ASME Considerations for HTR Graphite and Composite Components

DOE - Advanced Reactor Technologies

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Advanced Non-Light Water Reactors - Materials & Component Integrity Workshop

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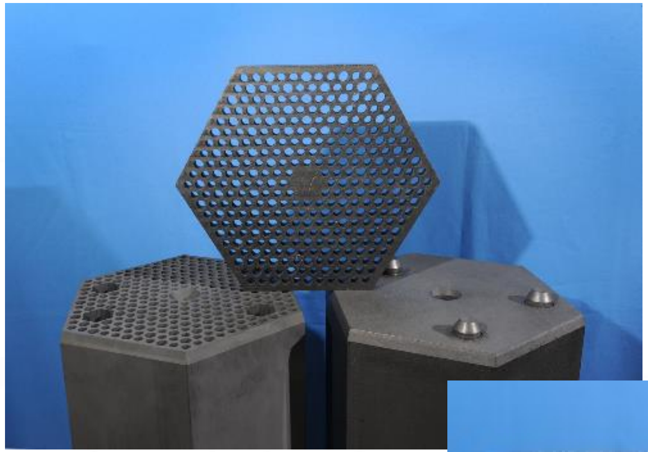
Idaho National Laboratory

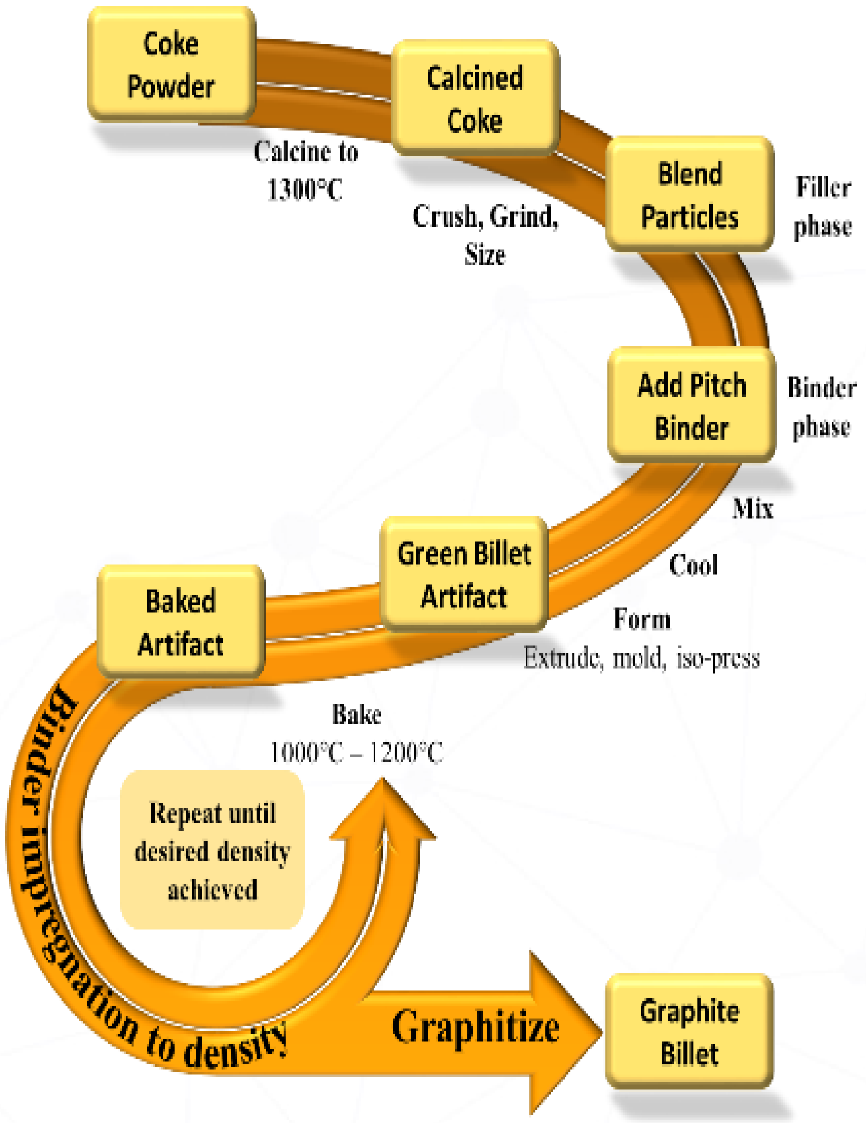
ADVANCED REACTOR TECHNOLOGIES

Discussion points

- Underlying graphite behavior behind ASME code development
  - Inherent graphite behavior
  - Degradation effects on properties and behavior
    - *Irradiation and oxidation effects*
- ASME code – as written to address graphite behavior
  - Probabilistic versus Deterministic failure assessments
  - Failure criteria
    - *Full assessment and simple assessment*
  - Unirradiated versus irradiated data requirements
  - Oxidation requirements
- Gaps in ASME graphite code
  - Preliminary gap analysis results on ASME Code



Graphite Manufacture & Unique Properties



- All graphite grades **are proprietary**. Only limited/general fabrication data is known.
  - It isn't like metals – there are no ASTM specified alloy compositions and fabrication processes
  - These are closely guarded, proprietary formulae for each grade
  - And no, graphite suppliers are not willing to give up their private recipes to the nuclear community
    - *Remember: no nuclear graphite has been ordered in decades*
- But the good news is that all grades react similarly under nuclear core conditions
  - Specific changes are dependent upon individual grade
- To understand graphite behavior need to know unique manufacturing processes
  - Graphite is a porous material (15-20%) - ***By design***!
  - Porosity provides thermal and irradiation stability
  - But porosity alone doesn't predict behavior
    - *Large flaws (cracks/pores) are built in from fabrication*
    - *But irradiation stability also comes from small (nm) pore structure*
  - Filler particles, binder phase, filler-binder ratio, fabrication method
    - *All affect performance*

Graphite Manufacture & Unique Properties

- Properties and performance influenced by both raw materials and processing
  - Isotropic (or near isotropic) material response
  - High thermal stability > 3000°C
  - High heat capacity (thermal sink)
  - High thermal conductivity (better than metal)
  - Neutron moderator – thermal reactor
  - Easy machinability / cheap material
  - Ceramic like material response
    - *Low fracture toughness (~ 1-2 MPa √m)*
    - *Quasi-brittle cracking*
    - *Low tensile strength (ceramic composites used)*
- Decent irradiation response
  - Dimensional change (life-limiting mechanism)
    - *Multiple decades of safe operation*
    - *And **even longer** at lower temperatures*
  - Graphite generally gets stronger with irradiation
  - Isotropy stays relatively constant
    - *A small reduction possibly*
  - Thermal stability and capacity are unaffected

PBMR (600MW) ~ 0.85 dpa/yr
SMR (200 MW) ~ 0.3 - 0.5 dpa/yr
Micro (5 – 50 MW) ~ 0.1 – 0.25 dpa/yr

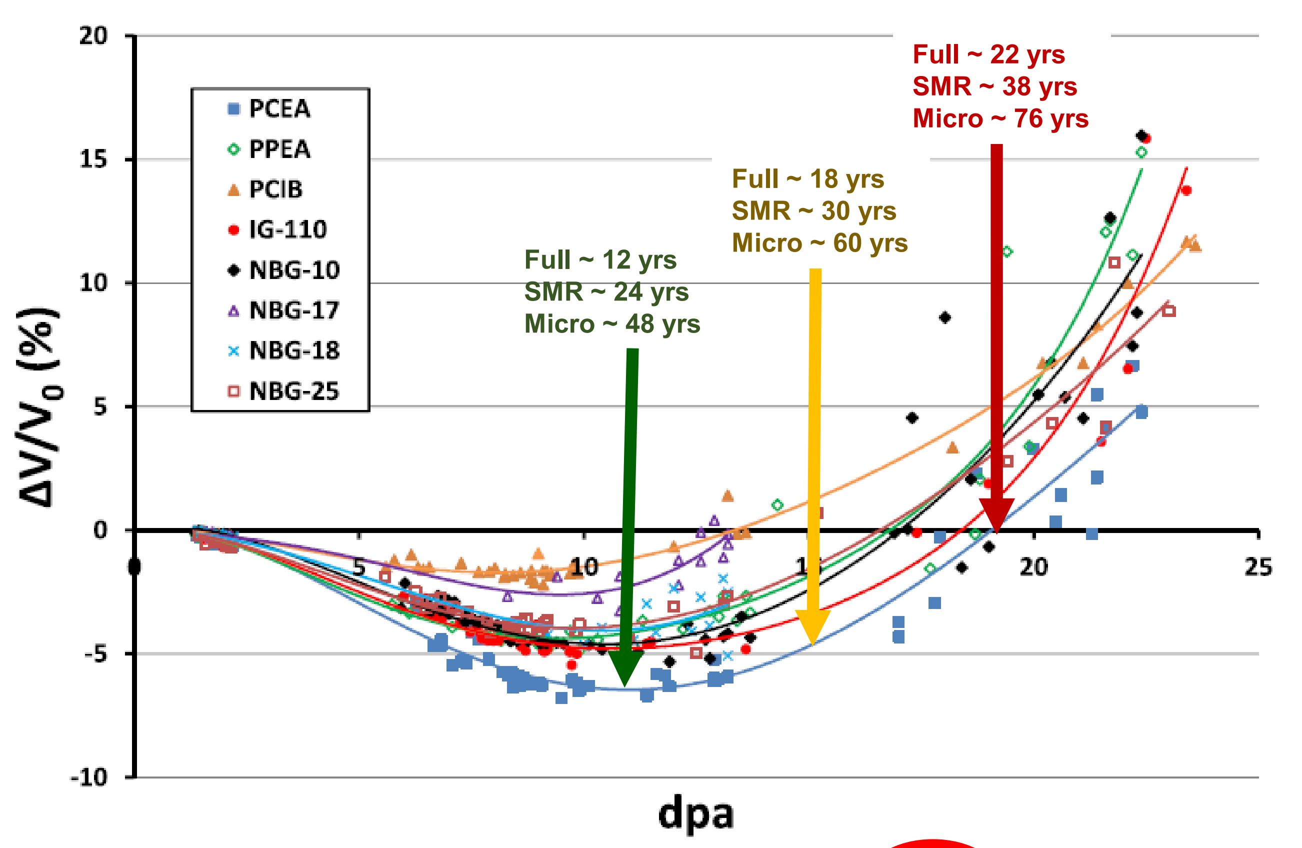
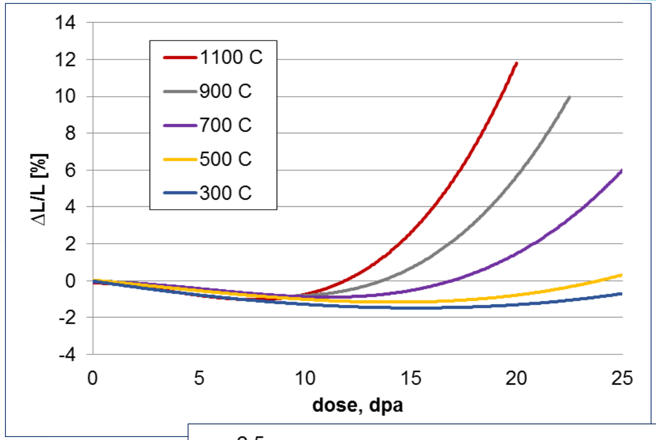


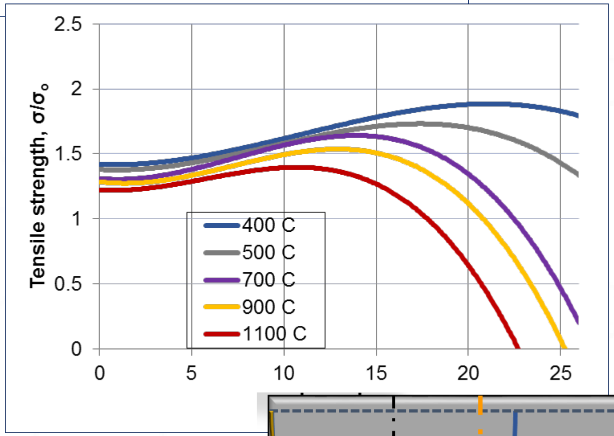
Fig. 2. Dimensional change as function of dpa at 750 °C.

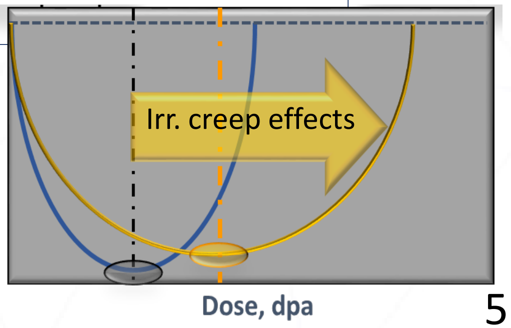
M.C.R. Heijna, S. de Groot, J.A. Vreeling, "Comparison of irradiation behaviour of HTR graphite grades", Journal of Nuclear Materials 492 (2017) 148e156

Irradiation Effects on Graphite Properties

- Irradiation induced changes **must** be considered in 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 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*
- Significant changes do not typically occur in the following properties:
  - Oxidation rate, neutron moderation, specific heat capacity, emissivity, heat capacity
- No Wigner energy release **if** components irradiated above 300°C.







What are the main parameters needed to develop ASME code?

1. There is no single “nuclear” grade of graphite
   - We can’t design around a specific nuclear grade as metals can (i.e., 316, 316L, 617, etc.)

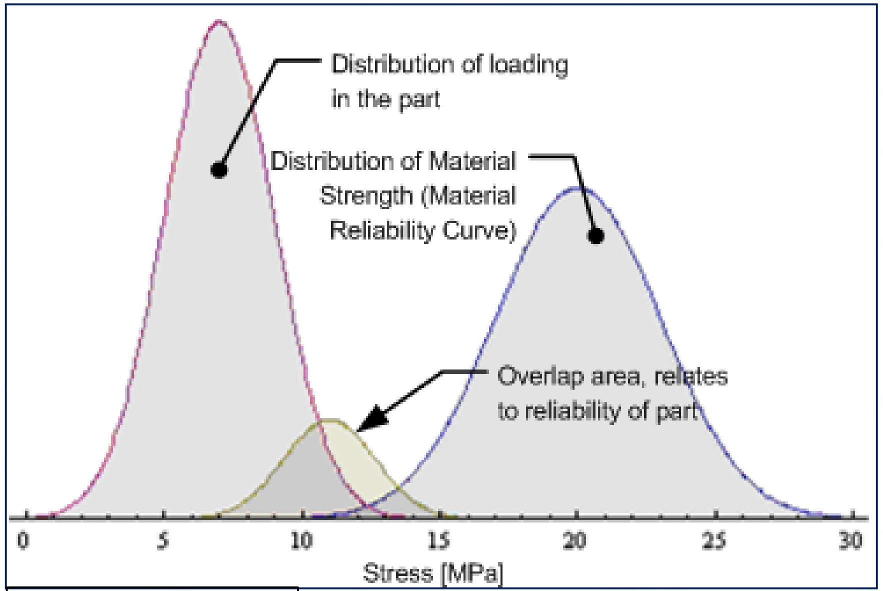
2. Graphite has significant flaws (pores/cracks) – by design
   - We do not want to eliminate these flaws

3. Graphite is **not** ductile
   - Brittle or quasi-brittle fracture behavior

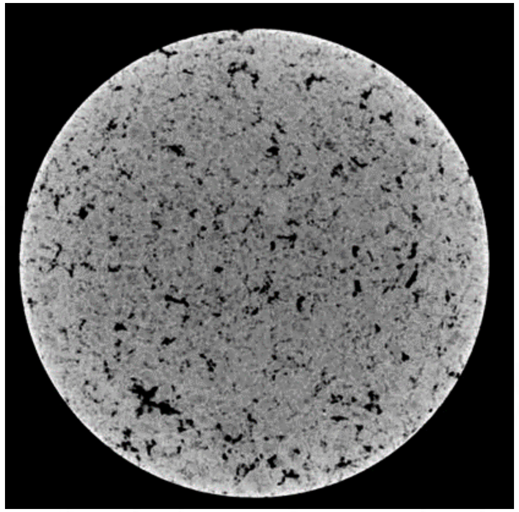
4. Irradiation significantly alters the graphite behavior
   - Behavior is completely different before and after Turnaround dose is achieved.

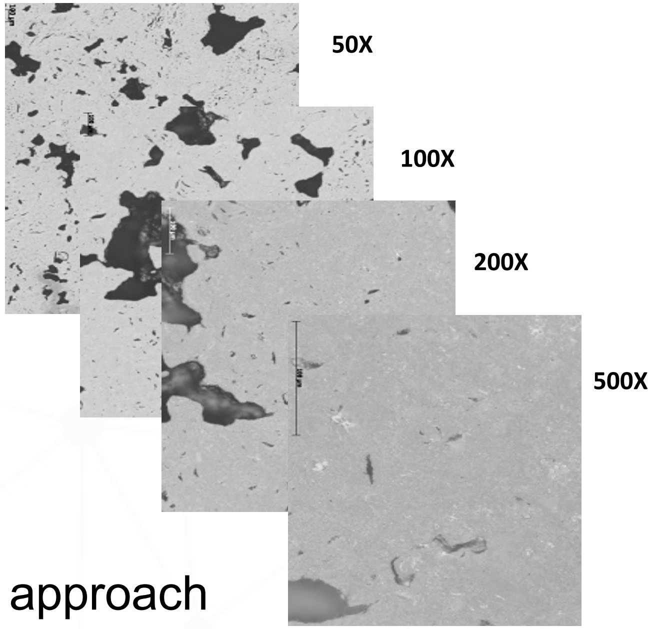
ASME Code Considerations

- Because all graphite has significant flaws
  - Some amount of failure (i.e., a crack) is certain
- Therefore, core components need to be designed to accept some amount of failure.
  - *Probability of failure approach is taken*
  - *Based upon overlap of applied stresses and inherent strength of the nuclear grade used*



From Dr. Mark Mitchell – PBMR Inc.





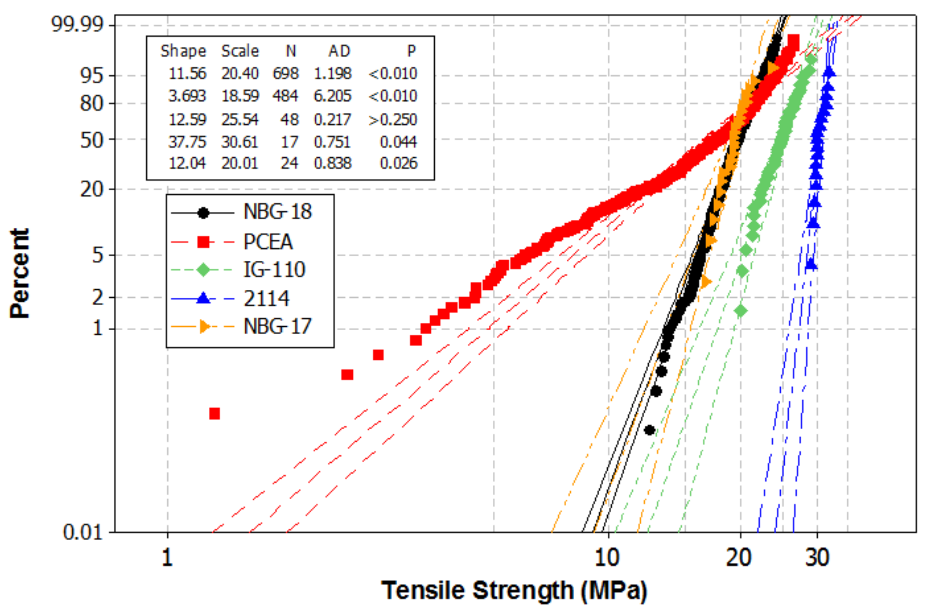
- **Probablistic** verses **deterministic** design approach
  - Deterministic is generally too limiting for a brittle material
  - A distribution of possible strengths in a material is needed for quasi-brittle materials (i.e., flaw size for graphite).
  - Probability of failure in component based upon inherent strength of graphite grade and applied stresses during operation.
- New graphite grades are consistent and ready for codification
  - Unfortunately, historical nuclear grades are no longer available
  - We also lack significant quantitative data on new graphite behavior at higher temperature and high dose applications
  - Need to correlate defined material changes to assist in failure analysis.

How the graphite (and composite) ASME Code works

Three methods are provided for assessing structural integrity

1. Deterministic
   - *Simplified conservative method based on ultimate strength derived from Weibull statistics.*
   - *Irradiation changes well contained within the operational envelope*
2. Full Analysis Method
   - *Detailed structural analysis taking into account stresses, temperatures, irradiation history, and chronic oxidation effects.*
   - *Weibull statistics used to predict failure probability*
   - *Maximum allowable probability of failure defined for three Structural Reliability Classes (**SRCs**), which relate to safety function*
3. Qualification by Testing
   - *Full-scale testing to demonstrate that failure probabilities meet criteria of full-analysis method.*

Structural Reliability Class	Maximum Probability of Failure
SRC-1	1.00E-04
SRC-2	1.00E-02
SRC-3	1.00E-01



The graphite code is a “**<u>process</u>**”. Not just picking a preapproved material

- *The applicant must demonstrate the graphite grade selected will consistently meet the component requirements.*

Getting the material property “proof” is responsibility of the applicant

Flow diagram for the Full Assessment

ASME Section III.5 Subsection HH Subpart B – 2017

Full Assessment: 3 parameter Weibull (Probabilistic Analysis)

Define the "**Material Reliability Curve**" by fitting a 3 parameter Weibull model to the measurement data.

(ref. HHA-II-3200 pg. 417)

→

Estimate 3 parameter Weibull parameters using MLE's .

(S_o, $m_{095\%}$ and $S_{c095\%}$)

→

Calculate the POF of the graphite core component using the "**Material Reliability Curve**" and stress distribution in the component.

(ref. HHA-3217 pg. 393)

→

$POF_{component}$

↓

Determine the allowable POF from the **Structural Reliability Class (SRC)**, and **Service Level Design Loading**.

(ref. HHA-3230 thru HHA-3237 pg. 397)

→

$POF_{allowable}$ ≤ 10-2 and ≥ 10-4

→

Evaluate the acceptability of the design

$POF_{component}$ < $POF_{allowable}$

Flow diagram for the Simple Assessment

ASME Section III.5 Subsection HH Subpart B – 2017

Simple Assessment: 2 parameter Weibull (Deterministic Analysis)

Estimate the scale and shape of a 2 parameter Weibull using a linear fit to **measured property data**

m^* and S_c^*

(ref. HHA-II-3100 pg. 414)

→

Using **m^*** and **S_c^*** determine the Weibull parameters corresponding to a 95% confidence interval

$m_{95\%}$ and $S_{c95\%}$

(ref. eq.6 and eq.7 pg. 417)

→

Using **$m_{95\%}$** and **$S_{c95\%}$** determine the “design allowable stress” as a function of POF = 10^{-4}, 10^{-3}, 10^{-2} and $5x10^{-2}$

$S_g(P)$

(ref. HHA-II-3300 pg. 418)

→

Calculate the ratio of flexural to tensile strength

R_{tf}

(Ref.HHA-II-2000 pg. 412)

→

$S_g(P)$

R_{tf}

↓

Perform a stress analysis of the graphite component

(ref. HHA-3215 pg. 392 and HHA-3216 pg. 393)

→

C_m = Combined Membrane Stress

C_b = Combined Bending Stress

F = Peak Stress

R_{tf} = ratio of flexural to tensile strength

→

Evaluate the acceptability of the design

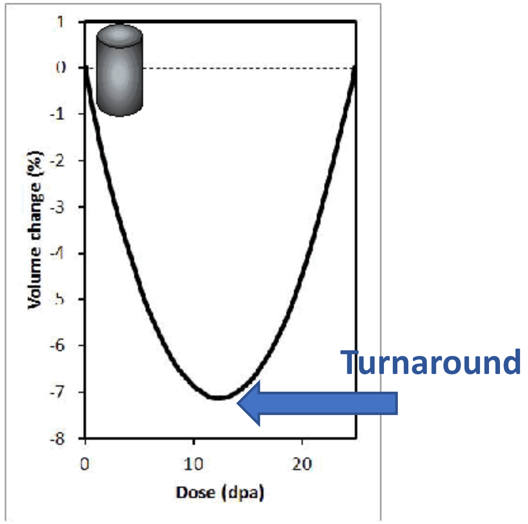
- $C_m < S_g(P)$

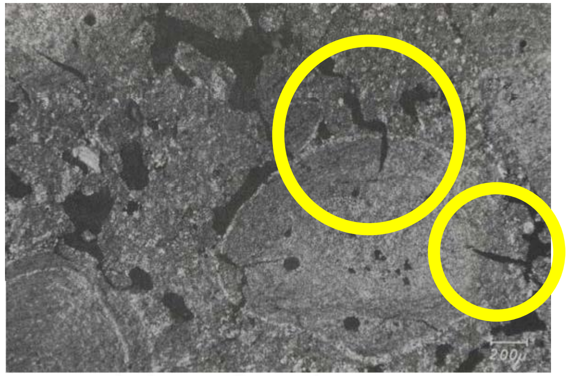
- $C_m + C_b + F < R_{tf} * S_g(P)$

(ref. HHA-3220 pg. 394)

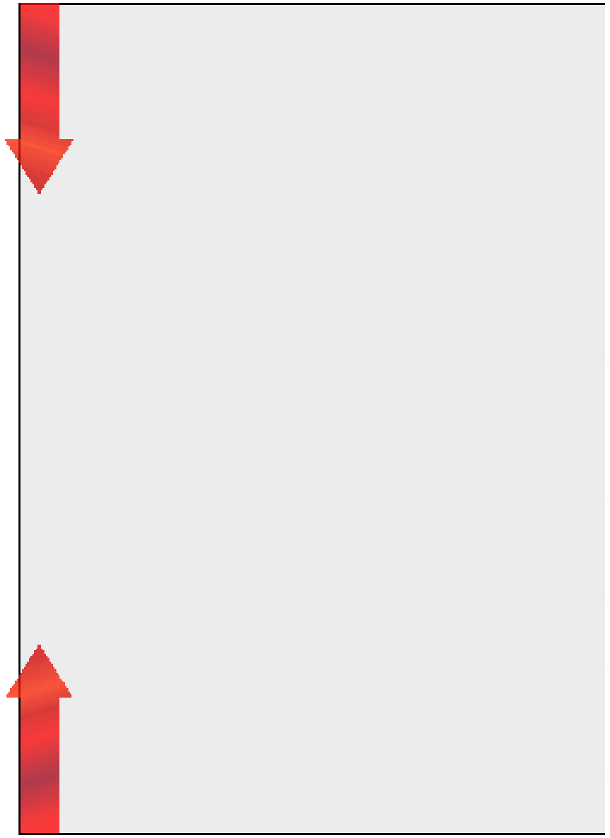
And then … the hard part

- Fundamental material properties change with irradiation/oxidation must be addressed
  - Applicant must assess changes to design of component due to Irradiation effects
    - *New cracks formed after Turnaround*
    - *Internal stresses from dimensional change. Need creep response, too*
    - *Changes to density, strength, CTE, thermal conductivity*





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



  - Applicant must assess changes to design due to Oxidation degradation
    - *Changes in density, strength, CTE, neutron moderation, and thermal conductivity.*

Finally a word on code improvements

- No one has used the new graphite or composite code
  - Very little feedback from vendors or applicants
- NDE and ISI are still outstanding issues in the code
  - In-situ inspections for continuous operating PB & MSR designs is difficult
- Some discrepancy between ASME code and available ASTM testing
  - Currently there are **no** standard test methods for
    - *Mechanical testing of small (sub-sized) specimens as needed for irradiation testing*
    - *No mechanical testing of oxidized specimens*
    - *Performing NDE techniques on large graphite components*
- Effects of oxidation on full-scale components
  - Current test standards compare graphite grades
  - Nothing to address the effects on large components
- Fatigue – does it apply?
  - No studies on fatigue of graphite components
  - U.K. shows low cycle – large stress events (fatigue) promote crack formation in bricks
- Underlying mechanisms are not well understood
  - Affects the code and how it is applied
  - Will lead to “standardized” nuclear graphite grades

New ASTM Test method:
Split disk development

INL

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