Department of Energy (DOE)
Advanced Reactor Technologies (ART)
R&D Program

Nuclear Graphite Research Needs

Will Windes
Idaho National Laboratory

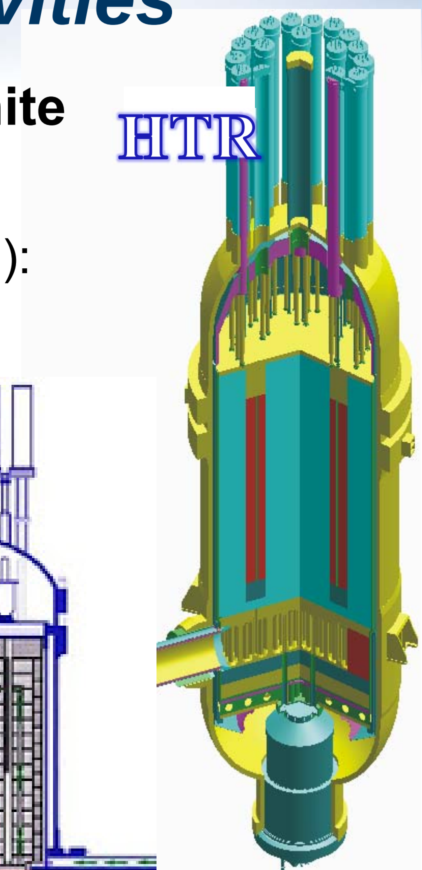
DOE-NE NEET Cross-cut Coordination Meeting August 15-16, 2016

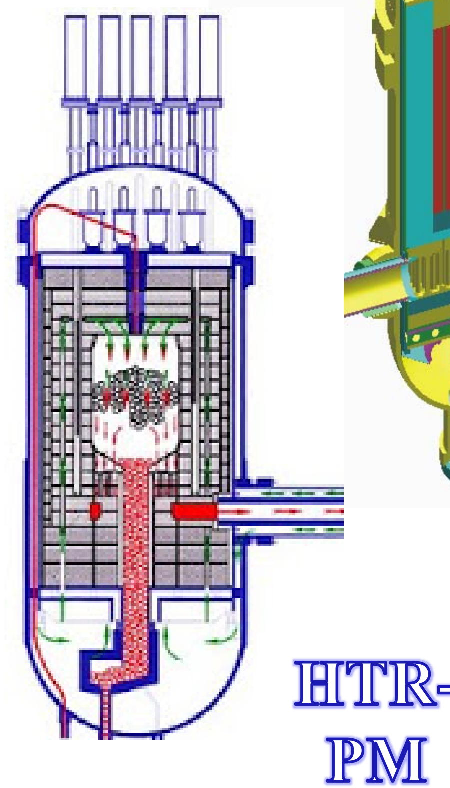
Why Research Graphite?

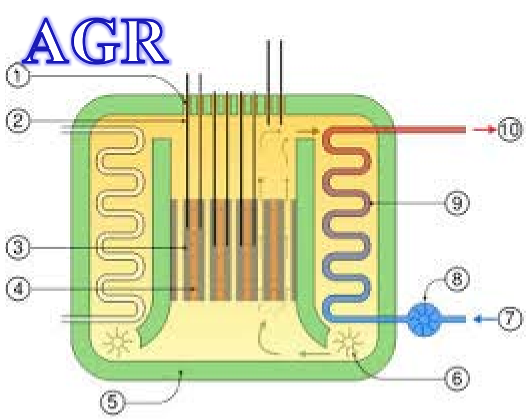
- Lessons we've learned from other graphite core reactor programs
  - After Reactor Start-up…
    - Interestingly - fuel is not considered life limiting component after start-up
    - **Graphite is life limiting component of reactor**
      - Degradation issues of graphite – normal and accident operations
      - Changes resulting from irradiation – structural integrity, cracks (irradiation creep), fracture
  - NRC will require understanding of the primary structural core material
    - Material properties needed for license approval before reactor start-up, and
    - Predicting core behavior during normal and off-normal operation
- Primary objectives of graphite components
  - Must keep the fuel safe
    - Must keep temperature "low" – thermal conductivity
    - Must maintain structural integrity – strength and irradiation behavior
      - **Creep behavior → Reduces cracks resulting from irradiation stresses**
  - Provides core structure
    - Cooling channel integrity, control rod insertion, and stable fuel configuration

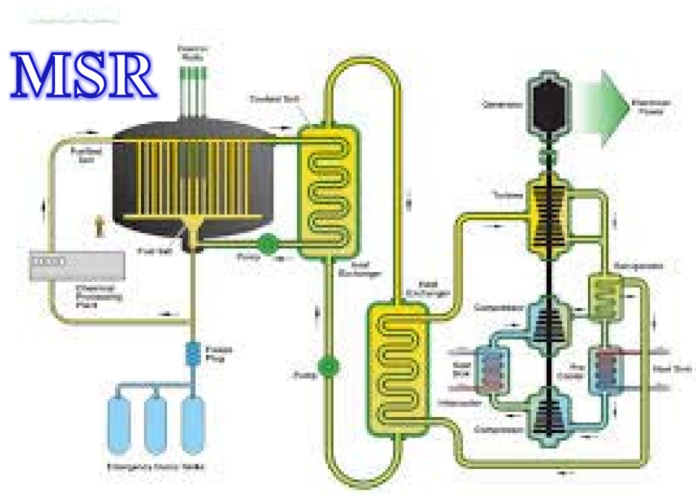
Primary function of Graphite R&D activities

- **Defines the safe working envelope for nuclear graphite**
  - Current and future nuclear graphite components
  - Applicable for multiple DOE reactor designs (cross-cutting):
    - HTR (both PB and Prismatic) and MSR designs
- **Data/analysis will be codified**
  - Data will be used in new ASME Code
  - Code requires use of irradiation data and high temperature behavior



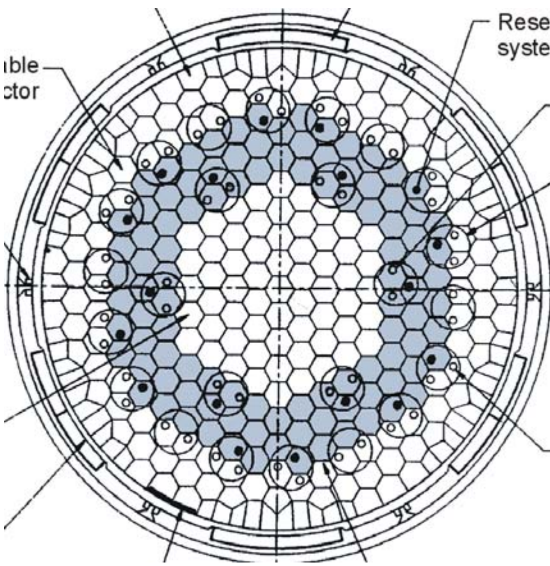


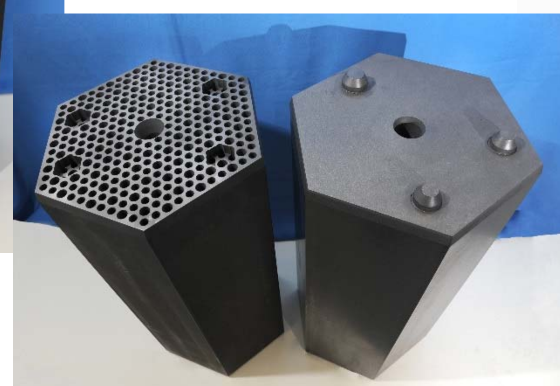
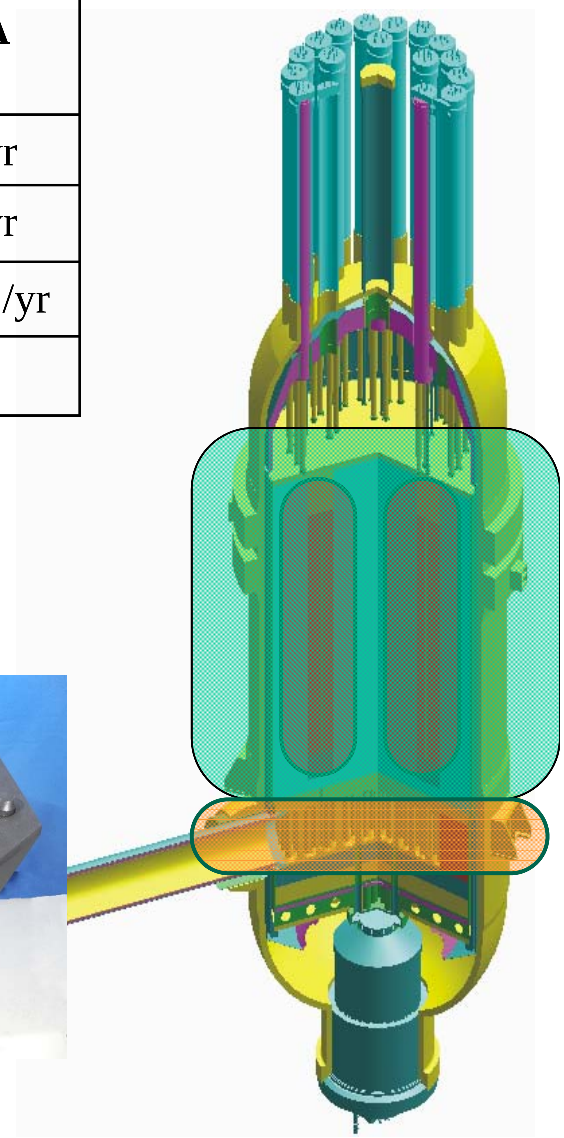




Graphite Core Components

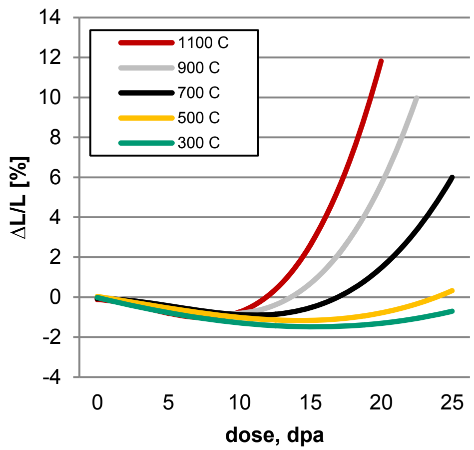
Component	Max. Normal Operation	Off-Normal	DPA
Graphite fuel block	900-1200ºC	~1400ºC	~ 0.8/yr
Reflector blocks	600-900ºC	~1200ºC	~ 0.5/yr
Core support columns	1000-1200ºC	~1200ºC	~0.001/yr
Other components	250 - 350ºC	~300-600ºC	Varies

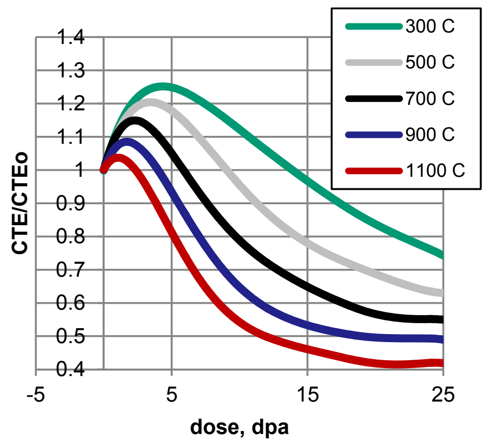


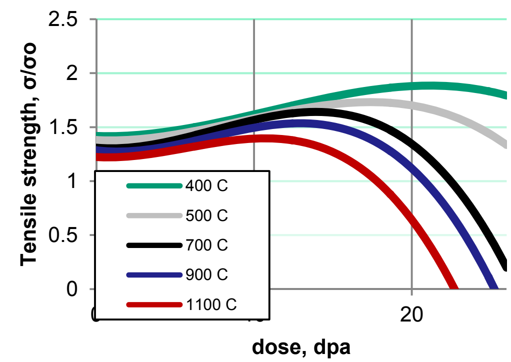



Material Issues

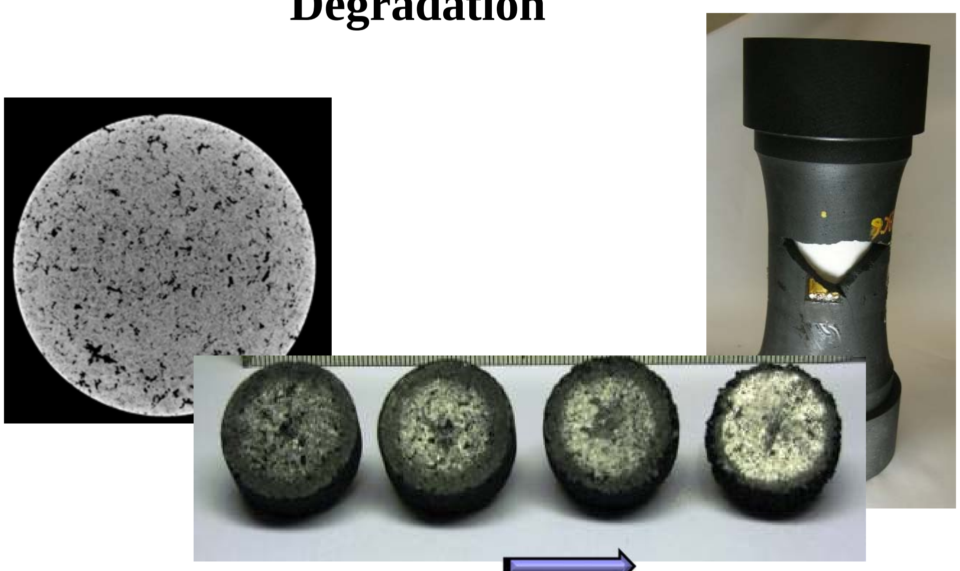
Property changes from irradiation and environment



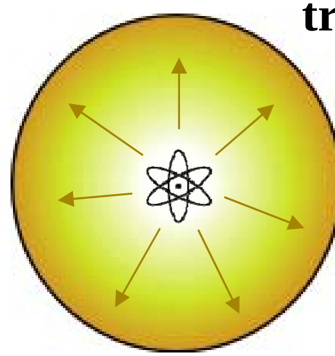


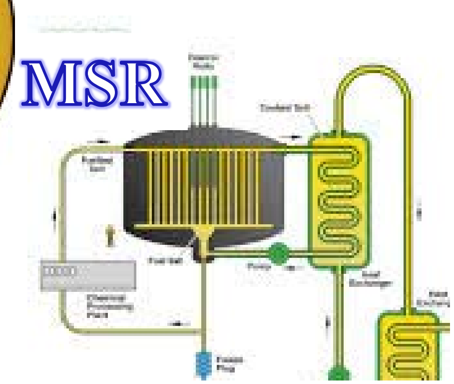


Degradation



Fission product transport/retention





Main Material Properties of Interest

Irradiation Dimensional Change

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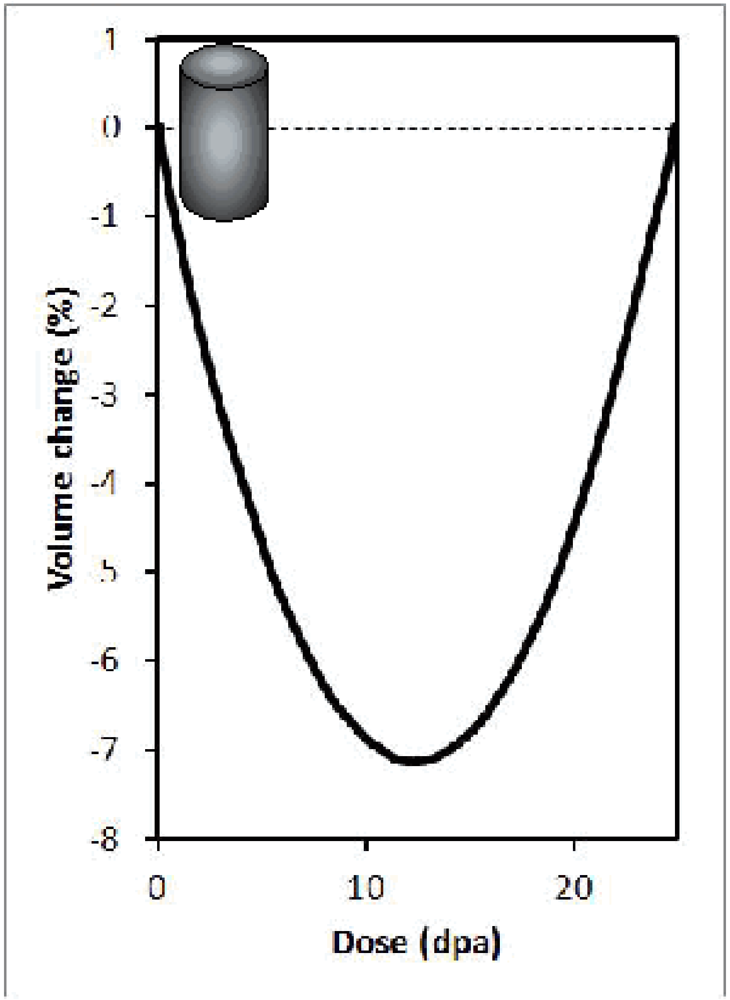

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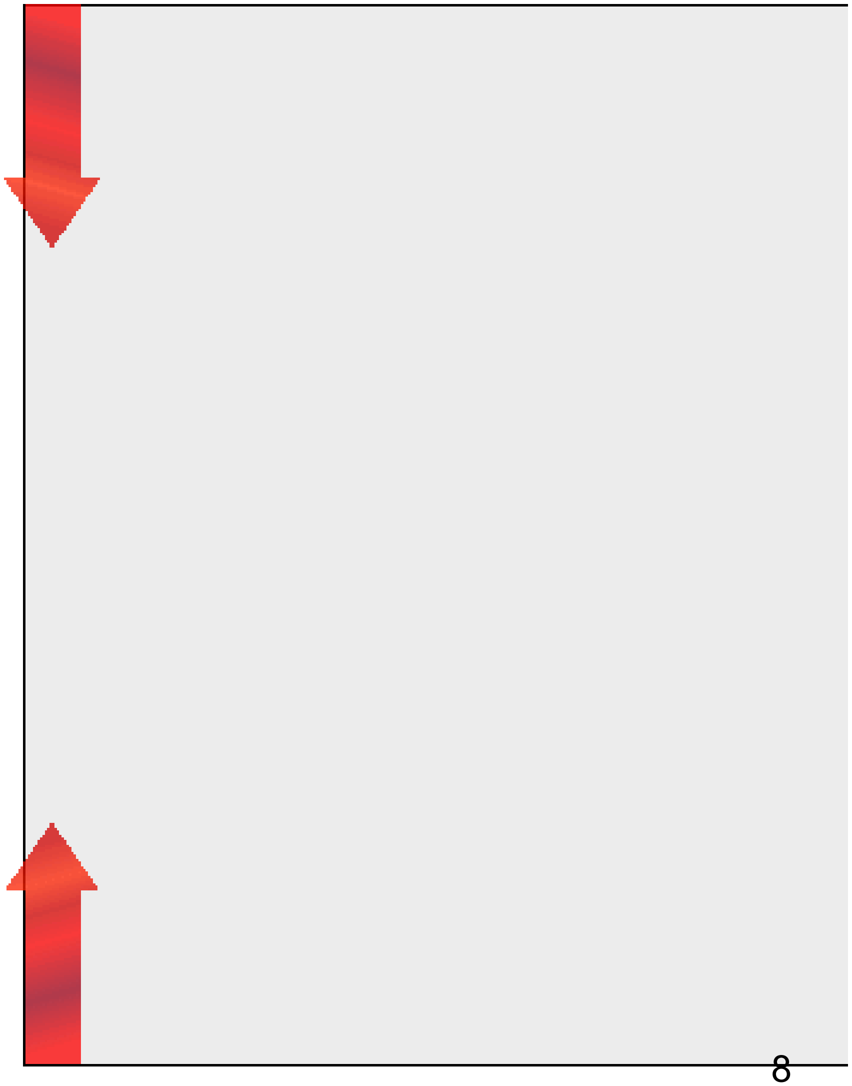

Main Material Properties of Interest

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

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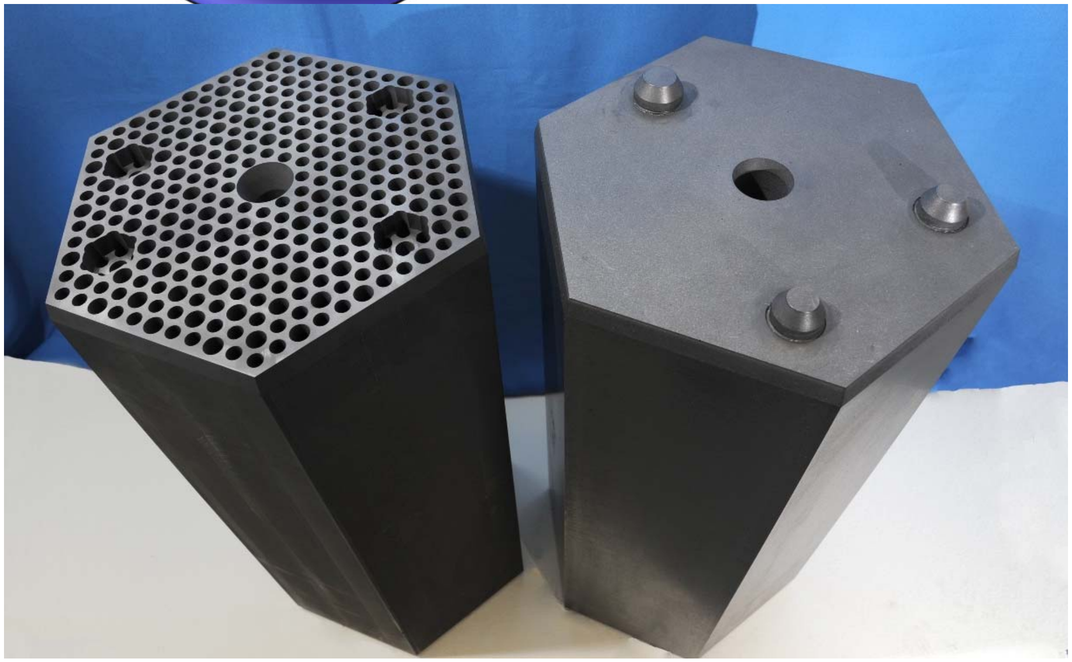

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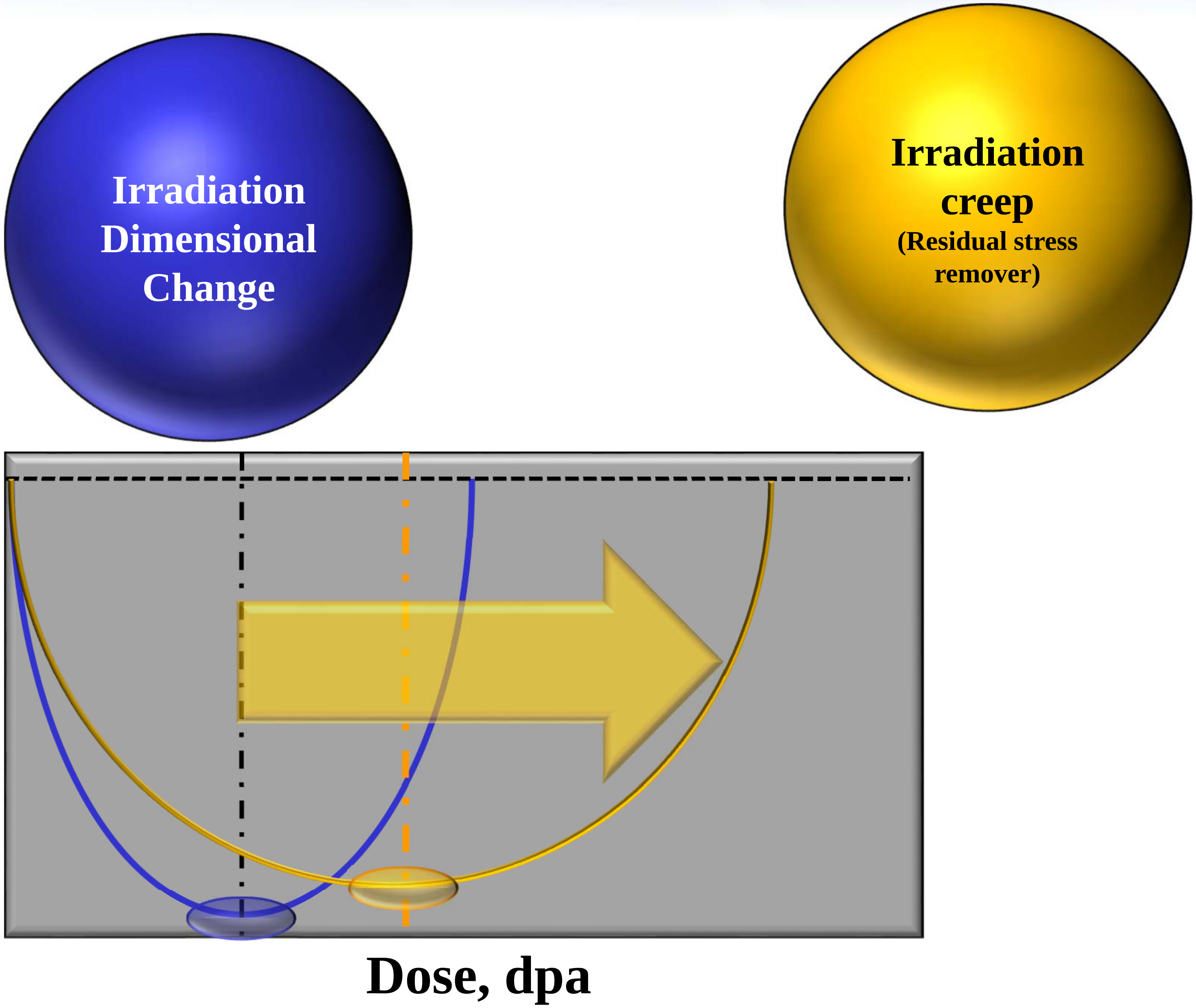

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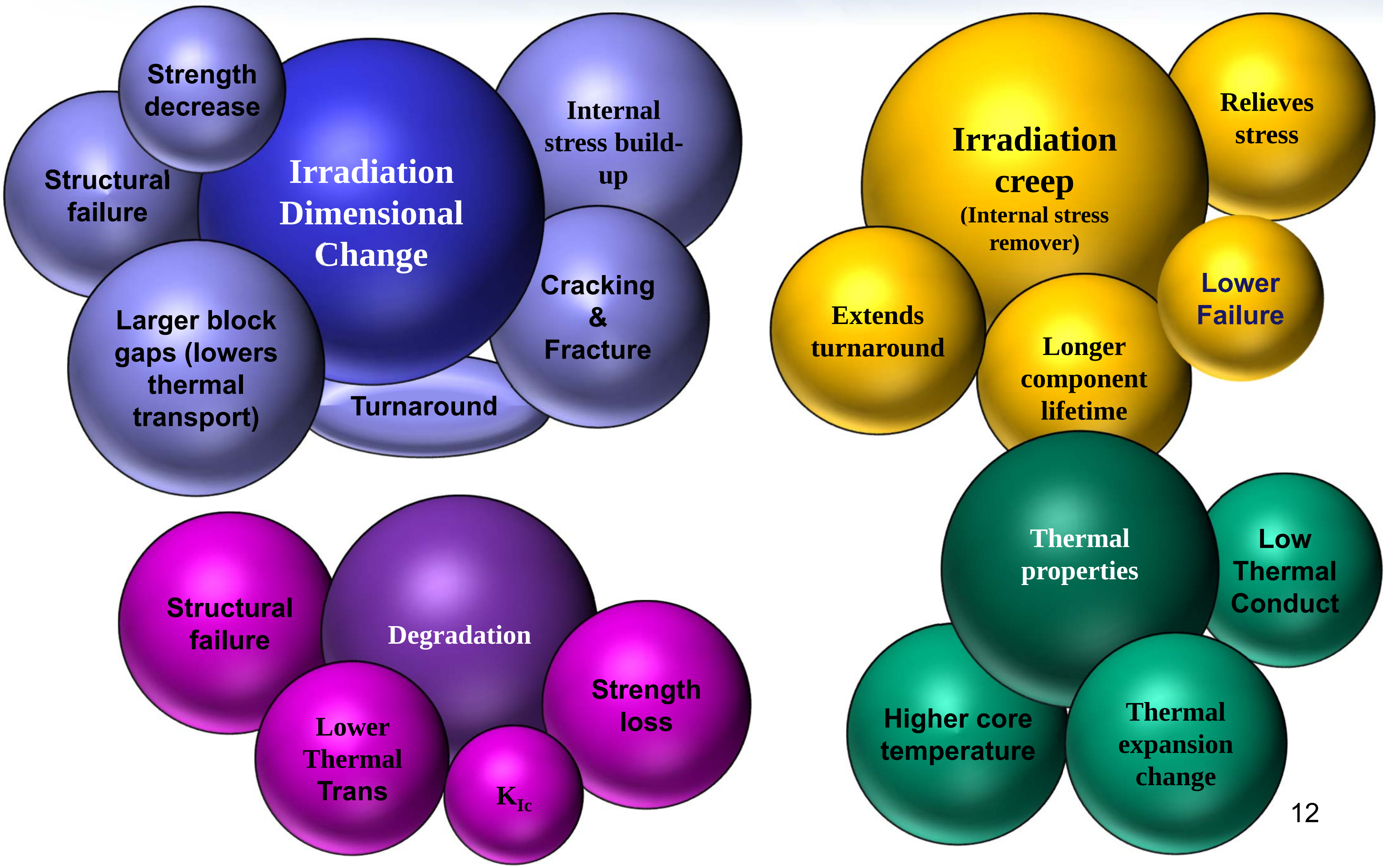


USA's 5 different research areas

Virgin Properties

- (Statistically) Establishes as-received material properties
- Baseline data used to determine irradiation material properties

Licensing & Code

- Establishes an ASME approved code (for 1st time)
- Develops property values for initial components and irradiation induced changes

Graphite R&D Program

Defines the safe working envelope for nuclear graphite and protection of fuel

Irradiation

- Determines irradiation changes to material properties
- Irradiation behavior for continued safe operation

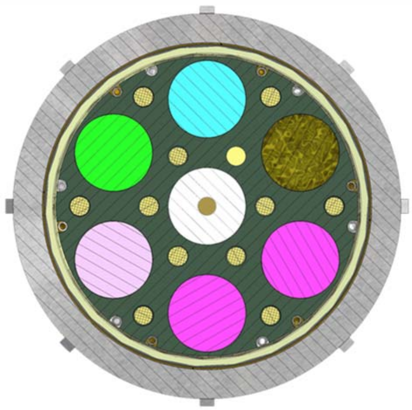
Behavior models

- Predicts irradiated material properties and potential degradation issues
- Irradiation behavior for continued safe operation

Mechanisms and Analysis

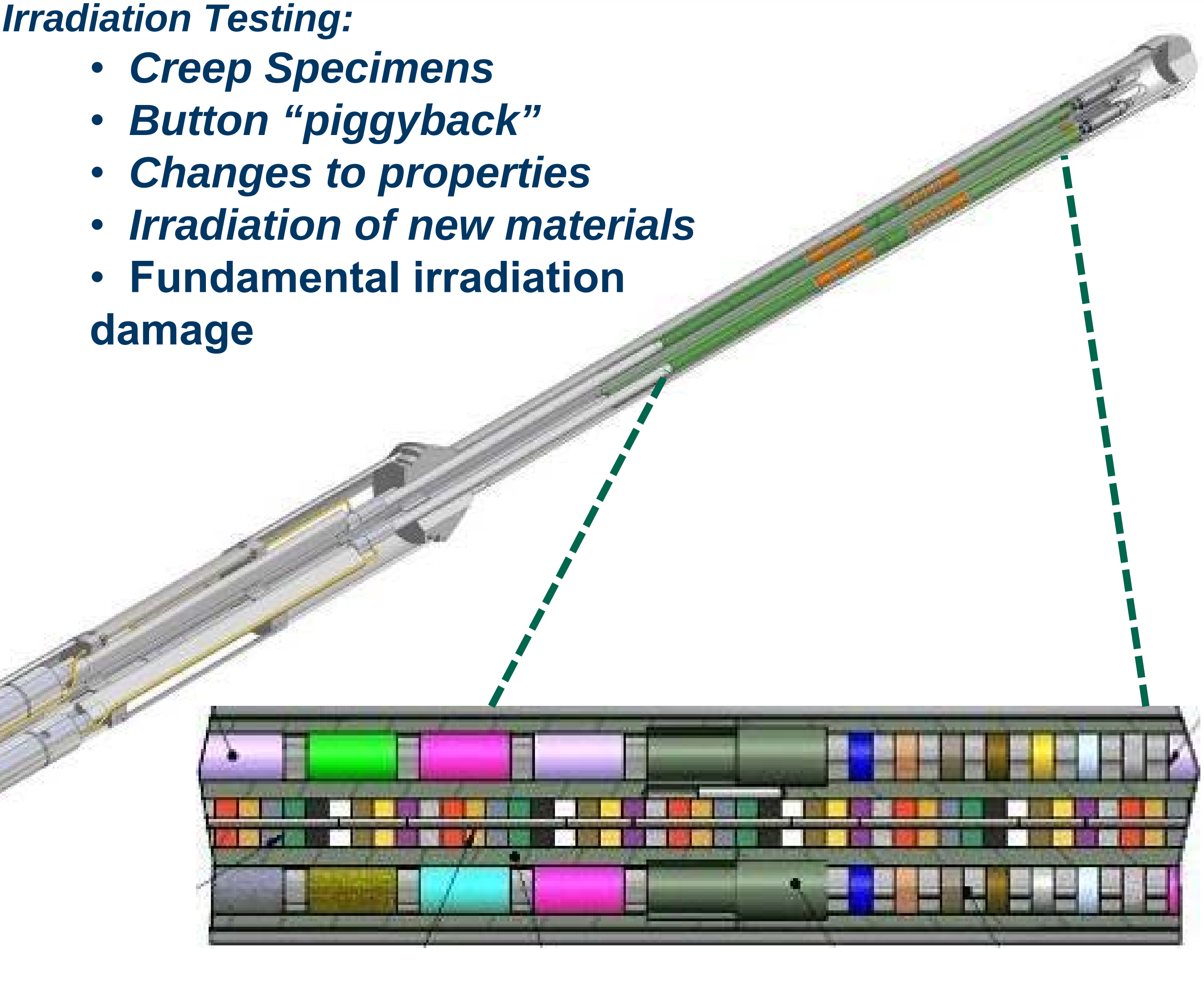
- Data analysis and interpretation
- Understanding the damage mechanisms is key to interpreting data

AGC Experiments



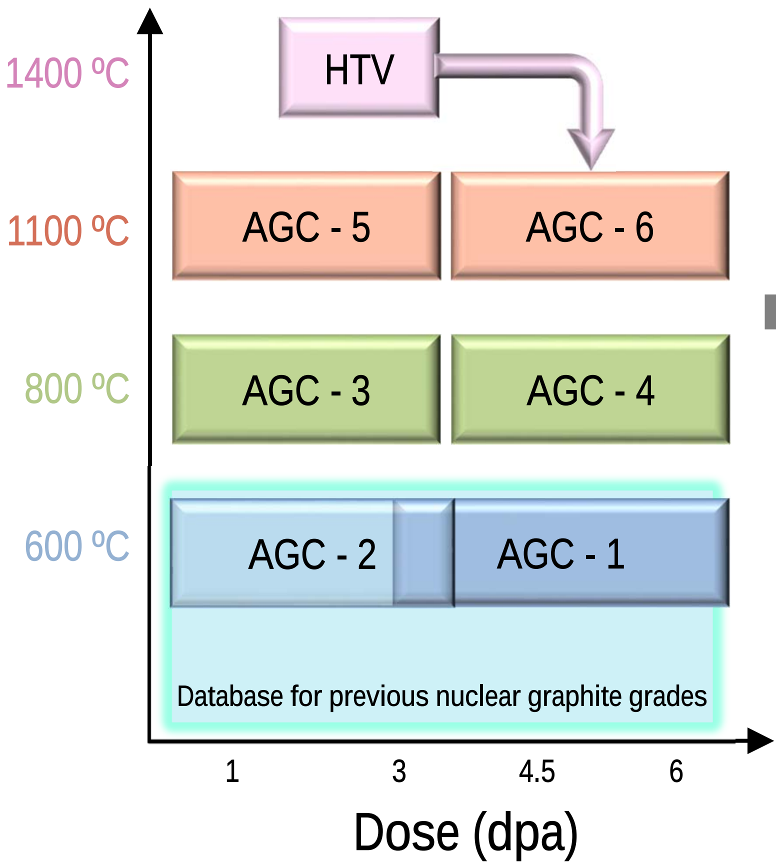
Irradiation Testing:

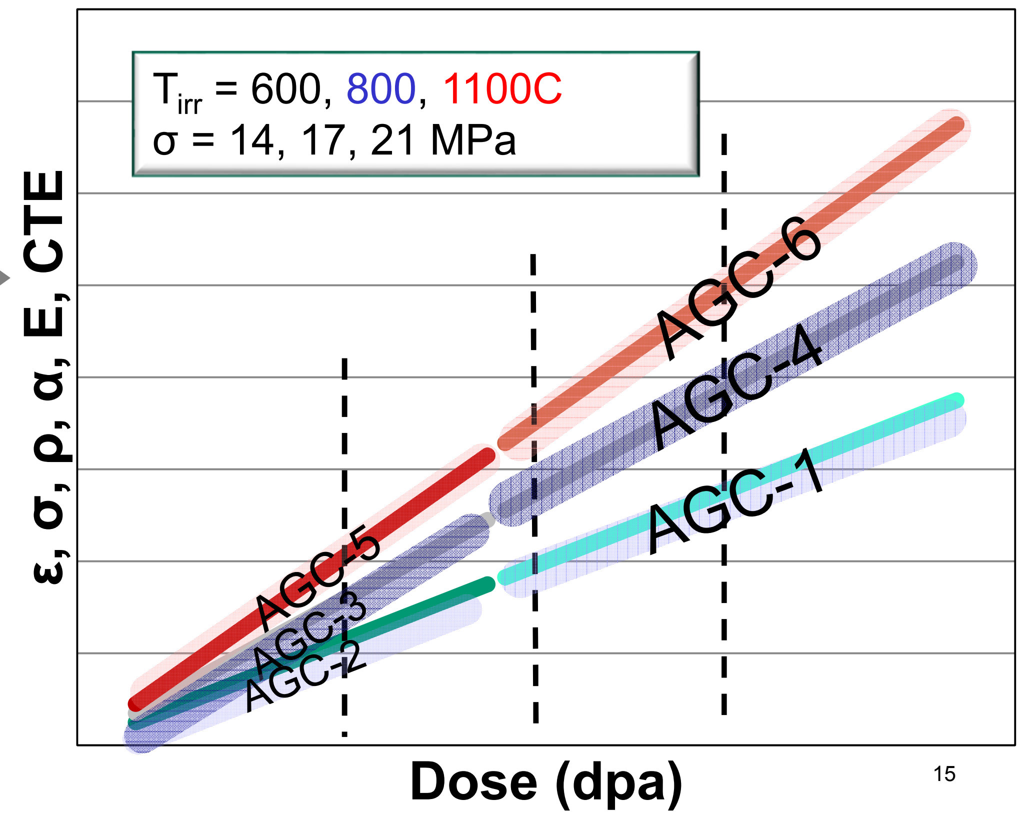
- ***Creep Specimens***
- ***Button "piggyback"***
- ***Changes to properties***
- ***Irradiation of new materials***
- **Fundamental irradiation damage**



AGC Experiment : Irradiation changes

- Three pairs of test capsules
  - 3 Temperatures
  - 3 Stress levels
  - Continuous dose (0.5 – 7 dpa)
- By comparing between test series
  - Property change by dose
  - Property change by temperature
  - Property change by stress





Areas of pertinent graphite research

DOE-ART focusing on large program activities

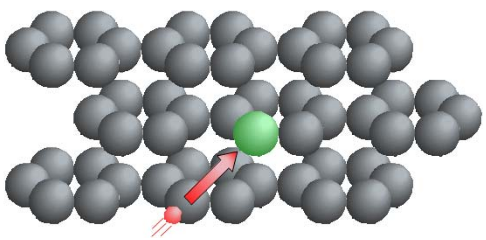
- Irradiation (AGC), Unirradiated data, Oxidation, ASME Code

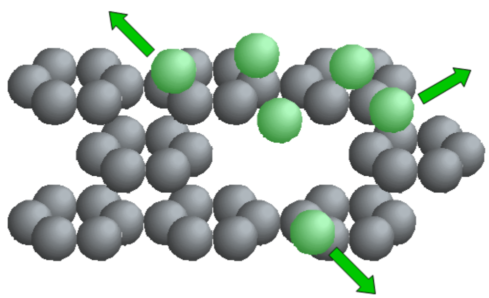
Areas of maximum interest

- Fundamental (*i.e., small*) irradiation studies
  - Irradiated defect structures - **creep** mechanisms
- Material property changes
  - Affect of irradiation and molten salt
- Fracture and strength
  - Fracture toughness and multi-axial fracture behavior
- Degradation (oxidation – salt erosion)
  - Development of oxidation/degradation models
  - Development of new oxidation resistant grades/components (dopants and coatings)
- NDE flaw detection
  - Flaw prediction and evolution during irradiation or degradation

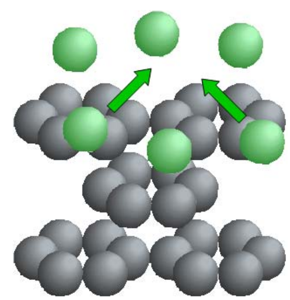
Fundamental irradiation studies

A real need to determine irradiated defect structures and how they affect behavior/performance.

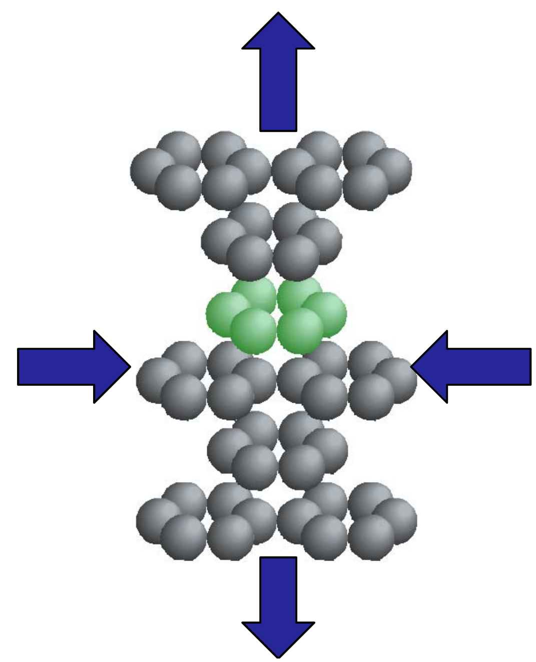




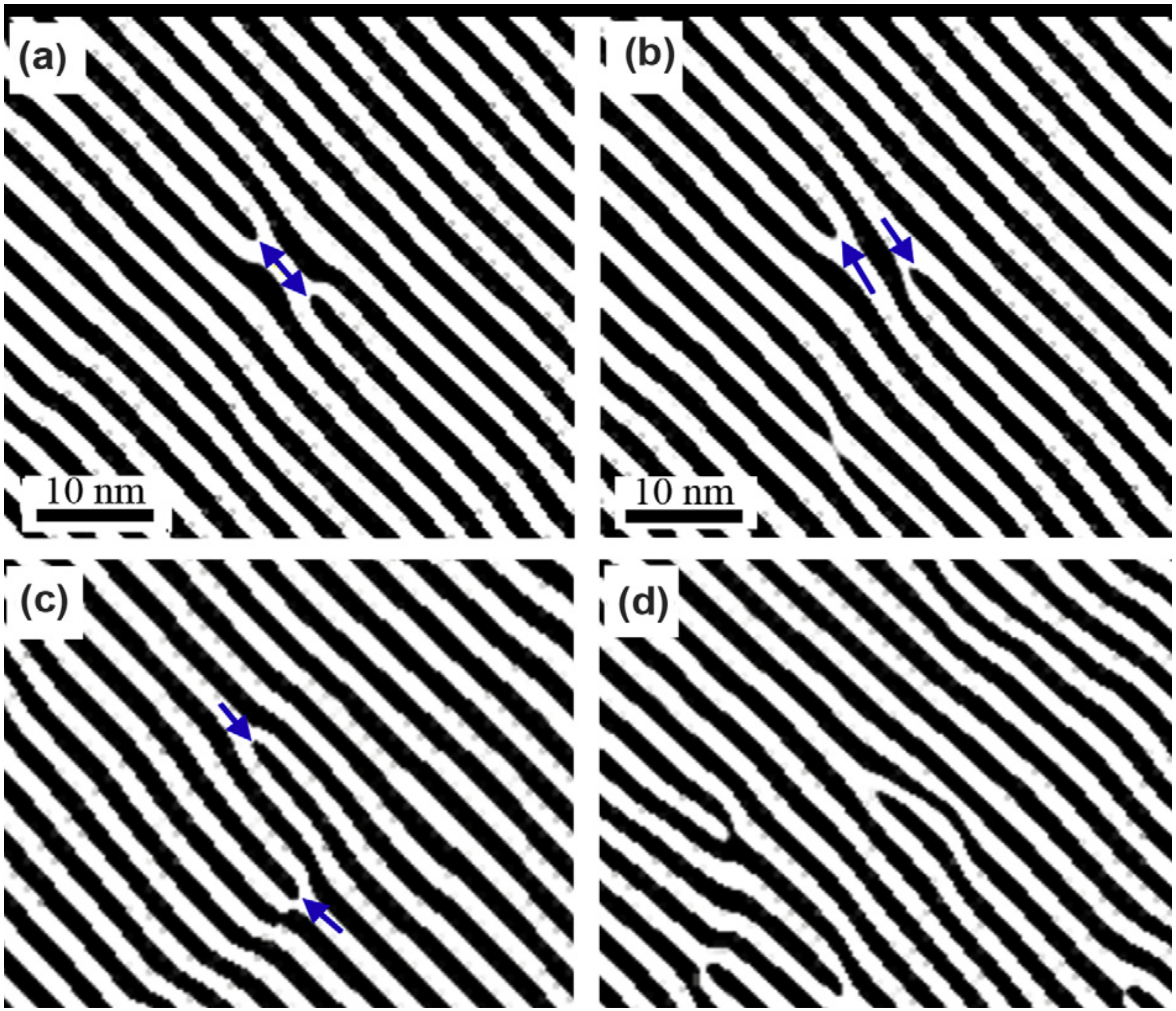
- Grains shrink parallel to planes and grow in perpendicular direction
  - Overall volume shrinkage



Cracks formed during fabrication accommodate swelling – *for a while*



Creep - Dislocation climb/glide

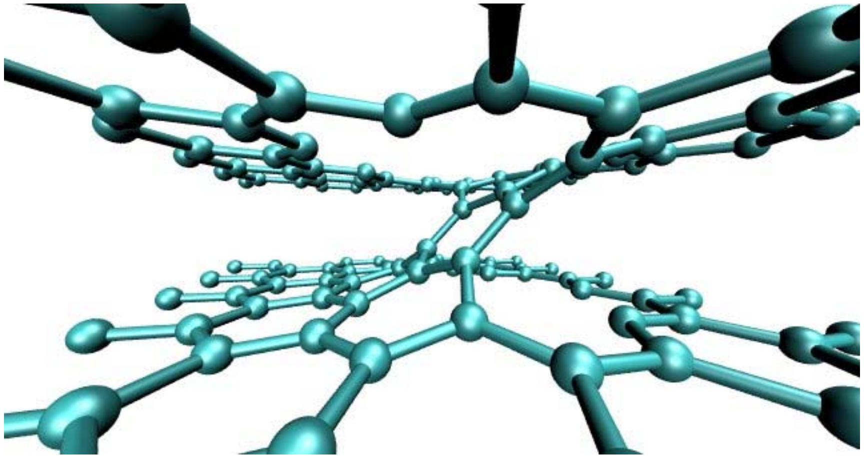


C. Karthik et al. J. Nuc Mat **412** (2011) 321–326

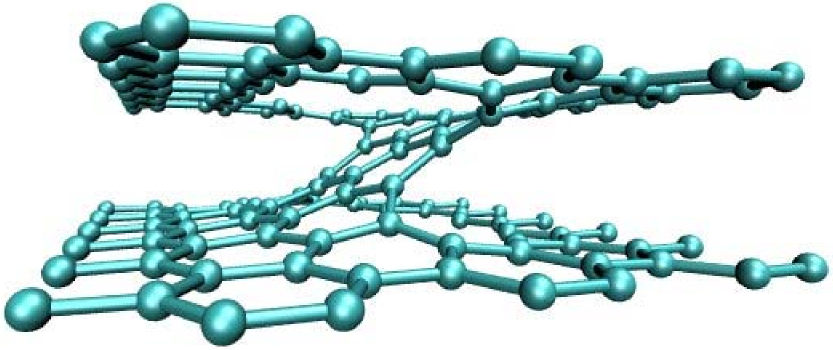
- Intriguing TEM images under electron beam
  - ‖ to Basal planes
  - Interaction of basal planes under irradiation
  - Does this show dislocation glide possibilities?
- ***Not supposed to happen in current model***

Dislocation climb/glide

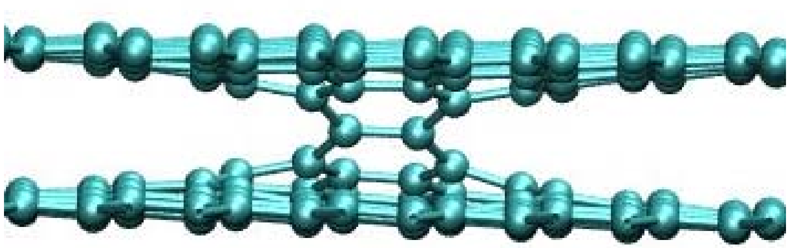
T. Trevethan et al, U of Sussex & U of Leeds, INGSM-13, Sept 2012



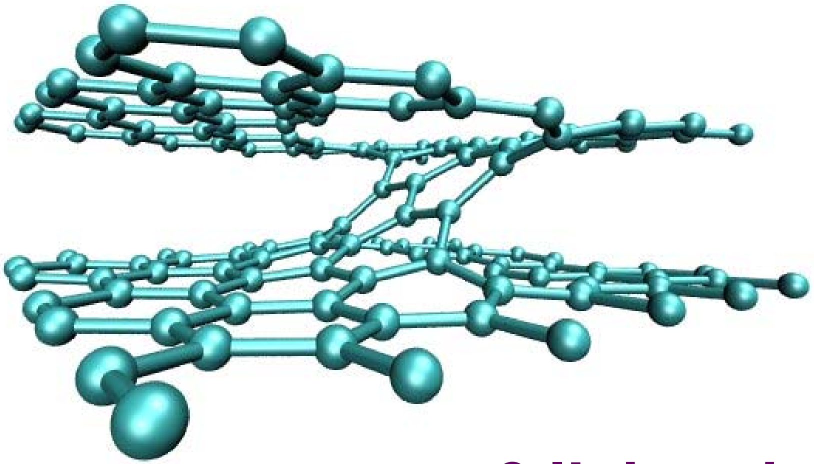
2 IL bonds



3 IL bonds



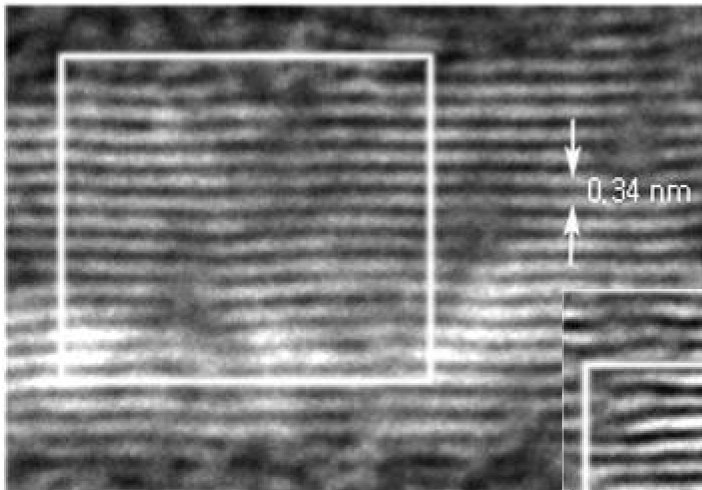
2 IL bonds



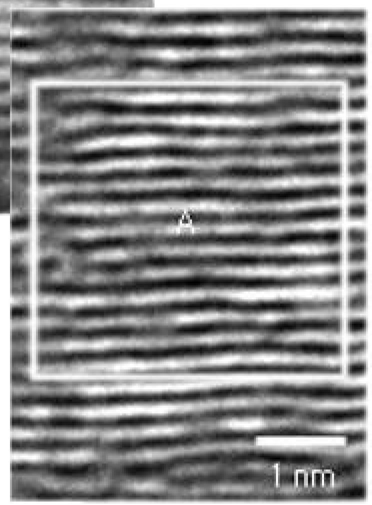
3 IL bonds

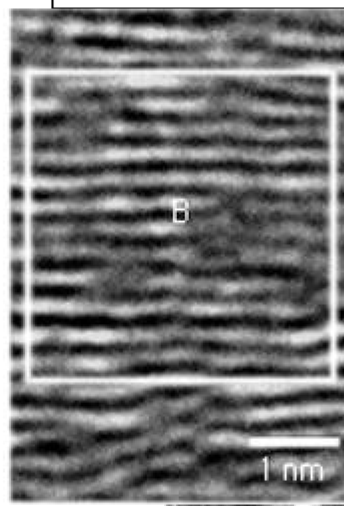
Evidence of irradiation damage in graphite

- T_{irr} = 333 K (60°C)
- $\varphi_{low} = 0.004$ dpa
- $\varphi_{high} = 0.24$ dpa

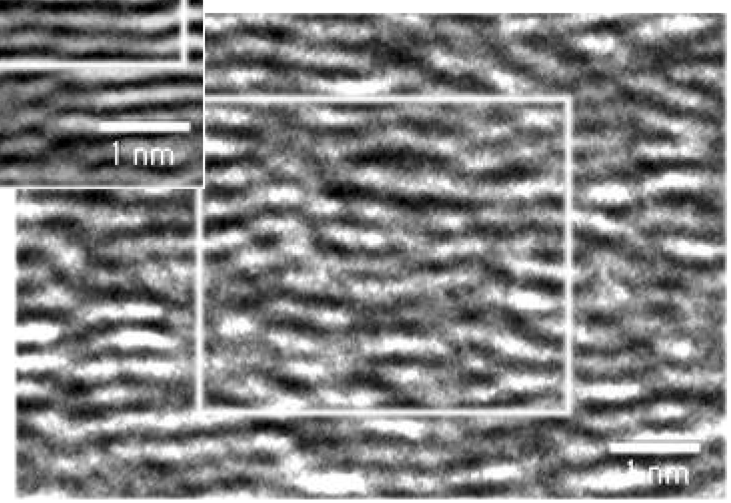


Unirr





γ_{low}



γ_{high}

- **No indication of sub-plane formation**
  - **Different from current model**

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

Questions

- **What /Which defect structure affects material properties**
  - What are real creep mechanisms? Defect structures
  - What defect structures affect strength/modulus?
    - How does this affect fracture behavior?
  - How is thermal diffusivity/conductivity affected?
  - Thermal expansion doesn't match up with current explanation of microstructure/defect changes. Why?
- **How does defect structure behave/interact**
  - Microstructure evolution
    - How does the defect microstructure change over increased dose and temperature?
    - Defect accumulation
  - How is porosity affected?
    - Pore generation in tertiary creep – but how/why?
- **Irradiated specimens - at National Labs (INL/ORNL)**
  - Collaborations and sharing of irradiated specimens is a priority
  - Independent (small) studies with university reactors is needed, too

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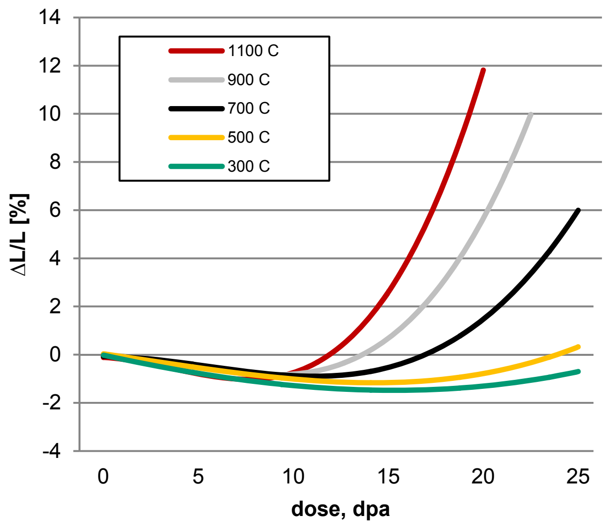
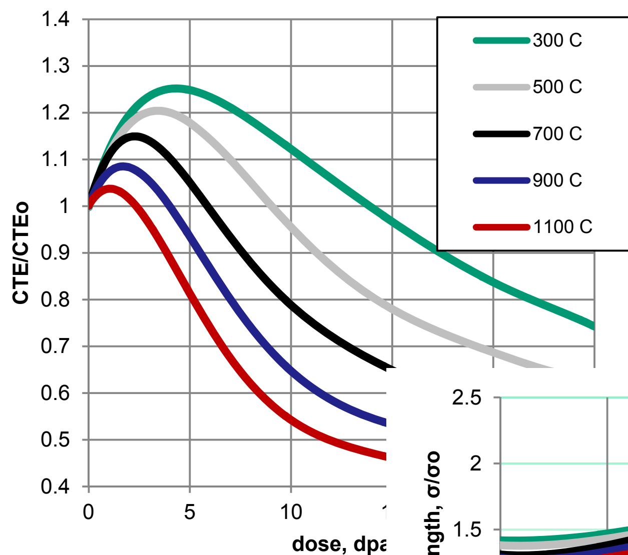
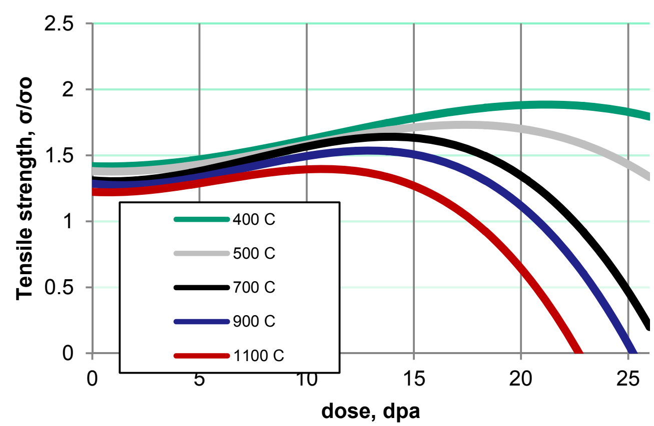
Material Property Changes



- **Irradiation shown to affect graphite properties**
  - Dimensional changes, internal stress
  - Increased stiffness and strength
  - Dramatic decrease in thermal diff.

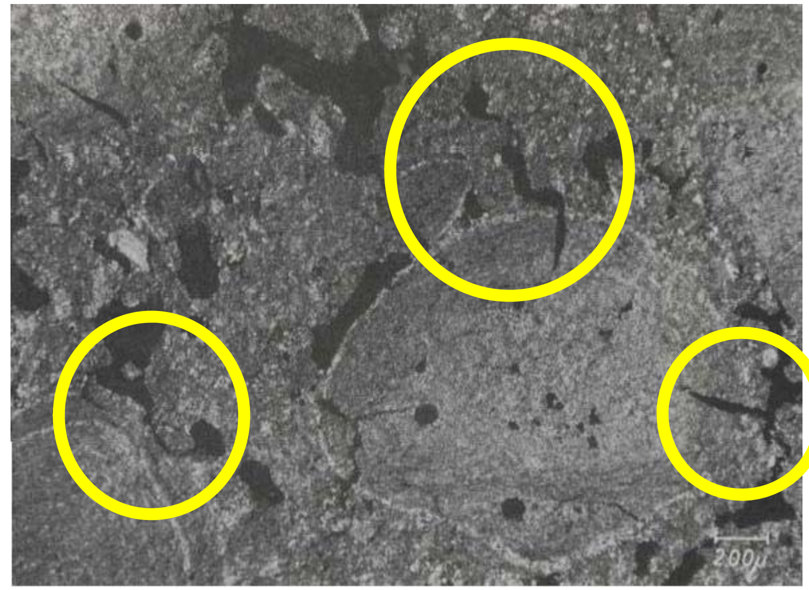




- **What about Molten Salt?**
  - ***If*** salt infiltrates graphite pores
  - Are basic properties the same?
  - Combination effects from irradiation and salt?

Fracture and Strength

- **Irradiation shown to affect graphite strength**
  - Initial strength due to dislocation pinning from point defects
  - But what about pore structure?
    - Microstructure evolution over dose?
  - Increased flaw population must change fracture behavior



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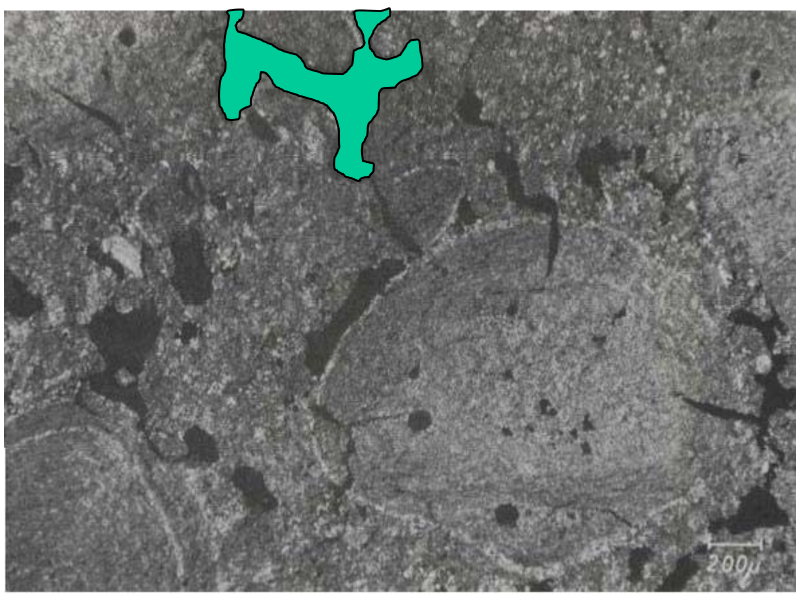
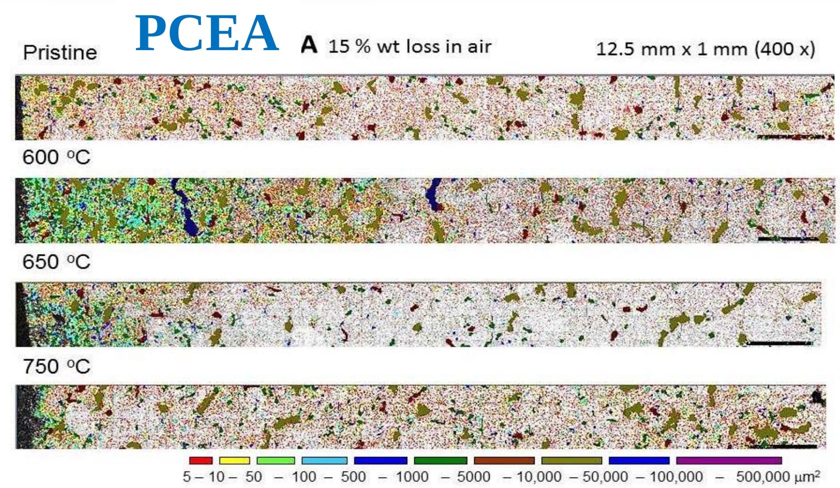


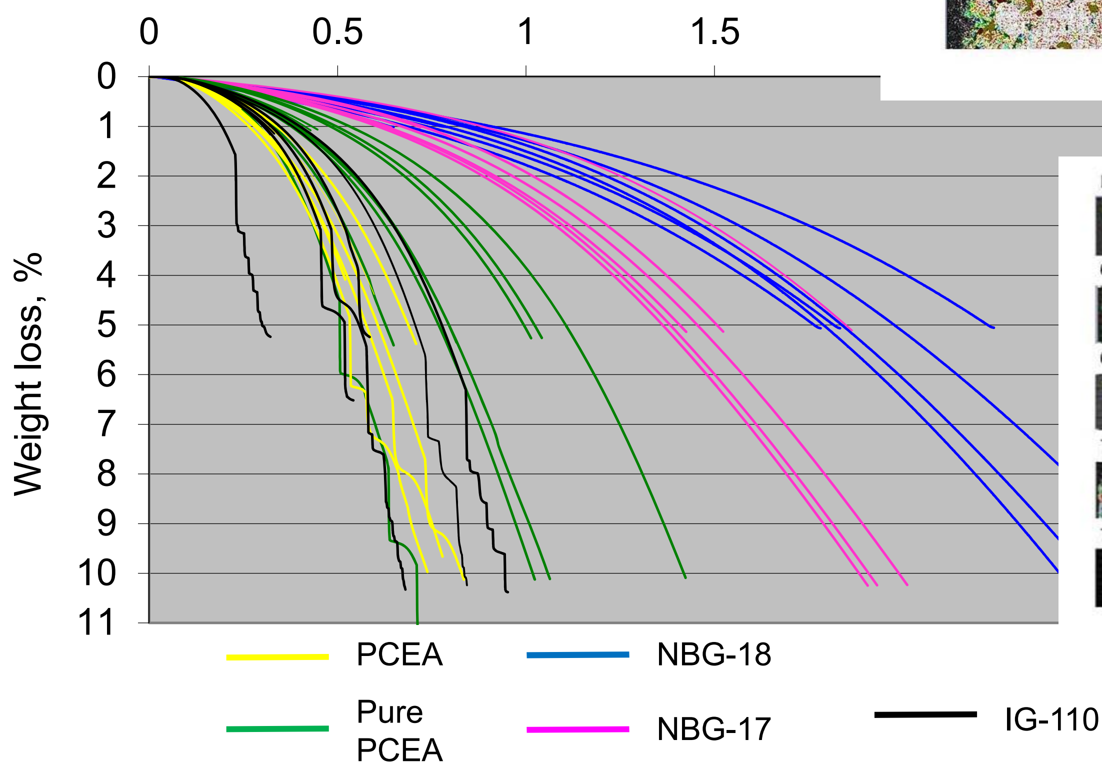
How does molten salt penetration into pores affect fracture behavior?

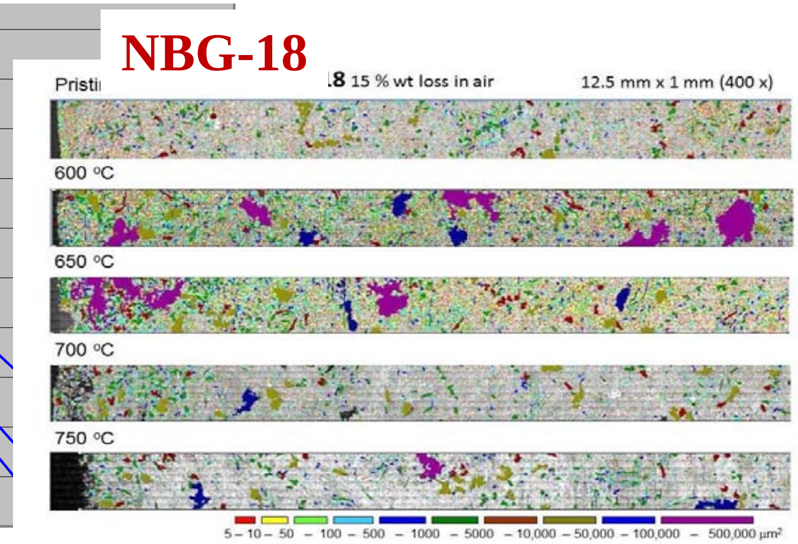
- Solidification of salt inside pores will create high internal tensile stresses
- Pore/crack growth will result.
- Exacerbates fracture?

Degradation - oxidation

- Lots of data and studies on graphite oxidation
- Need to ***develop improved models*** based on new data

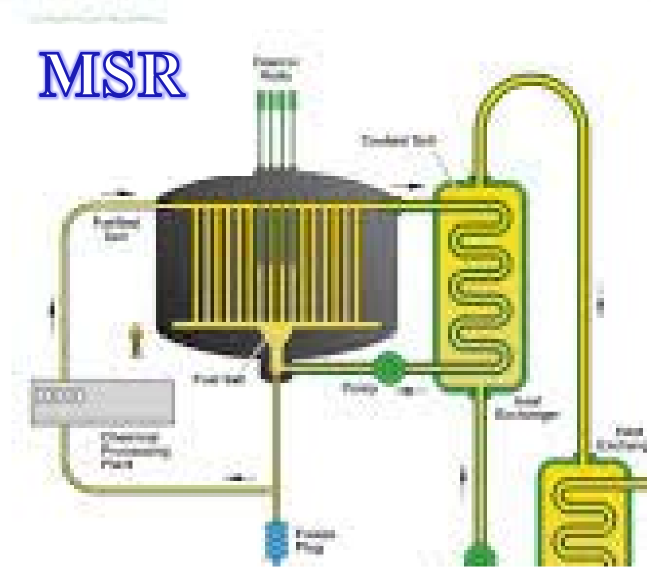


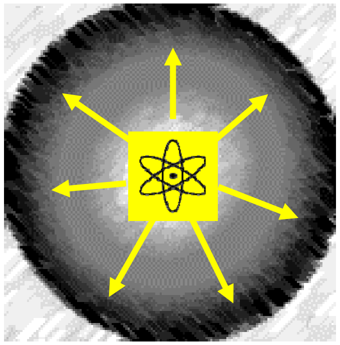


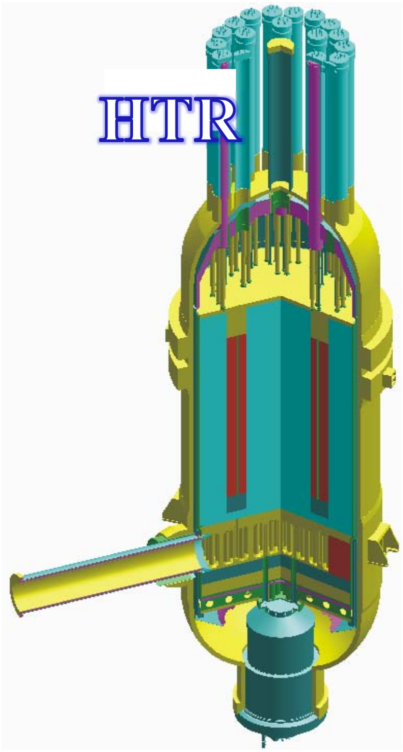


Radioactivity – tritium and fp build-up

- Build-up of tritium
  - Especially important for dissolved fuel
- Does graphite retain it? Diffusion rate?
  - Any build-up?



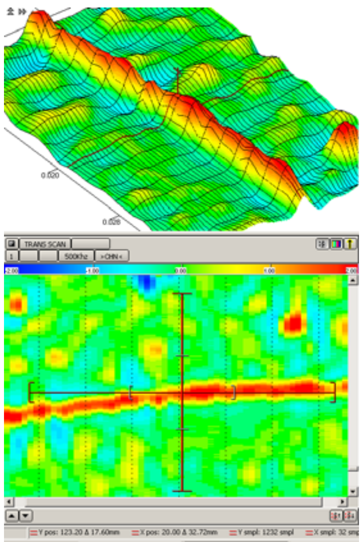


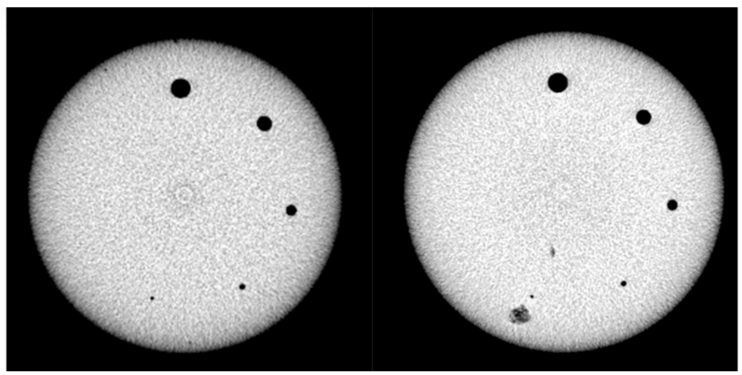


- Important for HTR design as well
  - Source term for accident calculations.
    - Waste disposal issues
  - How does temperature affect release rates (accident)?
  - Diffusion rate at accident temperatures?

Nondestructive Evaluation of Graphite

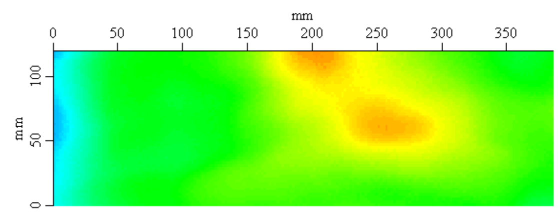
- Desperately need development of NDE Technologies for ***large components*** and ***In-Service Inspection (ISI)***
- Conventional NDE Inspection technologies applicable to Graphite
  - Eddy Currents, X-Ray Radiography, and Ultrasonics





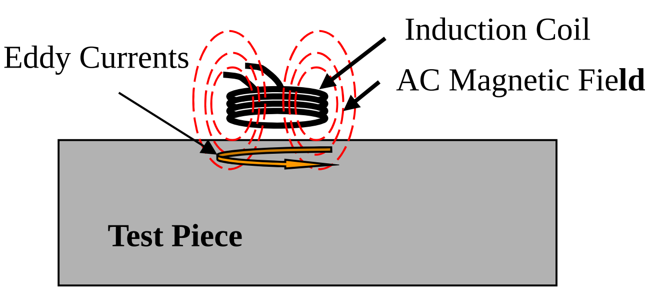
X-Ray Radiography

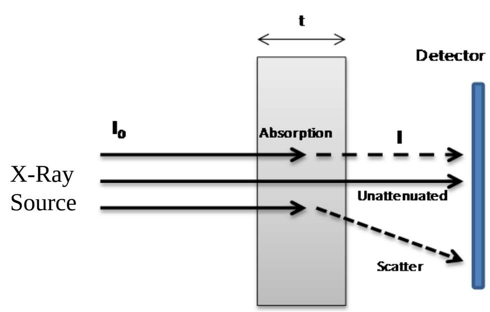
Contact UT

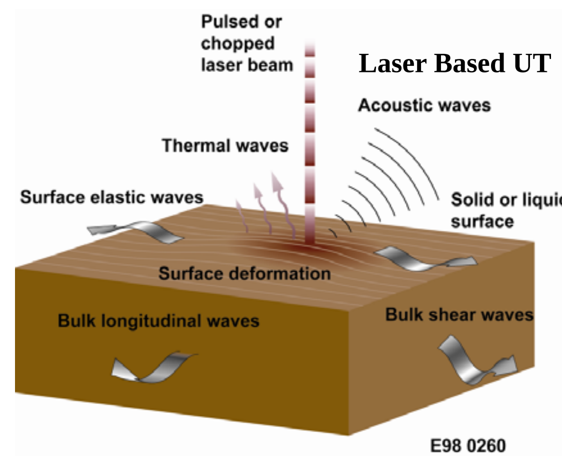


Ultrasonics

Eddy Currents







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