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

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Nuclear Energy University Program (NEUP) Fiscal Year 2021 Annual Planning Webinar Advanced Reactor Materials (Subtopics RC-1.1 & 1.2)

Sue Lesica
Office of Nuclear Energy
U.S. Department of Energy
August 10, 2020

Advanced Reactor Technologies (ART) Program

Mission:

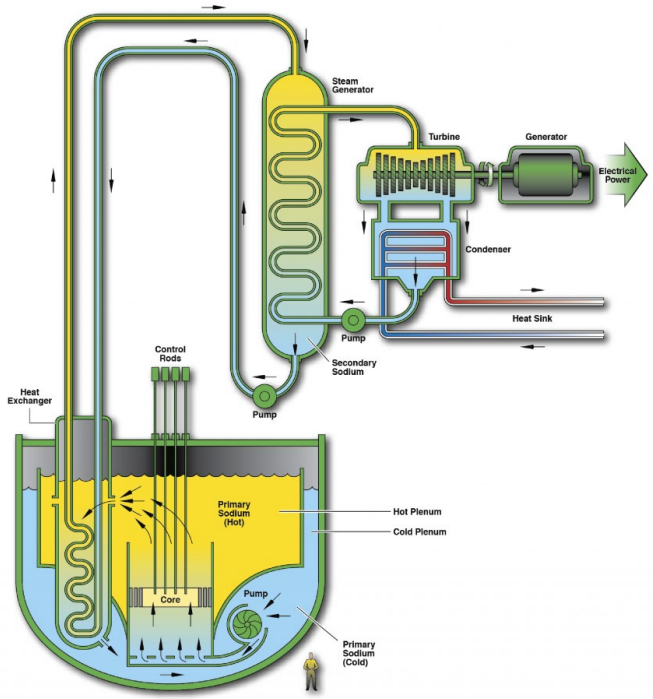
Identify and resolve the technical challenges to enable transition of advanced non-LWR reactor technologies and systems to support **detailed design, regulatory review and deployment** by the early 2030's

Objectives:

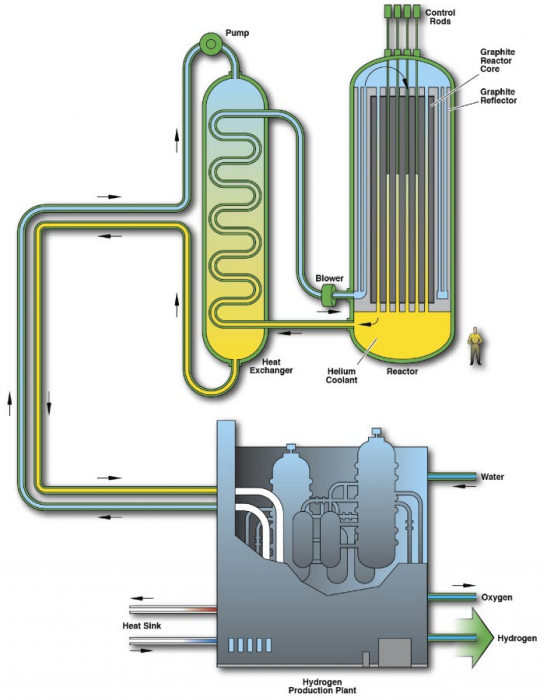
- Conduct focused research and development to **reduce technical barriers to deployment** of advanced nuclear energy systems
- Develop technologies that can enable new concepts and designs to achieve enhanced **affordability, safety, sustainability** and **flexibility** of use
- **Collaborate with industry** to identify and conduct essential research to reduce technical risk associated with advanced reactor technologies
- **Sustain technical expertise and capabilities** within **national laboratories** and **universities** to perform needed research
- Engage with Standards Developing Organizations (SDO's) to **address gaps in codes and standards** to support advanced reactor designs

ART Program Includes Advanced Reactor Materials R&D Activities

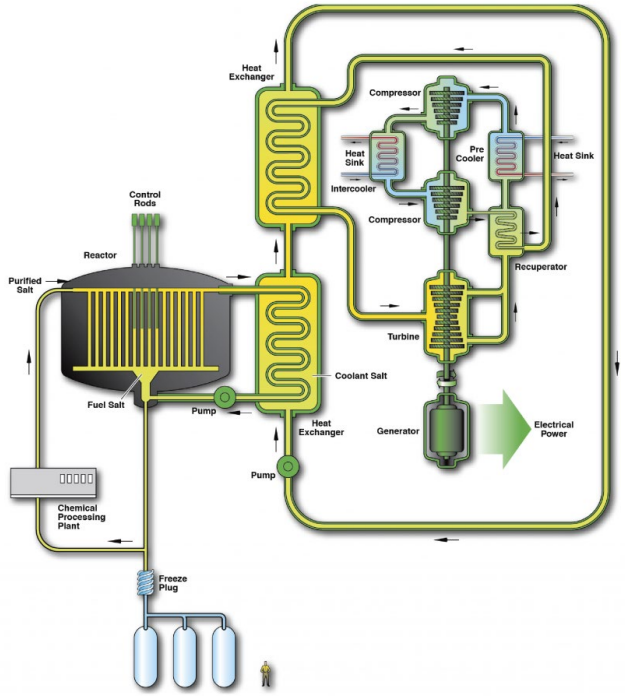
- Development and qualification of graphite and advanced alloys for advanced reactor systems
- Three advanced reactor systems to watch by 2030



Sodium Fast Reactor



Very High Temperature Reactor



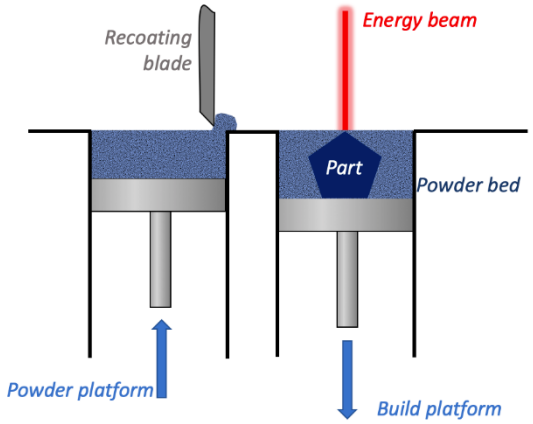
Molten Salt Reactor

Advanced Reactor Materials Addresses Two Significantly Different Materials Research Topics in FY21

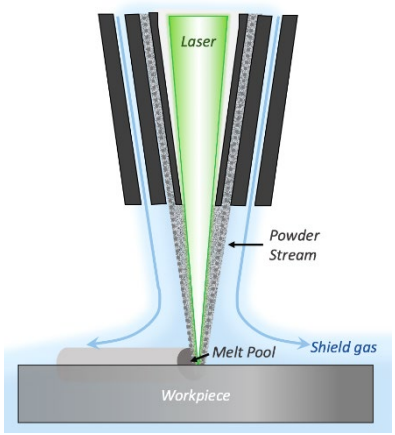
- RC-1.1 Qualification and acceptance protocols for additively manufactured metallic components
  - Additive manufacturing (AM) could lead to significant cost reduction and enhanced performance of advanced reactor systems
- RC-1.2 Effects of irradiation induced microstructure change in graphite
  - Understanding of irradiation behavior is important for the lifetime of graphite core components in thermal spectrum advanced reactors

RC-1.1 Qualification and Acceptance Protocols for AM Components

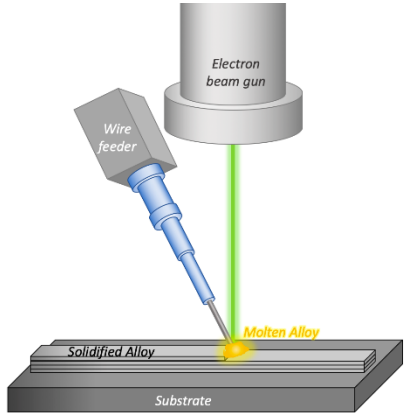
- AM could promote the deployment of future advanced nuclear reactors by enabling complex component geometries, increasing design flexibility and thus enabling more efficient designs
  - AM could include processes such as powder bed fabrications, wire feed methods and binder-jet processes, etc.



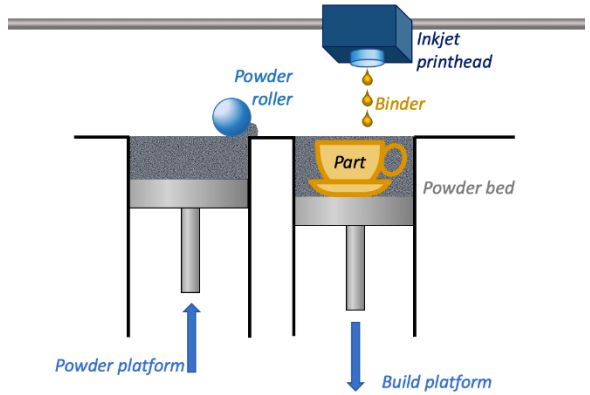
Schematic of Powder-Bed Fusion (PBF) process



Schematic of Directed Energy Deposition (DED) process with powder feed



Schematic of Electron Beam Welding (EBW) process with wire feeder



Schematic of Binder Jetting process with colored binder

Additive Manufacturing is a Disruptive Technology

- AM can reduce the number of steps in fabricating components compared to traditional fabrication processes – leading to significant cost reduction
- Future AM techniques could produce architected materials with performance and functionality that cannot be achieved using conventional manufacturing processes, hence could enable even more capable and compelling reactor designs
- Rapid advances in AM technologies are taking place across many sectors
  - DOE-NE (TCR, AMM), other agency and industry (NASA, DOT, aerospace, etc.)
- Advanced reactor applications are much more specialized as compared with the applications being addressed in this technology space
  - Elevated temperatures
  - Long design lifetimes (could be up to 60 years)
  - Time dependent structural failure modes: creep, fatigue and creep-fatigue
- Due to different reactor coolant environments, our materials selection is much more limited; there are only 6 qualified materials (in wrought product forms) in Section III, Division 5 of the ASME Code

Gaps in Applying AM to Support Advanced Reactor Deployment

- In order to leverage the AM technology to support advanced reactor deployment, reactor components fabricated by AM must be licensable by the U.S. NRC
- Similar to components fabricated from traditional technology, AM components must meet or exceed the expected properties used in the design of the part for the entire design lifetime, as required by the regulatory framework
- Due to differences in powder attributes, fabrication environment, and processing parameters in the AM methods, different material microstructures and/or defects structure can result in the build volume
- How to ascertain that a fabricator has met the contracted performance requirements is a key challenge in licensing AM components
- This needs to be addressed before the benefits of AM technology can be realized to support advanced reactor deployment

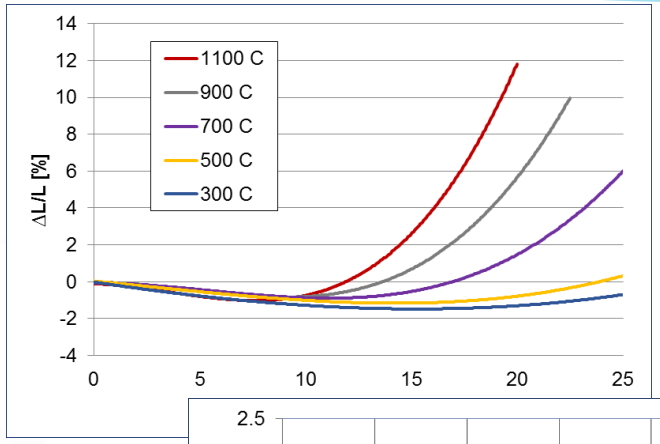
RC-1.1 Scope on AM Qualification and Acceptance Protocols

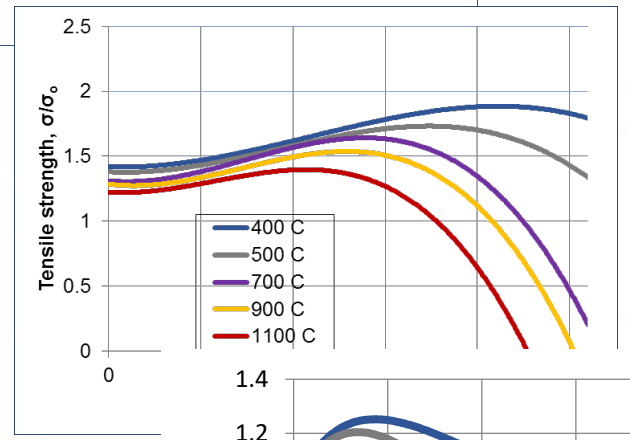
- Objective:
  - Develop qualification/acceptance protocols to provide a reasonable assurance for AM components to perform structurally as designed for elevated temperature cyclic service and intended design lifetime in order to meet regulatory requirements
- Protocols could based on
  - Inspection, testing, and characterization of AM witness samples
  - Data from in-situ process monitoring of the AM processes
  - Modeling and simulation techniques
  - Others
- Understanding the relationship between microstructure, properties, and performance could be helpful to identifying key microstructural features to be characterized
- Proposed work can be based on either Powder-Bed Fusion or Directed Energy Deposition
  - Material of interest is 316H, an ASME Section III, Division 5 qualified Class A material
  - A maximum operating temperature of 650C, a design lifetime of 100,000 h and some reasonable thermal transients can be assumed to demonstrate the effectiveness of the qualification/acceptance protocols
  - The proposed work will be more relevant if it covers both AM methods
  - Procurement of AM equipment is out of scope

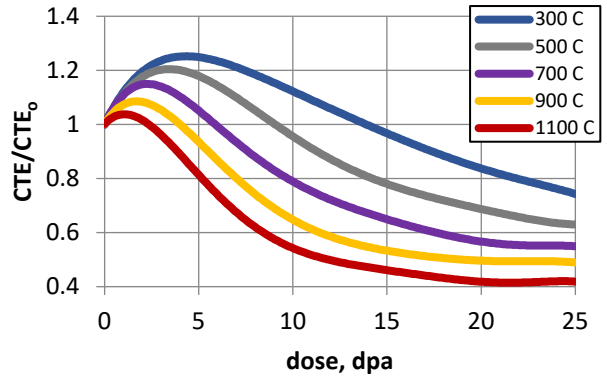
Irradiation Effects on Graphite Properties

ADVANCED REACTOR TECHNOLOGIES

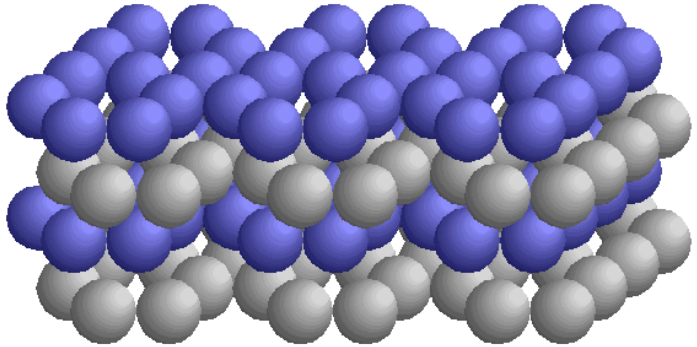
- Irradiation induced changes **must** be considered in core design
- Significant changes occur during normal operation in:
  - Component dimensions
    - *Components actually shrink …*
    - *Until **Turnaround** when they begin to expand until failure*
  - Density
    - *Components become more dense …*
    - *After **Turnaround** dose they decrease in density*
  - Strength and modulus
    - *Graphite gets stronger and stiffer with irradiation …*
    - *Until **Turnaround** dose is achieved. It then decreases*
  - Thermal conductivity
    - *Decreases almost immediately to ~30% of unirradiated values*
  - Coefficient of thermal expansion
    - *Initially increases but then reduces before **Turnaround** until saturation*
  - Oxidation rate
    - *Oxidation rate increase even under densification*
- Significant changes do not typically occur in the following properties:
  - Neutron moderation, specific heat capacity, emissivity, heat capacity

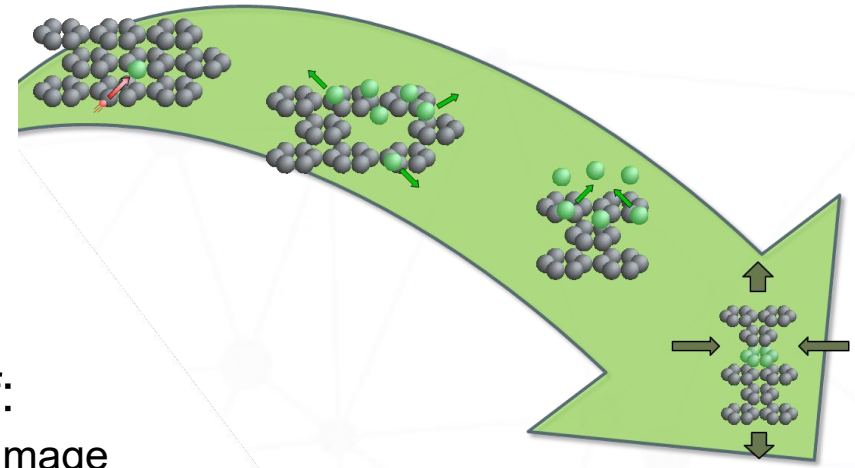






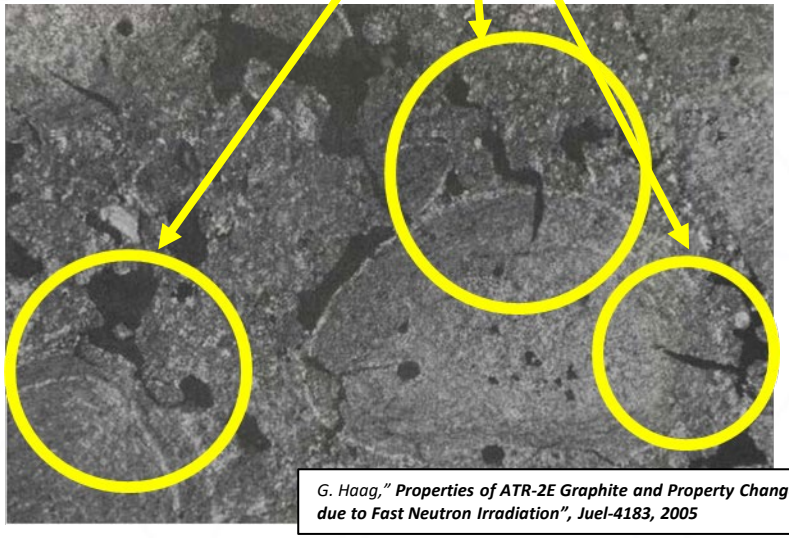
Graphite irradiation behavior





- A complex combination of:
  - Atomic & crystallographic damage
  - Formation of microstructure length-scale defects (porosity/cracks)
- Ballistic damage to atomic crystal structure
  - Atoms removed from crystal structure position
- Atomic damage propagates into bulk microstructures
  - Crystal deformations stack up within bulk microstructure
  - Porosity (cracks) are dose dependent

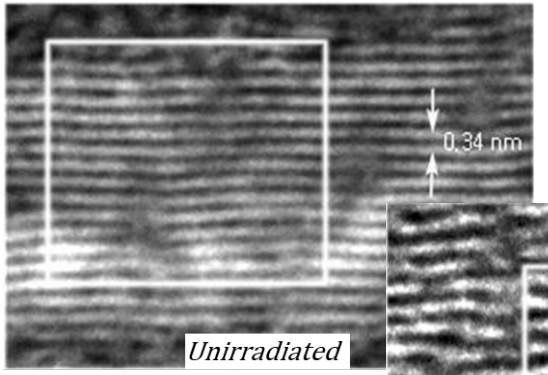
Cracks form after turnaround dose is achieved



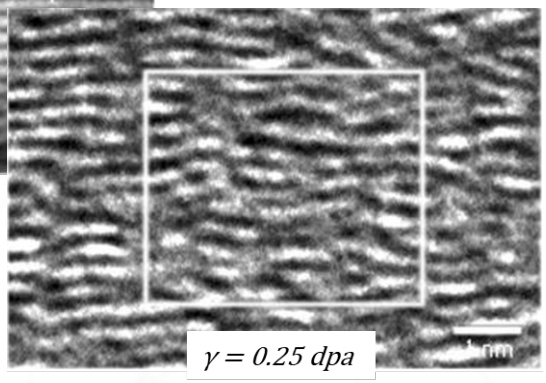
G. Haag," ***Properties of ATR-2E Graphite and Property Changes due to Fast Neutron Irradiation", Juel-4183, 2005***

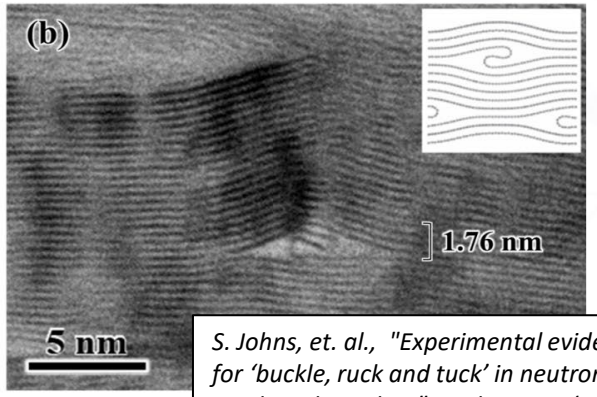
Atomic irradiation damage

- While we still need a lot more atomic displacement research
  - Many recent experimental studies have been conducted
  - Numerous models developed
- It's time to look at next step
  - Very important to licensing a new HTR design

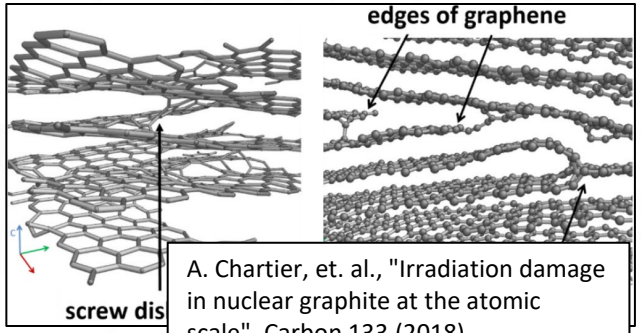


A. Asthana et al, J. Appl. Cryst., (2005) **38**, 361-367

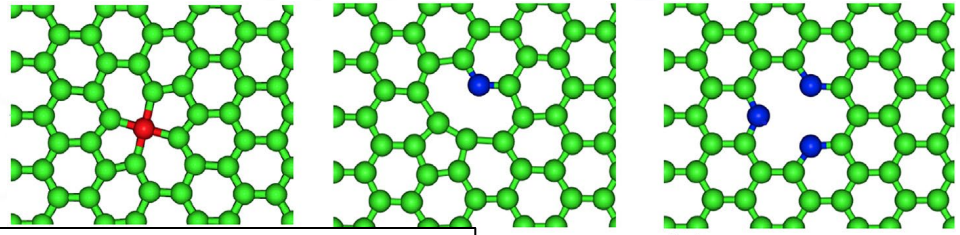




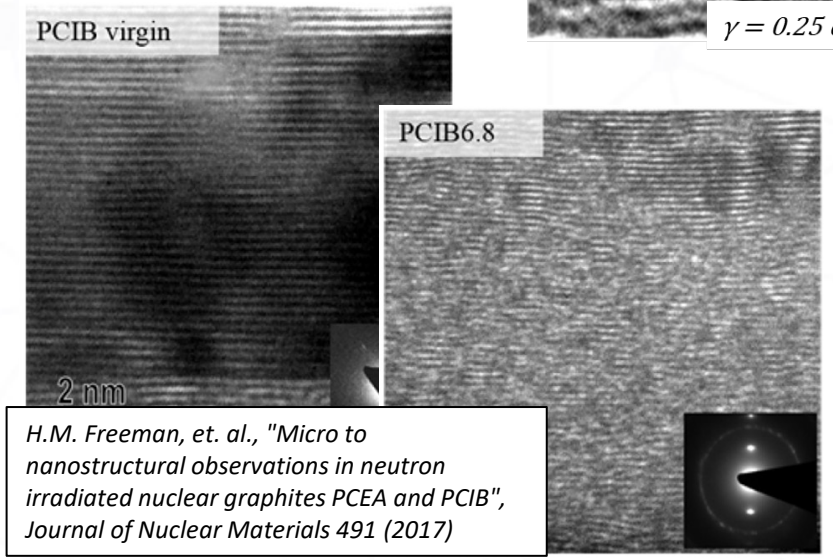
S. Johns, et. al., "Experimental evidence for 'buckle, ruck and tuck' in neutron irradiated graphite", Carbon 159 (2020)



A. Chartier, et. al., "Irradiation damage in nuclear graphite at the atomic scale", Carbon 133 (2018)

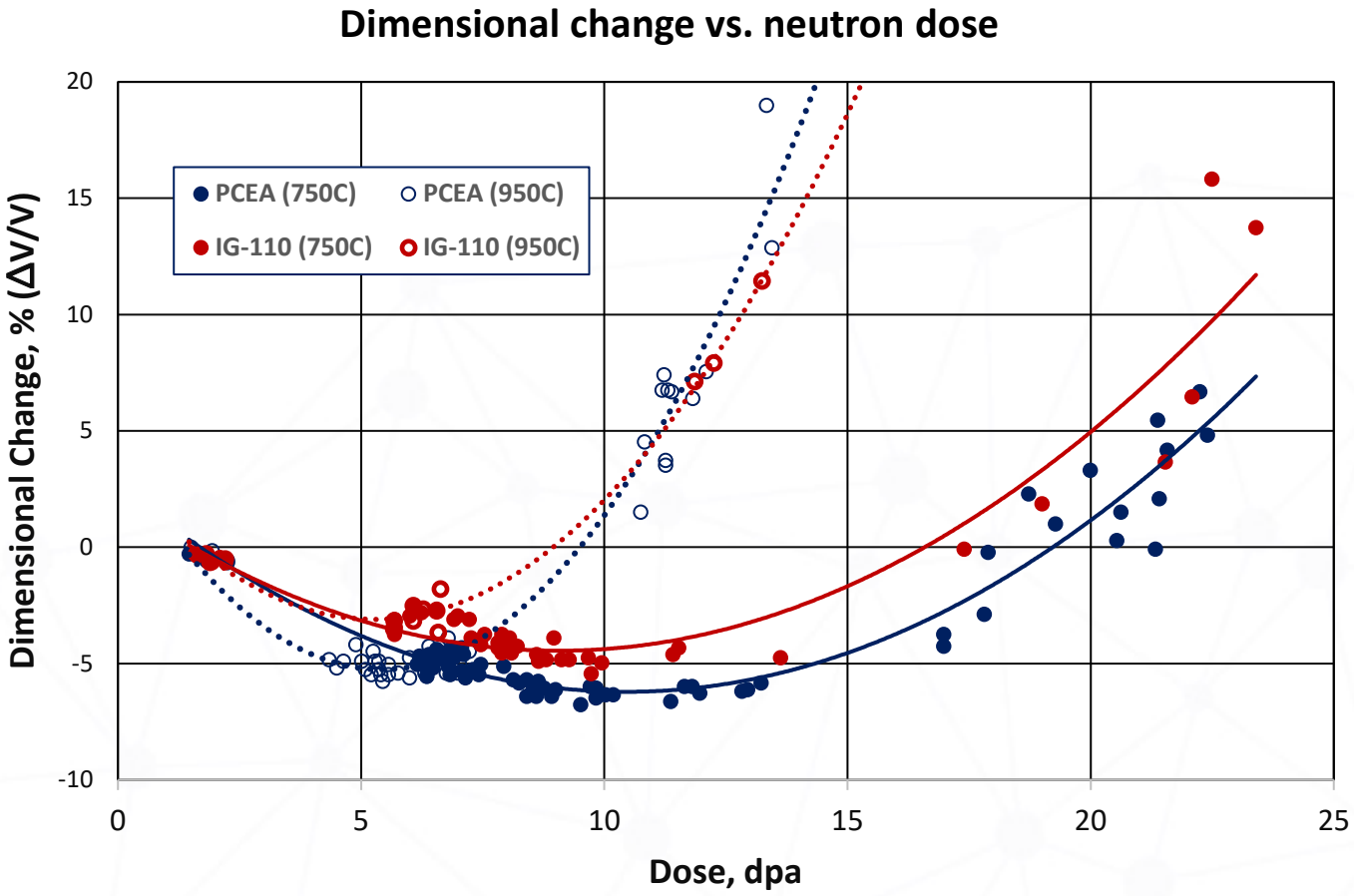


Y. Zhou, et. al. "Modelling defect evolution in irradiated graphite", Carbon 154 (2019)



H.M. Freeman, et. al., "Micro to nanostructural observations in neutron irradiated nuclear graphites PCEA and PCIB", Journal of Nuclear Materials 491 (2017)

Microstructure Change (Dimensional Change)



From: M.C.R. Heijna, S. de Groot, J.A. Vreeling, "Comparison of irradiation behaviour of HTR graphite grades", Journal of Nuclear Materials 492 (2017) 148e156

- What is it?
  - Point where "Bulk" microstructural **densification** stops. Microcracking begins.
  - Point where irradiation induced material property changes begin to reverse.
- What's going on?
  - Theory: C-axis growth & a-axis shrinkage of crystallites under irradiation
    - C-axis shrinkage is hidden by accommodating porosity/cracks
    - Only see a-axis shrinkage until accommodating porosity/cracks are filled
    - **This is a bulk observation** (Not microscopic)
  - Once accommodating porosity is filled the bulk response is volumetric expansion
- Turnaround dose changes significantly with temperature
  - IG-110 (50μm) ➔ 10 dpa to 5 dpa
  - PCEA (1800μm) ➔ 11 dpa to 6 dpa

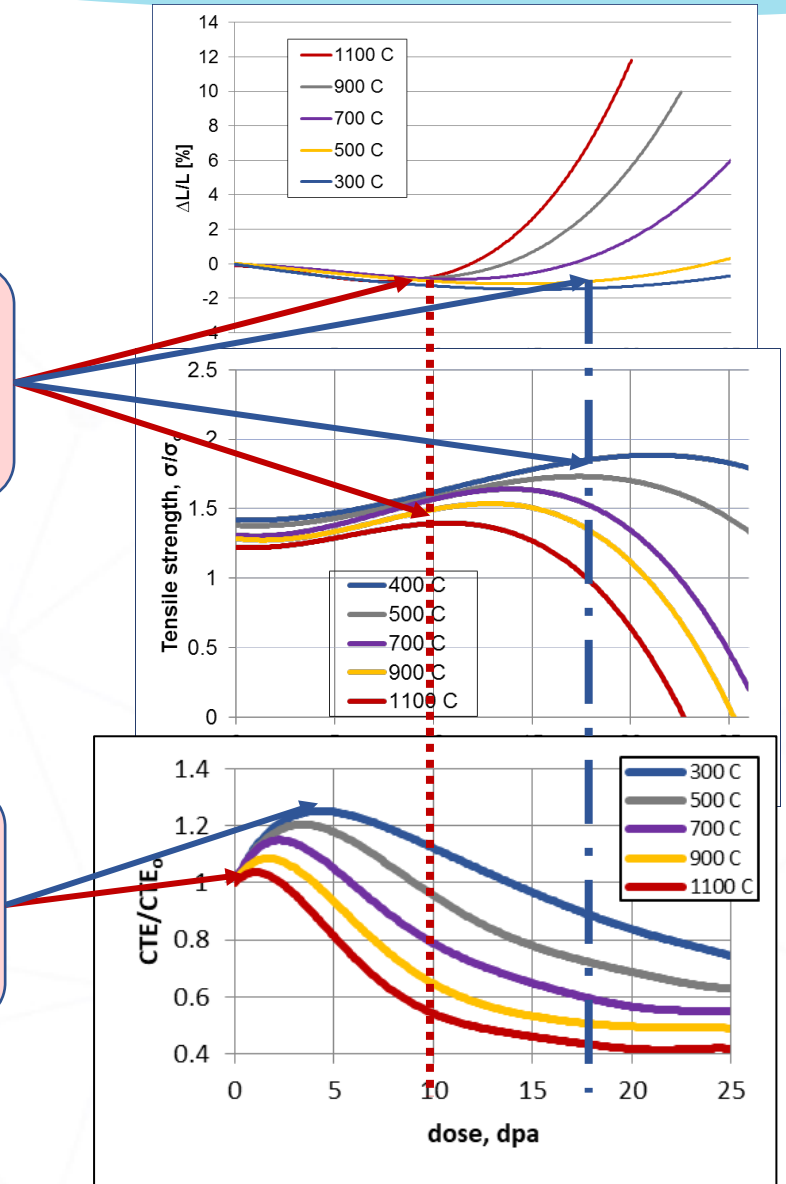
How does microstructure affect properties?

ADVANCED REACTOR TECHNOLOGIES

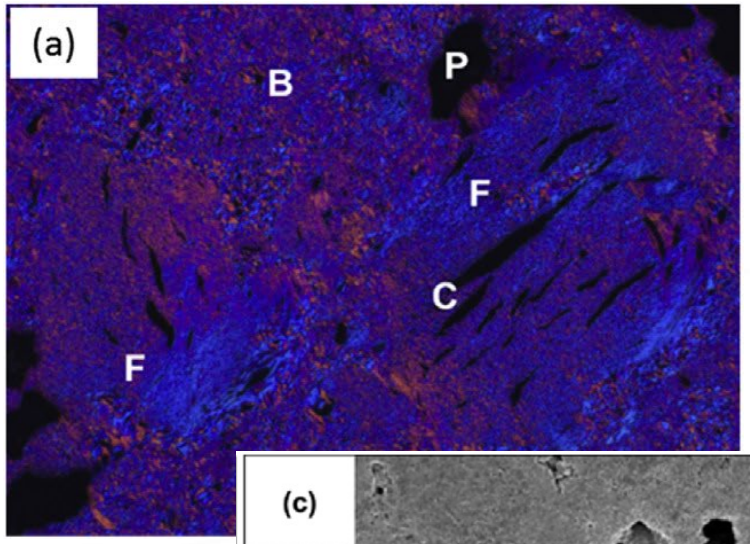
- Let's compare behavior to microstructure change (dimensional change)
  - The turnaround dose appears to have a large (direct ?) affect on bulk density, strength, and modulus (Young's and Shear).
  - But it appears that other bulk properties such as CTE, thermal diffusivity, and isotropy are affected differently.
- Why?
  - Obviously the bulk material properties have different sensitivities to microstructural changes
    - Densification versus volumetric expansion
    - Pore/crack growth
  - What part of microstructure change affects bulk material property?
    - What are the underlying mechanisms which determine the bulk material response?
    - Are they the same for all material properties?

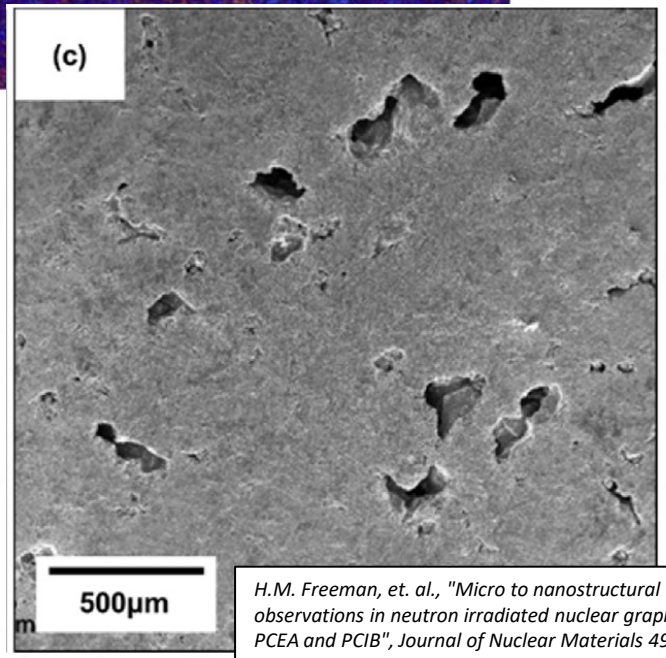
Strength starts to decrease right at turnaround dose

But CTE begins to decrease much sooner (lower dose)



Research Objectives





H.M. Freeman, et. al., "Micro to nanostructural observations in neutron irradiated nuclear graphites PCEA and PCIB", Journal of Nuclear Materials 491 (2017)

- Research should focus on determining what is responsible for bulk changes
  - What are underlying mechanisms?
    - Pore/crack growth
      - Size, shape, and orientation
    - Irradiation induced and fabrication defects
  - Consider the complexity of microstructure
    - Grain (filler) versus binder versus porosity versus microcrack phases
    - Densification in some microstructure areas while cracking in other areas
- Unirradiated and irradiated testing
  - Need to differentiate microstructure & irradiation damage
  - We're looking at microstructure changes *after* irradiation
    - Thermal treatment, chemical reactions, mechanical loading to induce microstructure defects which affect property
  - Will need to verify behavior with irradiated specimens
- Focus on mechanical properties
  - Density, strength, modulus, isotropy (grain orientation)

Points of Contact (POC)

- Federal POC
  - Sue Lesica
  - sue.lesica@nuclear.energy.gov
  - (301) 903-8755

- RC-1.1 Technical POC
  - Sam Sham
  - ssham@anl.gov
  - (630) 252-7873

- RC-1.2 Technical POC
  - William Windes
  - William.Windes@inl.gov
  - (208) 526-6985