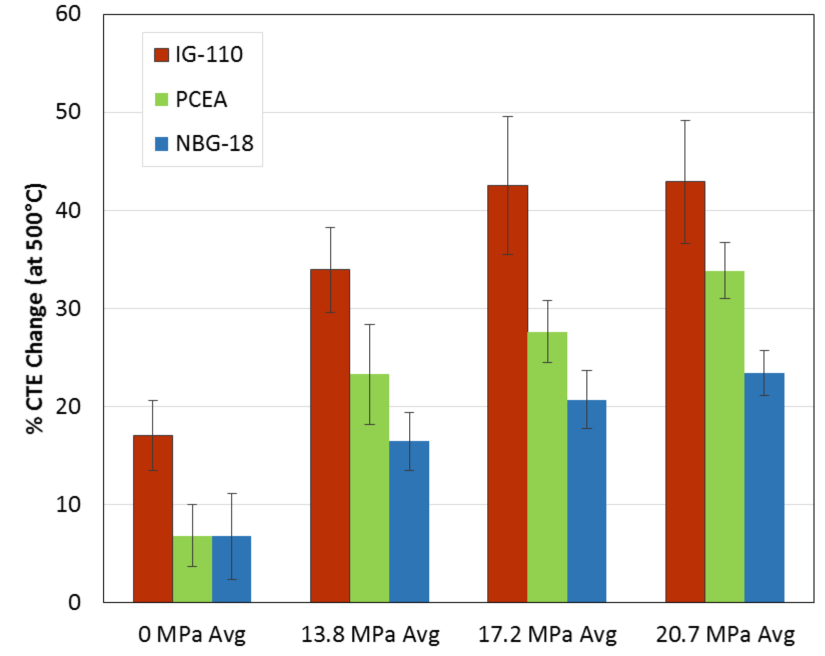
Crack closure

Johns, Windes, Rohrbaugh, and Cottle, "High-temperature annealing of irradiated nuclear grade graphite", Journal of Nuclear Materials, [154377 Vol. 779 June 2023]

Who/What will use the data?

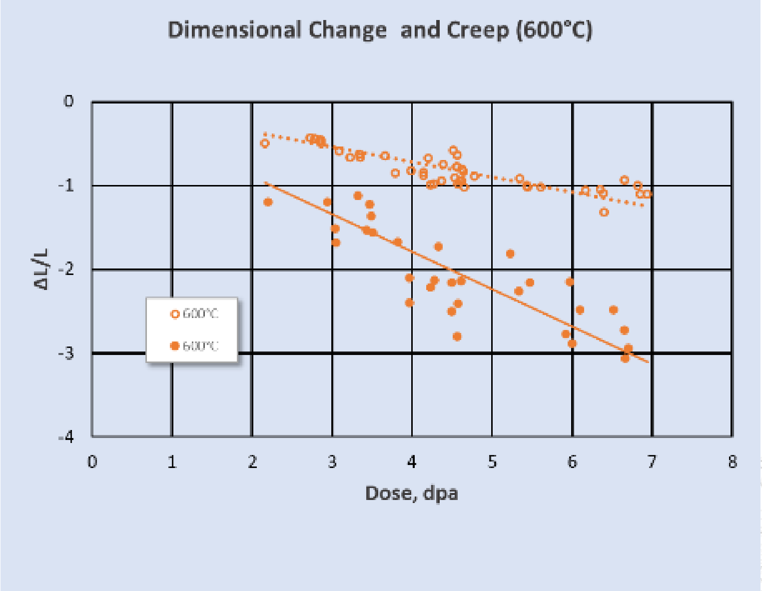
Commercial reactor design (Direct)

- Any design using the same parameters of AGC Experiment can use all data directly
  - *Same graphite grade,*
  - *T_{Irr} range : 500 – 850C,*
  - *Dose range : 1 to 8 dpa (15 dpa after HDG)*
- Irradiation dimensional change, creep rate, and material property changes
- Working how to provide commercial QA data from DOE QA data



Commercial reactor design (Indirect)

- Other HTR designs can indirectly use the AGC irradiation behavior and creep data
- *Combined with the ASME code methodology* the data can be used to demonstrate similar behavior
  - *Will need to justify how the graphite is similar*



ASME code development

- Potential code cases for
- Used to justify universal graphite response **up to turnaround**
  - *Up to turnaround: All grades behave similarly*
  - *Past turnaround dose: Grades are **not** similar*
  - *So long as your graphite grade is within the data "cloud"*
- Similar methodology for creep response/rate

Who/What will use the data?

NRC/Licensing questions on irradiation behavior

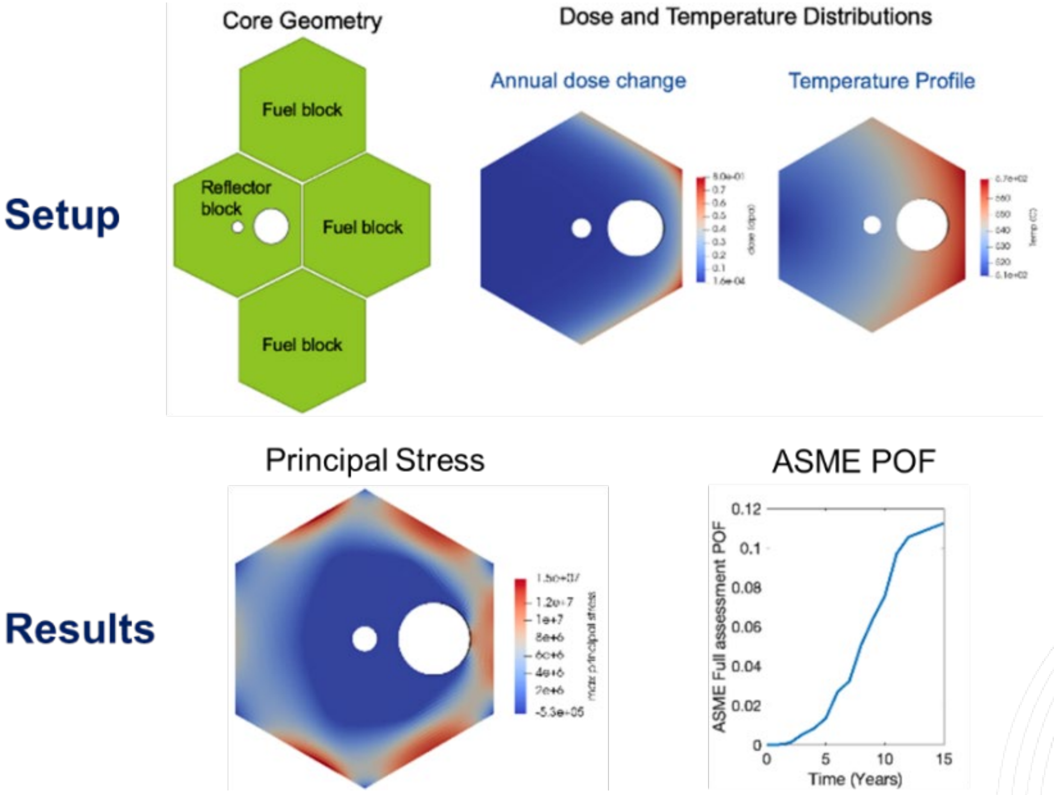
- Training, general questions, topical reports, etc.
- Assistance with acceptance of ASME code rules

Behavior model development

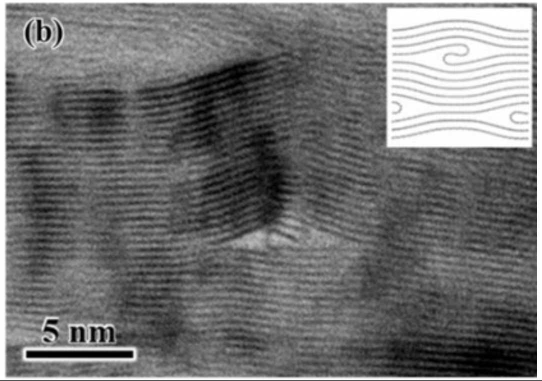
- Irradiation induced stress build-up (failure determination)
- Irradiated material property changes
- Combination of degradation (no empirical data possible)
  - *Irradiation + oxidation + Molten Salt*

• Other Collaborations

- GIF, IAEA, International and National fundamental studies



Fundamental studies are designed to explain the empirically measured results



Evidence of a "Buckle, ruck and tuck" defect proposed as possible underlying defect for irradiation creep

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