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Session 4: ASME Code Rules

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Changing the World's Energy Future

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Session 4: ASME Code Rules

NRC Graphite Behavior Model

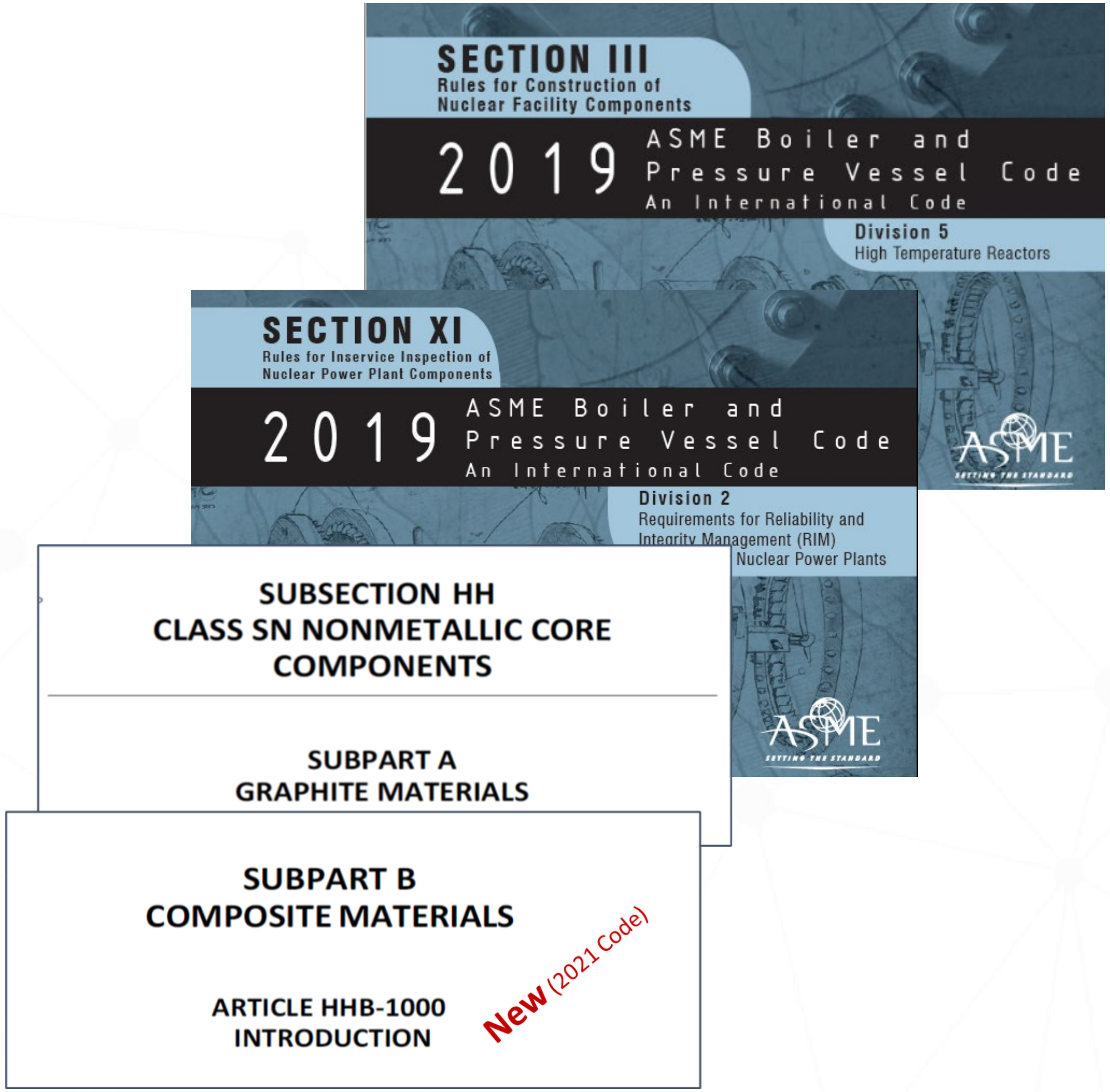
NRC Graphite Behavior Model Presentation
NRC Headquarters, Gaithersburg
1-2 August 2022

ADVANCED REACTOR TECHNOLOGIES

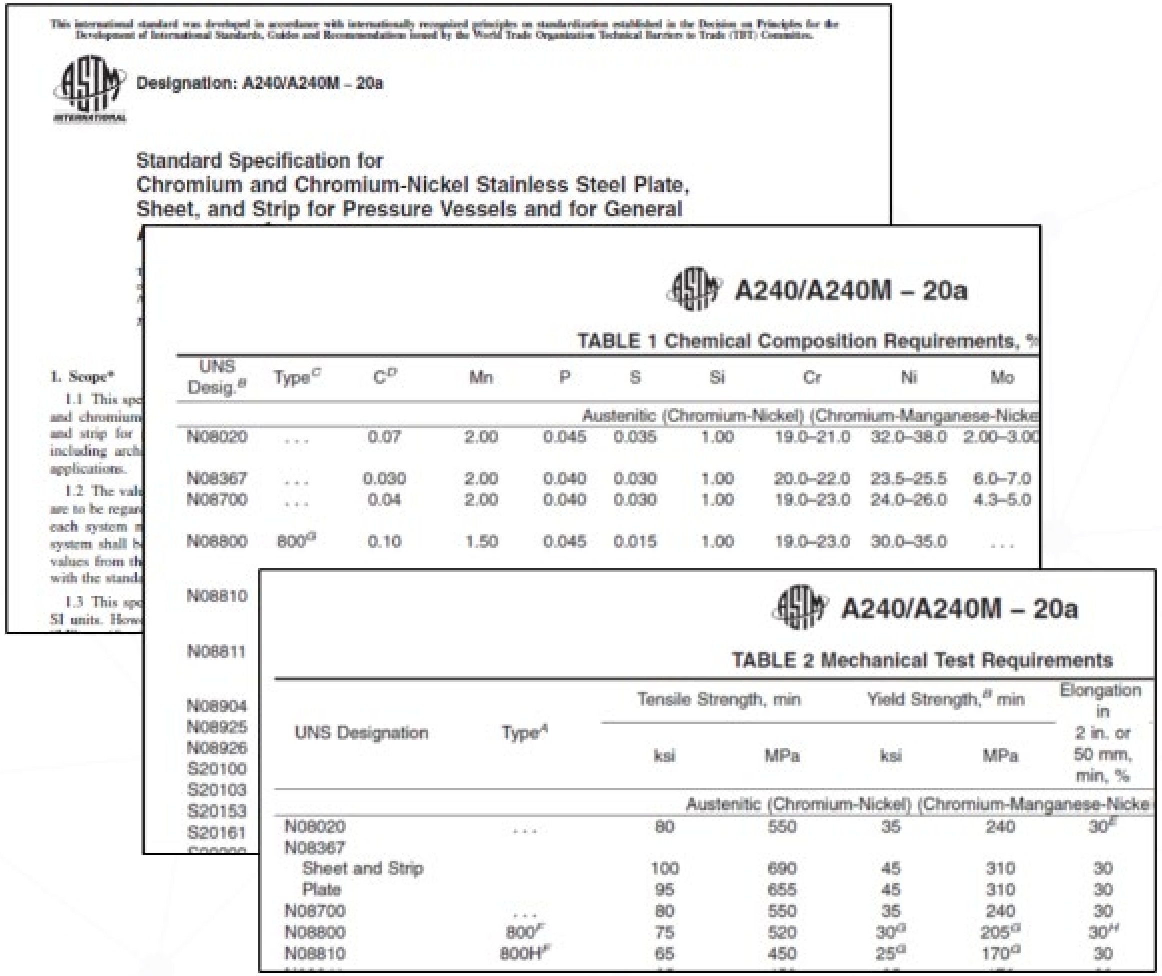
ASME Code Rules: Topics

ADVANCED REACTOR TECHNOLOGIES

- General review of code rules
  - What do they cover. What they don't.
    - *Underlying assumptions*
  - Probability of failure
    - *Material property parameters*
    - *Stresses and loads*
    - *Degradation*
- What is Nonmetallics Work Group (NWG) doing?
  - Failure in components
    - *Redefining failure*
  - Degradation rules
    - *Oxidation degradation*
    - *Irradiation degradation*
  - Molten Salt Issues
    - *Abrasion/Erosion*



Licensing challenge: No graphite fabrication standards



This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

Designation: A240/A240M – 20a

Standard Specification for
Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General

A240/A240M – 20a

TABLE 1 Chemical Composition Requirements, %

UNS Desig.[B]	Type[C]	C[D]	Mn	P	S	Si	Cr	Ni	Mo
Austenitic (Chromium-Nickel) (Chromium-Manganese-Nicke									
N08020	. . .	0.07	2.00	0.045	0.035	1.00	19.0–21.0	32.0–38.0	2.00–3.00
N08367	. . .	0.030	2.00	0.040	0.030	1.00	20.0–22.0	23.5–25.5	6.0–7.0
N08700	. . .	0.04	2.00	0.040	0.030	1.00	19.0–23.0	24.0–26.0	4.3–5.0
N08800	800[G]	0.10	1.50	0.045	0.015	1.00	19.0–23.0	30.0–35.0	. . .
N08810									
N08811									
N08904									
N08925									
N08926									
S20100									
S20103									
S20153									
S20161									

1. Scope*

1.1 This spe... and chromium... and strip for... including arch... applications.

1.2 The valu... are to be regar... each system m... system shall b... values from th... with the standa...

1.3 This spe... SI units. How...

A240/A240M – 20a

TABLE 2 Mechanical Test Requirements

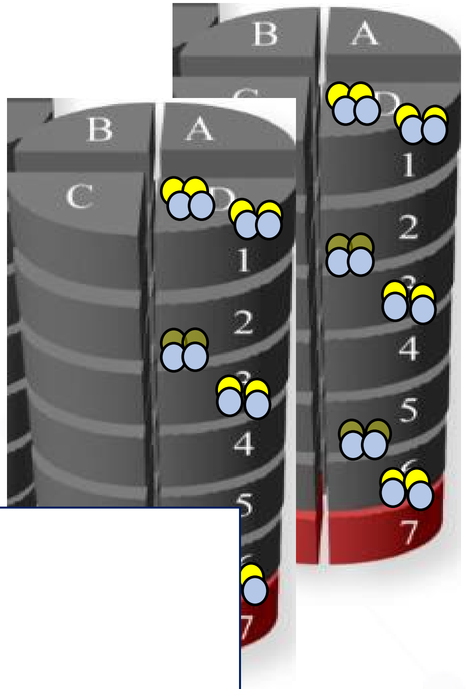
UNS Designation	Type[A]	Tensile Strength, min		Yield Strength,[B] min		Elongation in 2 in. or 50 mm, min, %
		ksi	MPa	ksi	MPa	
Austenitic (Chromium-Nickel) (Chromium-Manganese-Nicke						
N08020	. . .	80	550	35	240	30[E]
N08367						
Sheet and Strip		100	690	45	310	30
Plate		95	655	45	310	30
N08700	. . .	80	550	35	240	30
N08800	800[F]	75	520	30[G]	205[G]	30[H]
N08810	800H[F]	65	450	25[G]	170[G]	30

- No "Standard" nuclear graphite
  - Nothing like metals have
  - ASTM D7219 provides minimum property values (not fabrication standard)
  - This is a geologic material
- All graphite grades **are proprietary**. Only limited/general fabrication data is known.
  - Each grade has closely guarded, proprietary formulae owned by graphite suppliers
  - **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

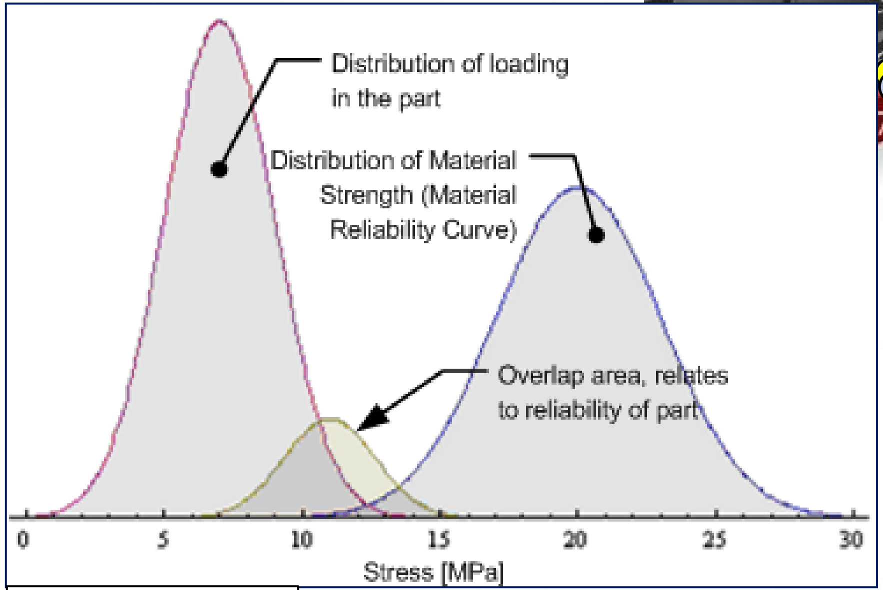
What ASME Code Rules DO cover?

Generally, the rules are pretty good and cover most of the critical areas of interest to establish a safety envelope.

- Robust undegraded (unirradiated) construction rules
- Their weakness is in the details: How to establish and apply degradation, how to define component failure, how to calculate the probability of failure, etc.



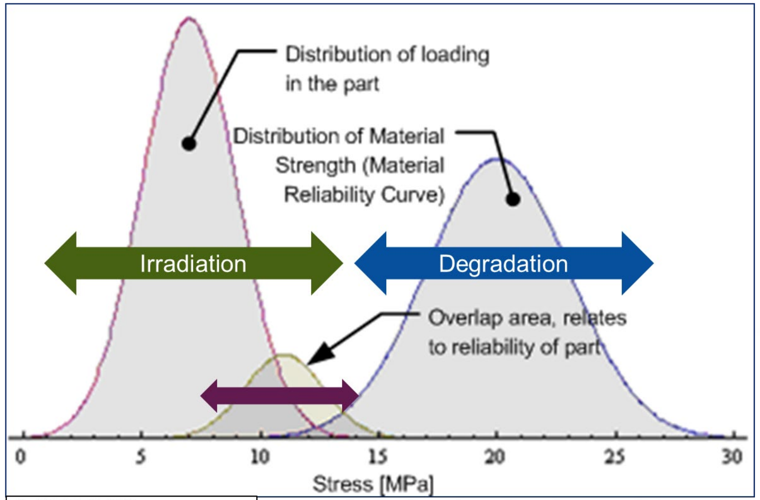
- What they **do** cover:
  - Establishes a workable probabilistic methodology
  - Establishes specific rules for probability of failure (POF)
    - *Three Assessments (Simple, Full, Test)*
  - *Establishes material properties of interest*
    - *Material Data Sheets (MDS)*
  - Establishes minimal test matrix for graphite qualification
    - *144 specimens with grain/144 against grain*
  - *Establishes <u>some</u> degradation issues*
    - *Oxidation, irradiation, combined Irr & Oxid*



From Dr. Mark Mitchell – PBMR Inc.

What ASME Code Rules DO NOT cover?

ADVANCED REACTOR TECHNOLOGIES



From Dr. Mark Mitchell – PBMR Inc.

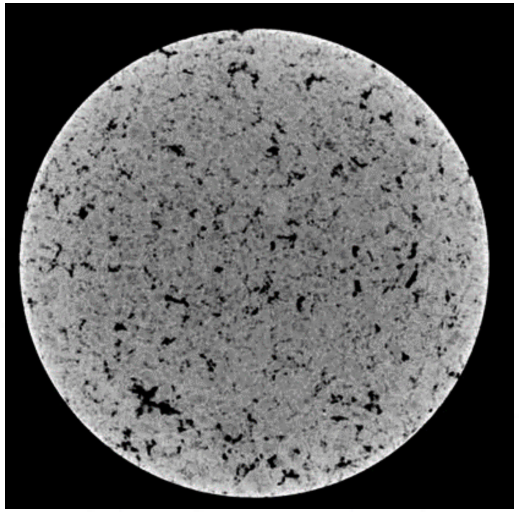
Salt residue

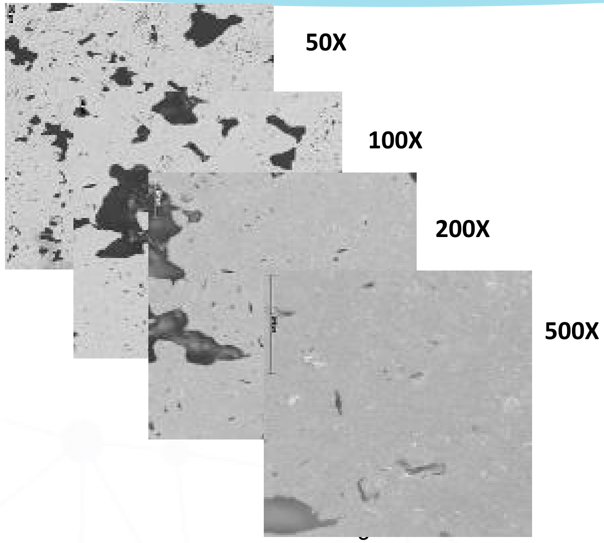
After immersion in FLiNaK

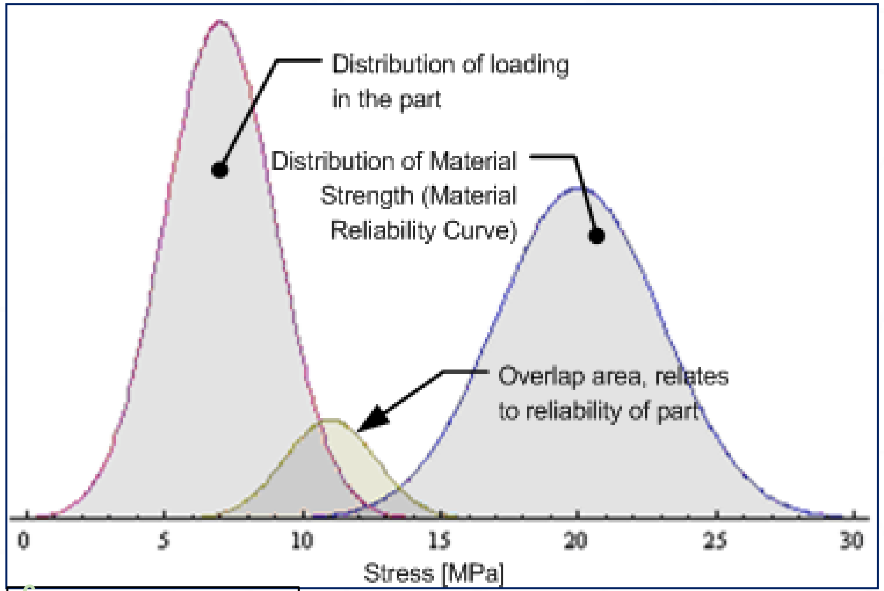
- In General, rules don't have enough detail on how to handle degradation
  - Section III, Div-5 are **Construction** code rules
  - But where should the degradation rules be written?
- Specifically, there are a few conspicuous areas where we are currently struggling
  - Failure and calculating failure of components
    - *Propagation of a single crack is not failure*
    - *The FEA mesh size and volume grouping methodology*
  - How to handle irradiation induced changes
    - *Before and after turnaround dose changes are critical*
      - ***Code case for each graphite grade? Or uniform behavior?***
    - *Temperature effects on irradiation changes*
  - Combined degradation effects
    - *Irradiation induced changes of oxidized material*
    - *Irradiation induced changes in molten salt environment*
  - Lack of testing standards
    - *ASME requires degraded properties but no way to get them*
  - Molten salt specific degradation issues

Probabilistic design

- We know nuclear 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.

How probabilistic design is implemented in the code

ADVANCED REACTOR TECHNOLOGIES

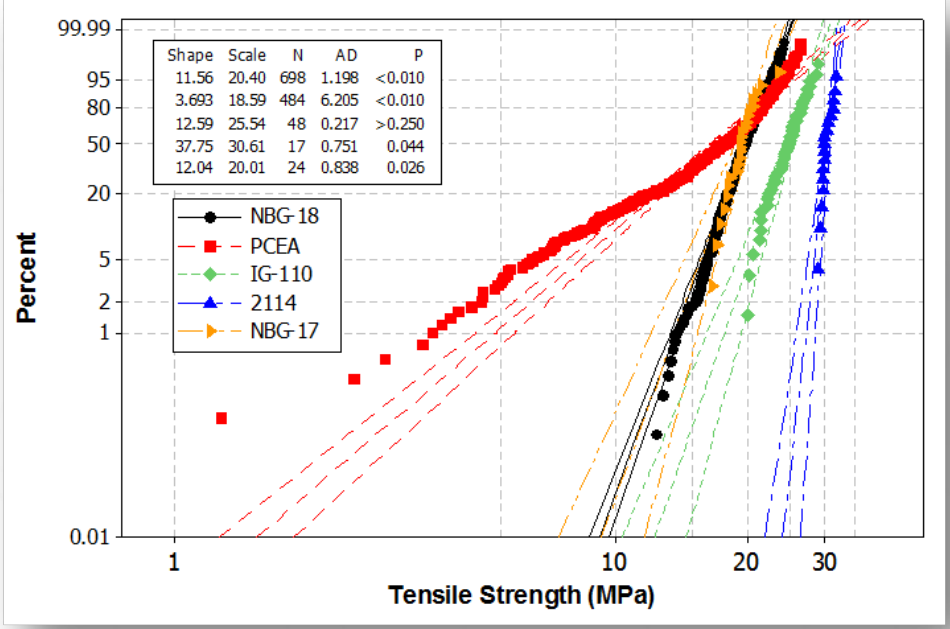
Three methods are provided for assessing structural integrity

1. Simple Assessment: Simple allowable stress
   - *Empirically derived material properties compared to maximum allowable stress*
   - *Simplified conservative method based on Weibull derived ultimate strength*
   - *Degradation changes **well contained within the operational safety envelope***
2. Full Assessment Method: Probability of Failure
   - *Detailed structural analysis taking into account stresses, temperatures, irradiation history, chronic oxidation effects, and molten salt issues.*
   - *Weibull statistics used to predict failure probability over the stress distribution in component. It gives a full statistical analysis of the entire stress distribution through the component volume.*
   - *Smaller safety envelope but material and anticipate stresses are better defined*
3. Qualification by Testing
   - *Full-scale testing to demonstrate that failure probabilities meet all 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.*

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



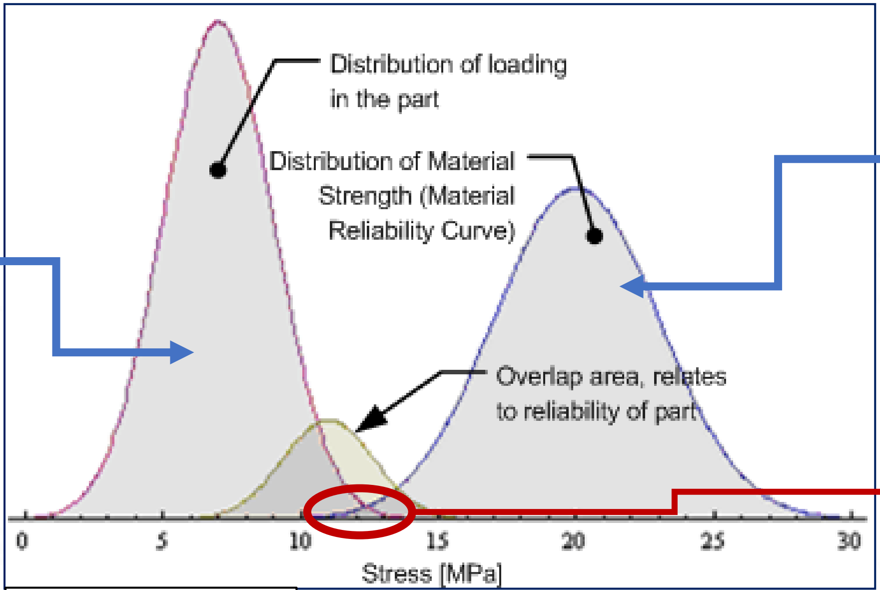
Getting the material property "proof" is responsibility of the applicant

Probabilistic Approach

ADVANCED REACTOR TECHNOLOGIES

Design

- *Values calculated from the reactor design.*
- *Received dose and temperature for all core components.*
- *FEM volume elements of core components*
    - *Normal and off-normal conditions*



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Material Property

- *Inherent material properties of selected graphite.*
- *Strength and thermal conductivity.*
    - ***Not** just average strength.*
- *Approach = Weibull str. analysis*

Reliability of Part

Probability of failure (POF)

Overlap of ***design stress*** and inherent ***material strength***

Where is component "loading" coming from?

- Thermal gradients
- Physical loads (extremely small)
- **Irradiation effects**
    - Dimensional change imposes huge internal stress
    - These stresses *will* lead to cracks (*U.K. bricks)*
    - Stress buildup = Dependent upon component dose and temperature

Strength distribution comes from "baseline" testing

- Brittle strength dependent upon flaw sizes.
    - *Due to large flaw size range it can theoretically break at any stress*
- Must determine range of strength values
    - *Determine failure over entire stress range*
    - *Can't use average strength*
- Variations of the Weibull distribution best describe the graphite reliability curve.

Graphite Degradation (ASME Material Data Sheets)

ART ADVANCED REACTOR TECHNOLOGIES

FORM MDS-1 MATERIAL DATA SHEET (SI UNITS)

Grade Designation

Material Grade ____ Material spec. ID ____ ASTM spec. ____

Max. grain size (mm) ____ Designation ____

Temperature-Dependent Parameters

Property	Units	Orientation	20°C	200°C	400°C	600°C	800°C	1000°C [Note (1)]
Bulk density	kg•m⁻³	...						
Strength – tensile	MPa	WG, AG						
Strength – flexural (4-point)	MPa	WG, AG						
Strength – compressive	MPa	WG, AG						
Elastic modulus (dynamic)	GPa	WG, AG						
Elastic modulus (static)	GPa	WG, AG						
Coefficient of thermal expansion	°C⁻¹	WG, AG						
Thermal conductivity	W/m•k	WG, AG						

Graphite Oxidation – Effect

Property	Units	2%	4%	6%	8%	10%
Strength [.]						
Elastic modulus (dynamic) [.]						
Thermal conductivity [.]						

Irradiated Graphite

Property	Units	WG	AG
Dimensional change [.]			
Creep coefficient [.]			
Coefficient of thermal expansion [.]			
Strength [.]			

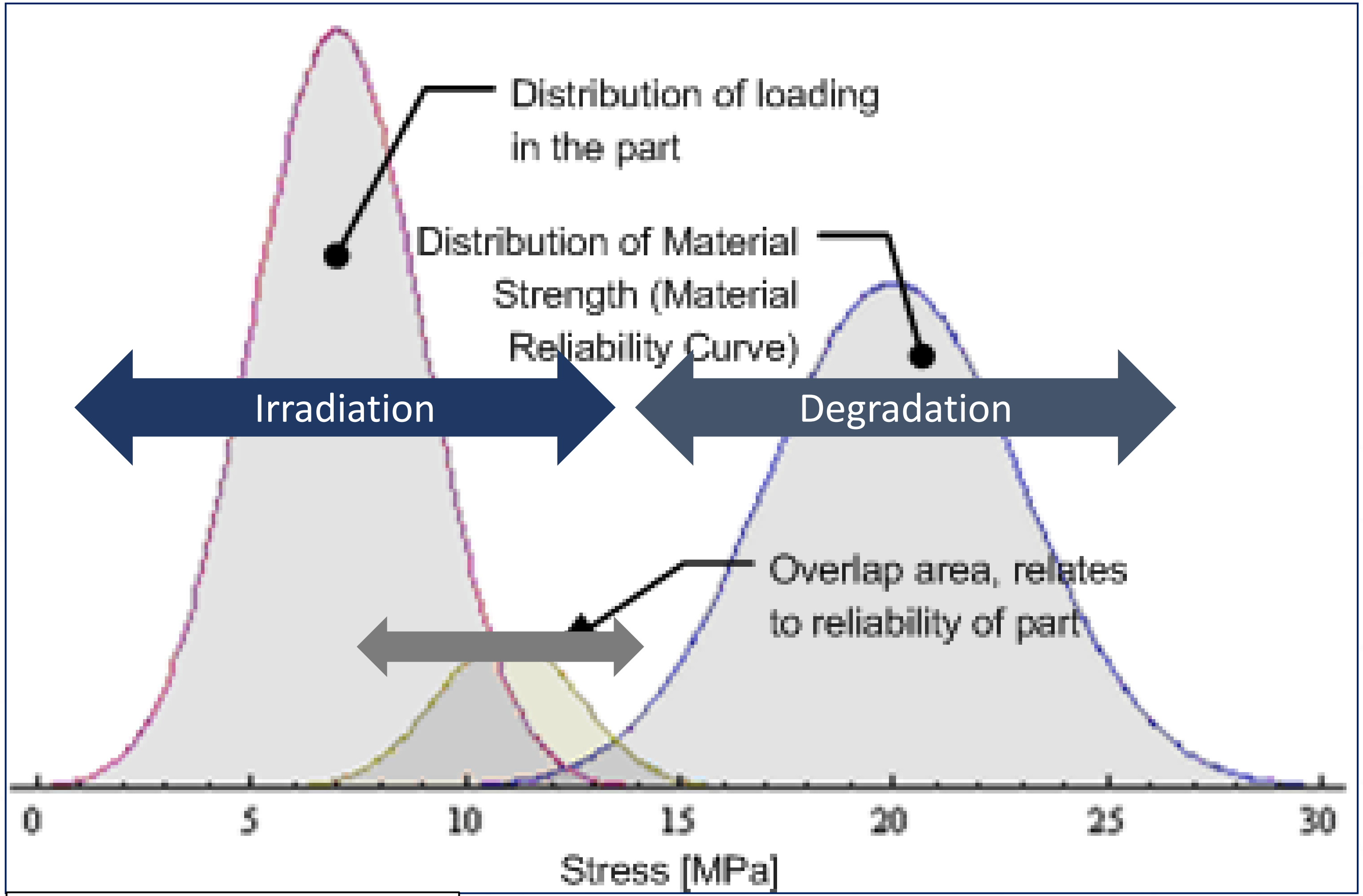
ASME Data sheets capture most of the graphite material properties of interest:

- Properties
  - *Density*
  - *Strength*
  - *Elastic modulus*
  - *CTE & Conductivity*
  - *Anisotropy*
- Temperature dependence
  - *Temperature affects everything*
- Irradiation effects
- Oxidation effects

Not covered (yet)

- Molten salt issues
- Abrasion/erosion
- Combination of degradation processes
- Details on how to use irradiation data

Applying degradation to POF

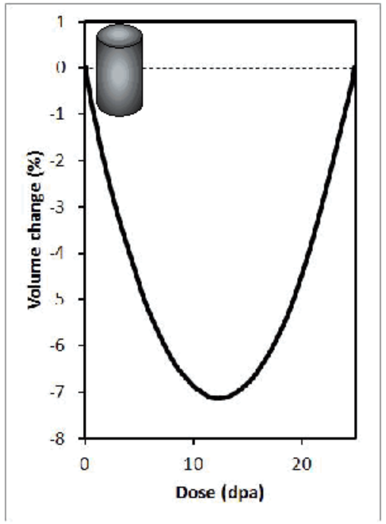


From Dr. Mark Mitchell – PBMR Inc.

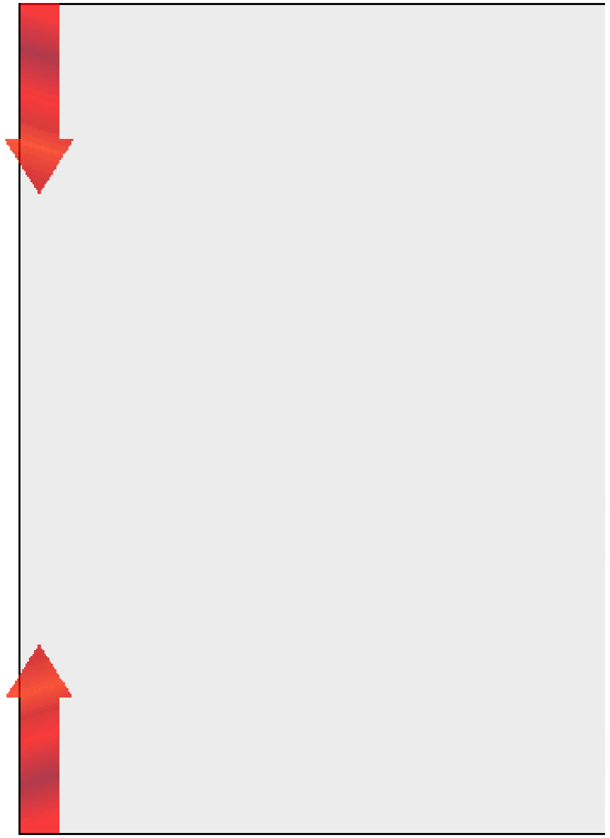
- Degradation changes the material properties
  - Irradiation strength increases
  - High temperature increases strength
  - Oxidation strength decreases
  - Molten salt strength (maybe) decreases
- Irradiation changes stress loading of the part
  - Dimensional change increases stress
  - Irradiation creep relieves stress
- Overlap will change.
  - POF will change

Induced stresses

- Fundamental material properties change with irradiation/oxidation/MS must be addressed
  - Applicant must assess stresses within component due to irradiation and thermal effects
    - *Internal stresses from dimensional change (Need creep response, too)*
    - *Turnaround dose is critical to assumptions of material response (tensile/compressive*
  - New cracks formed after turnaround



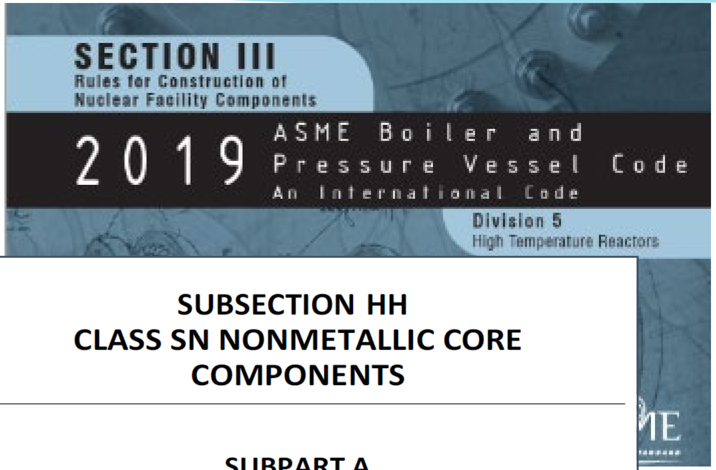
G. Haag," ***Properties of ATR-2E Graphite and Property Changes due to Fast Neutron Irradiation", Juel-4183, 2005***



– Applicant must also assess property changes to design due to irradiation, oxidation, and molten salt degradation
  - *Changes in density, strength, elastic modulus, CTE, erosion/wear, and thermal conductivity.*

Design Specifications: Impact on design rules

- ASME Nonmetallic Core Component code rules have been difficult to write
  - BPVC has focused primarily on metals
  - Very little operational experience with Nonmetallics
  - Data is not generally suitable for Pressure Vessel criteria
- Then there is the problem with graphite non-standards
  - Basically anything that works and is safe, is OK
- Up to the Designer/User to qualify the components
  - Designer must show that graphite is safe to use within the core design specifications
  - ASME nonmetallic code is more ***method*** than ***rules***
  - So what's "safe" is left up to the Users more than metallic code
- Puts a huge burden on regulators
  - They have to truly understand ***how*** graphite behaves in order to assess licensee's data and interpretations



SUBSECTION HH
CLASS SN NONMETALLIC CORE COMPONENTS

SUBPART A
GRAPHITE MATERIALS

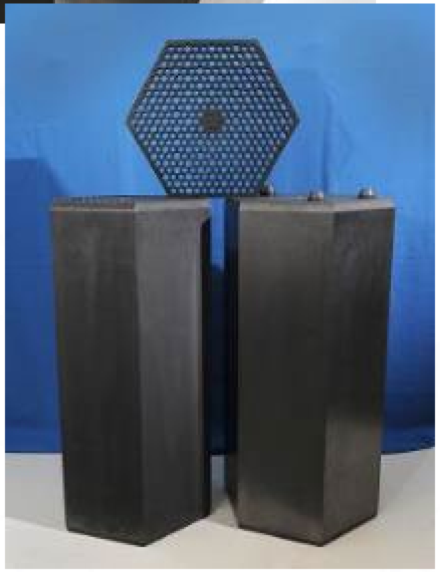
SUBPART B
COMPOSITE MATERIALS

ARTICLE HHB-1000
INTRODUCTION

Design Specifications: Impact on design rules

- Depending upon design, the “same” core component can either be safe or not safe
  - Lower or higher energy density (low/high dose per year):
    - *Internal stress development, component operational life-time*
  - Lower or higher operating temperature
    - *Component operational life-time (yrs), oxidation behavior, material property change rate*
  - Helium or Molten-salt cooled:
    - Oxidation potential, molten salt interactions, erosion
- The designers and regulators must understand what happens within all design options
  - What happens at higher dose rates and what happens at low?
  - What happens at higher and low temperatures?
- Implies a certain level of expertise in graphite behavior to really assess what is going on
  - These scenarios are not covered within the design code





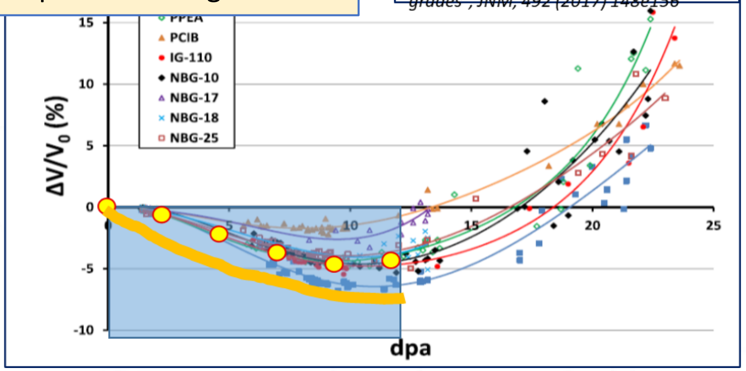
Current Nonmetallics Work Group (NWG) tasks?

Task Groups formed within NWG:

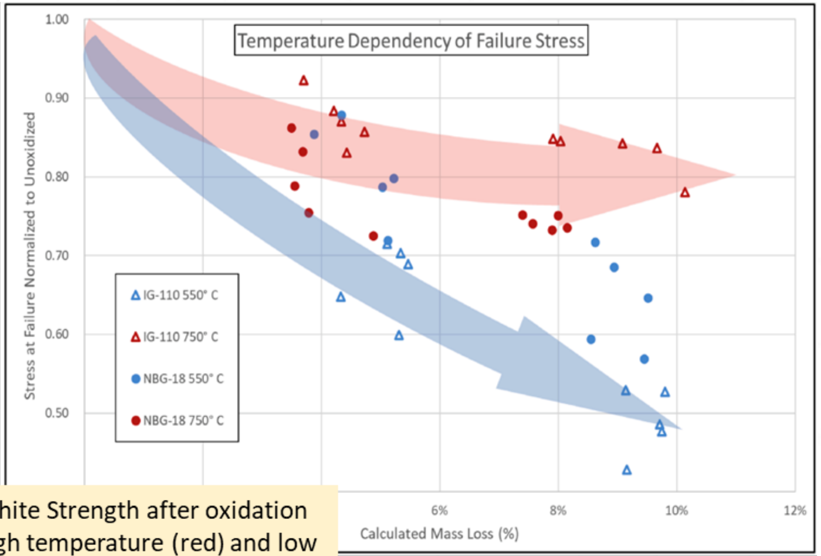
- Failure in graphite components
  - Redefining failure other than a crack propagating
  - Review of POF assessments
    - *Underlying assumptions and why they are conservative*
- Degradation rules
  - Oxidation degradation
    - *Low temperature – maximum penetration*
    - *Component failure through oxidation*
  - Irradiation degradation
    - *Before – After turnaround induced changes*
    - *Affects on material properties, stresses, and POF*
- Molten Salt Issues
  - Molten salt degradation issues
    - *Salt intrusion*
    - *Abrasion/Erosion issues*

Before turnaround: common response for all grades

M.C.R. Heijna, et. al, "Comparison of irradiation behaviour of HTR graphite grades", JNM, 492 (2017) 148e156



Cracked AGR core brick at Hunterston B power station



Graphite Strength after oxidation at high temperature (red) and low temperature (blue)

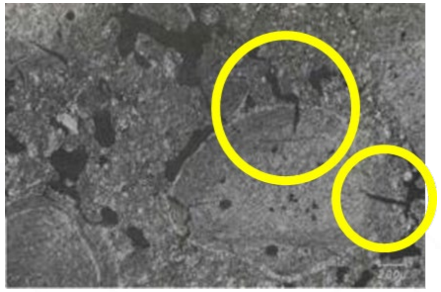
Issues beyond NWG Tasks groups

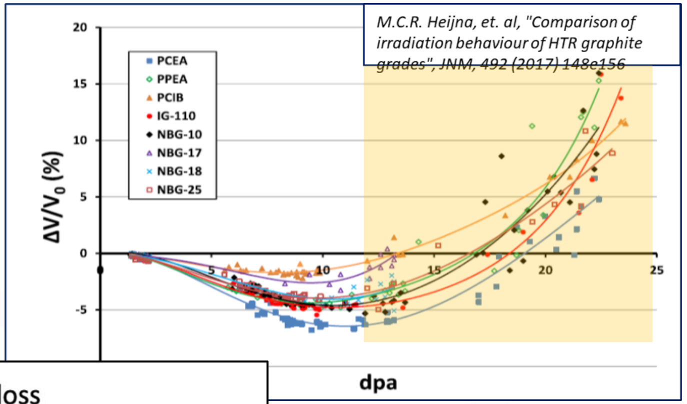
Complex issues that still need addressing:

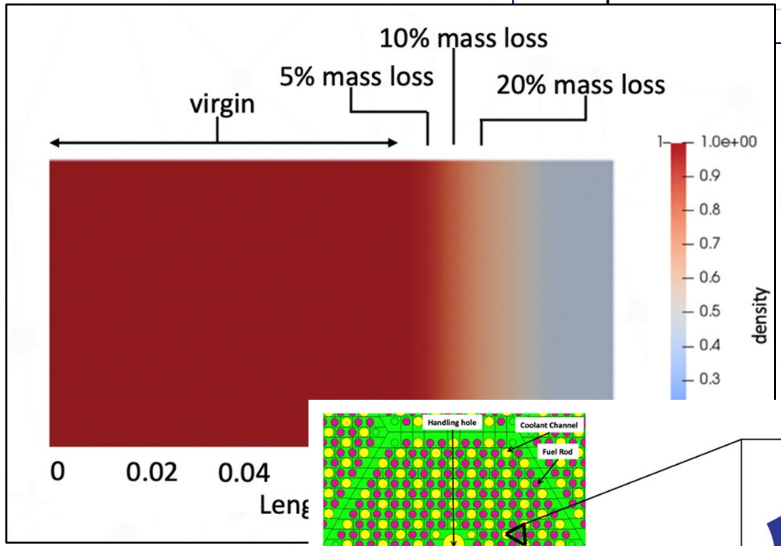
- Failure in graphite components
  - Is current methodology correct?
- Degradation rules
  - Oxidation degradation
    - *Large component vs small sample (the same?)*
  - Irradiation degradation
    - *After turnaround induced changes and stresses*
  - Molten Salt Issues
    - *Intrusion issues for post-turnaround crack formation*
- Combination effects
  - Molten salt + irradiation, Oxid + Irr, etc.
  - Large components vs small samples

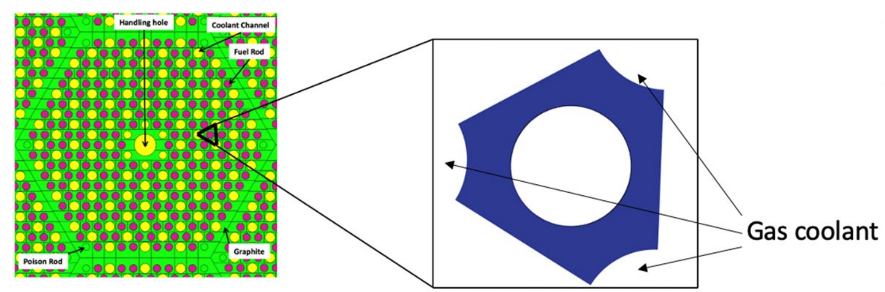
Behavior Model(s) needed

- Empirically based, mechanism informed
  - Scale-up to component and core assembly size
  - Predictive in areas without data
  - Combination effects are possible









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