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

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

• Probabilistic 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.

The graphite code is a “process”. 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
Define the "Material Reliability Curve" by fitting a 3 parameter Weibull model to the measurement data. Estimate 3 parameter Weibull parameters using MLE’s. ($S_0$, $m_{095\%}$ and $S_{c095\%}$)

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

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

Evaluate the acceptability of the design $POF_{\text{component}} < POF_{\text{allowable}}$

$POF_{\text{allowable}} \leq 10^{-2}$ and $\geq 10^{-4}$

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

(ref. HHA-3217 pg. 393)

(ref. HHA-3230 thru HHA-3237 pg. 397)
Flow diagram for the Simple Assessment
ASME Section III.5 Subsection HH Subpart B – 2017

Simple Assessment: 2 parameter Weibull (Deterministic Analysis)

- Perform a stress analysis of the graphite component
  - $C_m = \text{Combined Membrane Stress}$
  - $C_b = \text{Combined Bending Stress}$
  - $F = \text{Peak Stress}$
  - $R_{tf} = \text{ratio of flexural to tensile strength}$

- 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 $5 \times 10^{-2}$
  - $S_g(P)$
  - (ref. HHA-II-3300 pg. 418)

- Calculate the ratio of flexural to tensile strength $R_{tf}$
  - (Ref.HHA-II-2000 pg. 412)

- Evaluate the acceptability of the design
  - $C_m < S_g(P)$
  - $C_m + C_b + F < R_{tf} \cdot S_g(P)$
  - (ref. HHA-3220 pg. 394)

- Using $m^*$ and $S_c^*$ determine the Weibull parameters corresponding to a 95% confidence interval
  - $m_{95\%}$ and $S_{c95\%}$

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

  ▪ 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