July 14, 2021

Josina W. Geringer
Material Science and Technology Division, ORNL

ASME: Sec III.5 nonmetallic design and materials status and task group activities

ART Gas-Cooled Reactor Program Review

ART
Advanced Reactor Technologies

Non-metallic Code and Standards Development

- The graphite and composite code development work is undertaken by the two Working Groups on Nonmetallic Design and Materials (WG-NDM), and General Requirements for Graphite and Ceramic Composite Core Components and Assemblies (WG GR GCCCCA) within ASME BPVC Section III (Nuclear), Division 5 (High Temperature Reactors). With leading efforts from Idaho National Laboratory and Oak Ridge National Laboratory.

The working group mandates

WG-NDM:

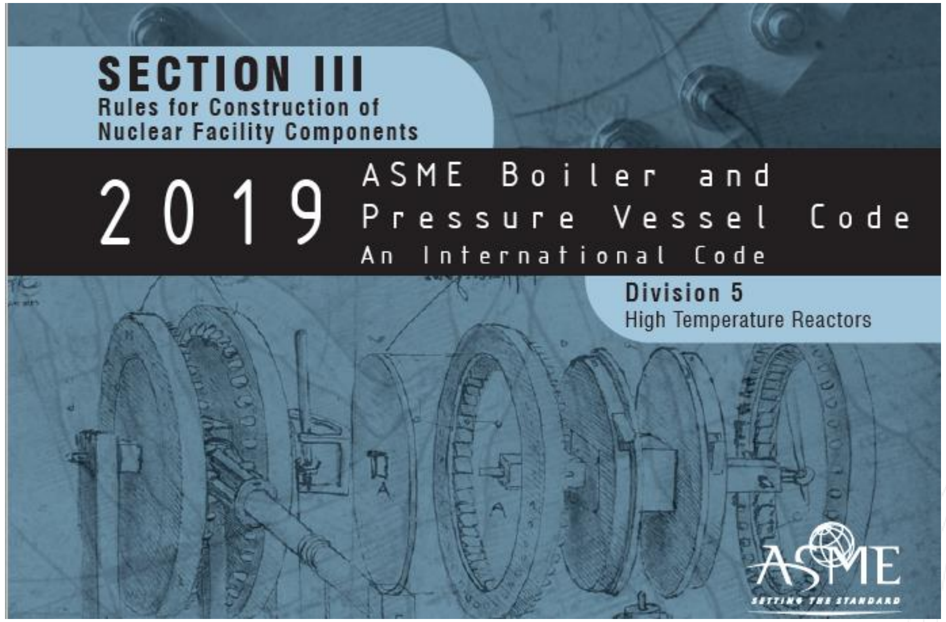
- To establish the rules, standards, and guides for design, material qualification, fabrication, testing, installation, examination, inspection, certification and the preparation of reports for nonmetallic internal components that are defined as components contained within a fission reactor pressure vessel and manufactured from graphite or ceramic matrix composites.

Focus: All current articles included under Sec III.5 HHA and Sec III.5 HHB

WG-GR GCCCCA:

- To develop the requirements for Duties, Responsibilities, Quality Assurance, Stamping, Authorized Inspection and associated Mandatory and Nonmandatory Appendices for all graphite and ceramic composite core components and assemblies.

Focus: All current articles included under Sec III.5 HAB



Standards developed under ASTM subcommittees D02.F on manufactured carbon and graphite materials and C28.07 on ceramic matrix composites, have been adopted to support the ASME code development.

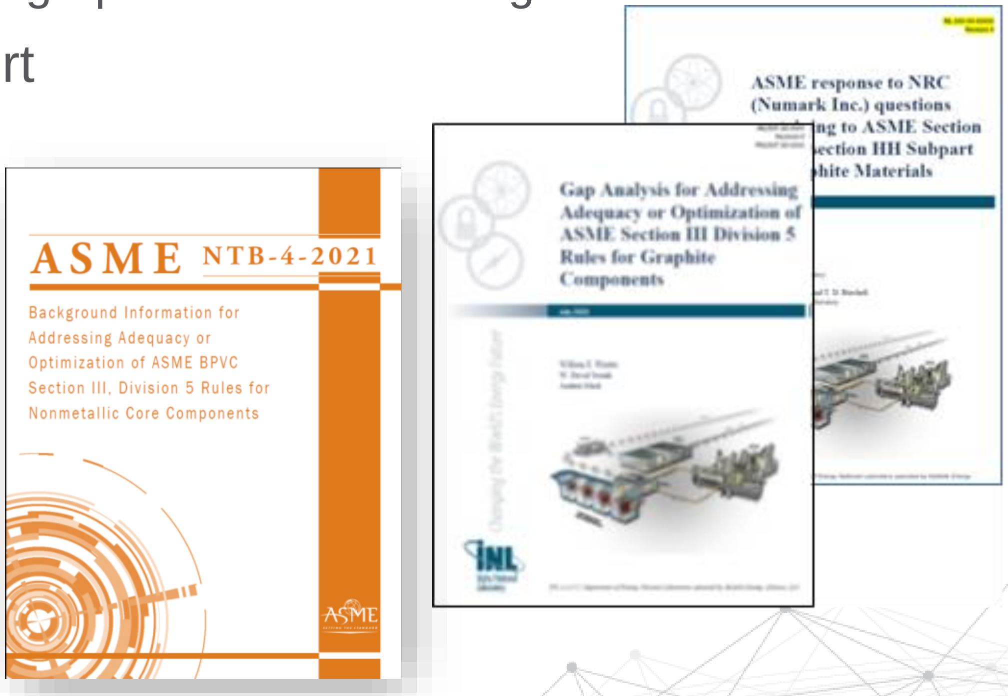
NRC Endorsement of ASME Section III, Division 5 -Status

- Nuclear Regulatory Commission (NRC) is currently assessing ASME Section III, Division 5 (2017 Edition) and accompanying Code Cases for endorsement
- Draft Regulatory Guide (DG-1380) and draft NUREG are scheduled to be issued for public comment by July 2021, per update by NRC staff
  - Likely to include a number of conditions, in the areas of general requirements, mechanical design, metallic materials allowable stresses, and graphite materials/design
- Several documents compiled to support this effort

Nonmetallic WG focus areas:

- ✓ **Adequate practices**: noteworthy parts of the code addressed.
- ▪ **Currently Optimizing**: Issues actively being addressed.
- ▪ **Requires Optimization**: Issues that have been identified but need to be addressed by experts.

Expert Task Groups



WG-NDM Task Group Approach

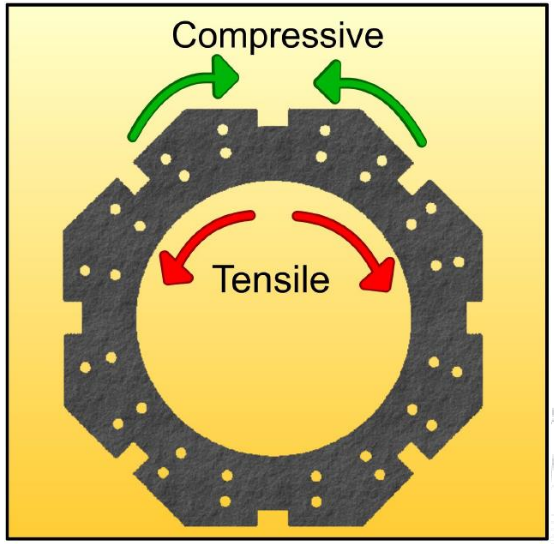
- Analyze the approach to identified topic in ASME BPVC Section III Division 5 Code
  - Propose a generic strategy for example, the probabilistic evaluation of oxidation-induced property changes and of their effects on reactor's safe operation
  - Determine whether changes, clarifications or additions are needed
- Include experts with diversified background (from national laboratories, universities, industry).
- Draft White Paper(s) to justify proposed changes, documented by reliable and authoritative expert publications in the literature
  - Use external information from experimental and technical literature on graphite materials for HTGR components
  - Learn from world-wide experience of previous design codes for gas-cooled and molten salt reactors

Identified Optimization Areas

- Deformation limits and the definition of “damage tolerance”
  - TPOC: M. Metcalfe
- Oxidation criteria
  - TPOC: C. Contescu
- Irradiation dose limits and data interpolation vs extrapolation
  - TPOC: J. Geringer
- Irradiation data integration
  - TPOC: W. Windes
- MSR conditions and material properties affected as result
  - TPOC: N. Gallego
- Defined Weibull and allowable stress calculations
  - TPOC: A. Mack

Damage Tolerance

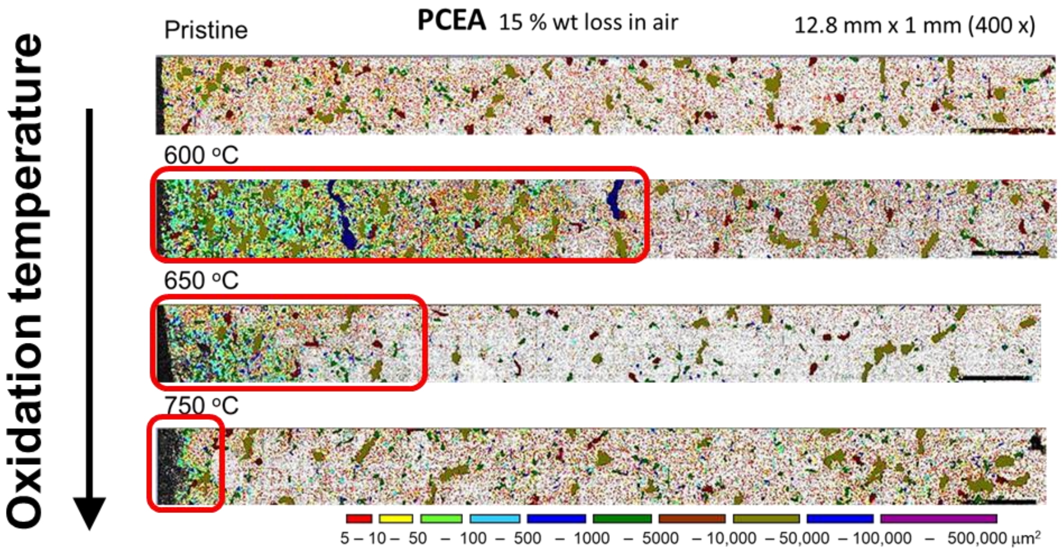
- Acceptable deformation: Maintaining function during reactor operation
  - To not compromise free movement of control rods and fuel rods during graphite component lifetime
- Damage tolerant requirement: When is a crack in a graphite component considered “a crack”?
  - Important to define terminology associated with graphite microstructure and perceived damage to components
- Damage tolerance is design-dependent and it is incumbent on designers to fully assess graphite core component functionality and the consequences of cracking.
  - “Adopt methodology to apply probabilistic assessments that focus on the tolerability of selected bounding levels of damage.” *Dr. M. Metcalfe*
- Lessons from Magnox-GCR and AGR operational experience
- Sec III vs Sec XI?
  - Validation of predictive models using monitoring methods

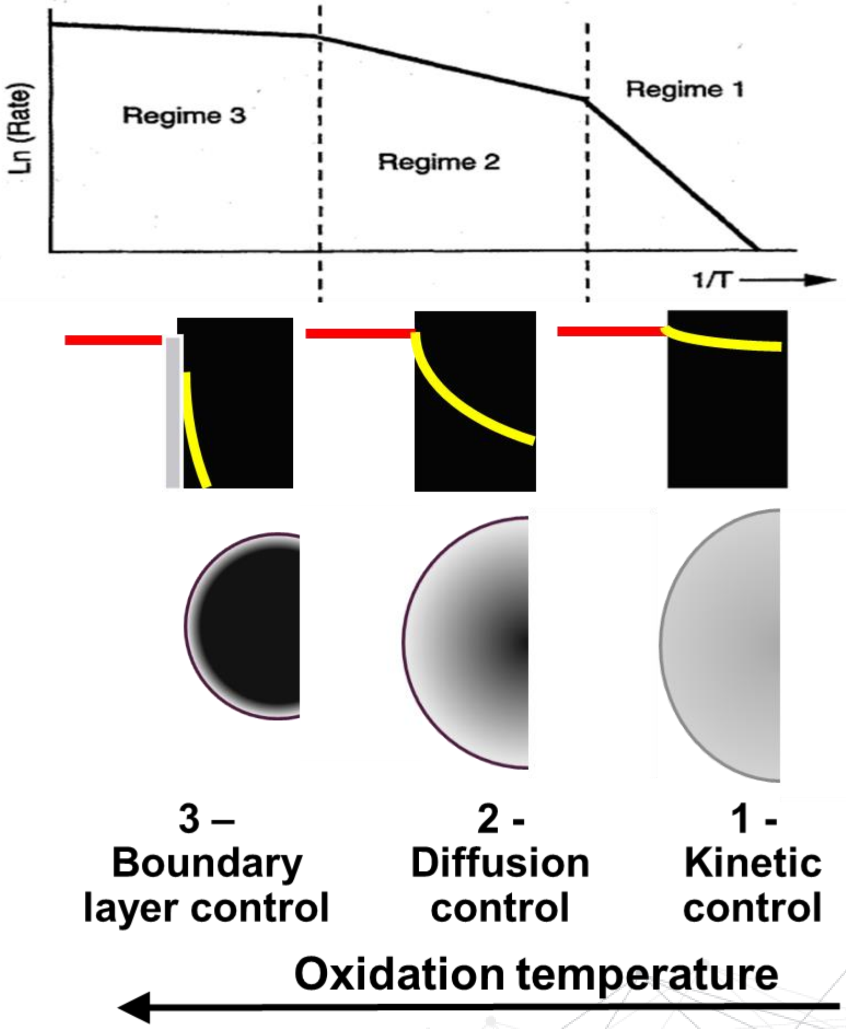


M. Metcalfe

Oxidation Criteria – How is weight loss defined?

- **Oxidation is local**
  - Irradiation is not local
- **Weight loss is local**
  - Intrinsic factors (microstructure, raw materials, forming method)
  - Extrinsic factors (temperature, oxidant supply, flow conditions, shape and size)





C. Contescu

Optimization considerations on graphite oxidation

- **ASME code requires that detailed properties characterization must be done for each graphite grade**
  - As-manufactured condition
  - Oxidized at various weight-loss levels [1]
    - Strength
    - Elastic modulus
    - Thermal conductivity

    ASTM methods available
  - Designers must determine which materials and test conditions are needed
- **Oxidation behavior of irradiated graphite**
  - Irradiated graphite are small specimens
  - Small specimens cannot be oxidized according to ASTM D7542 (vertical furnace)
    - INL demonstrated that limited consistency exists between results obtained with TGA and vertical furnace methods [2]
  - Strength measurements [3] on irradiated & oxidized specimens must use test methods specific to small size specimens like ASTM D8289 (split disc)
    - Their relationship with classical method results still needs to be proven by more results

[1] R.E. Smith, A.C. Matthews, W.D. Swank, Oxidation and materials properties effects on graphite, INL/MIS-20-59011
[2] R.E. Smith, Comparison of oxidation performance of graphite samples in TGA versus vertical furnace, INL/EXT-19-54584
[3] A.C. Matthews et al. Degradation of strength under various oxidizing conditions for nuclear graphites, INL/EXT-19-53753

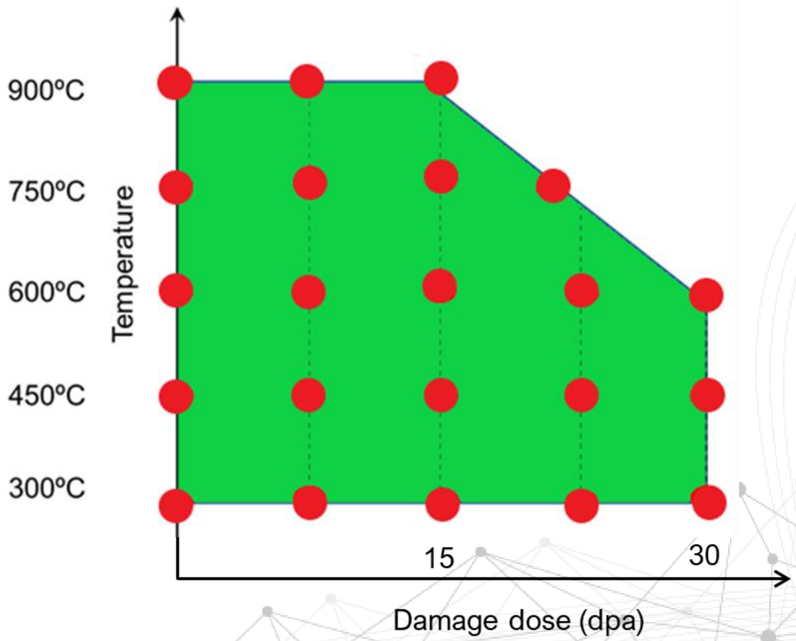
Input from C. Contescu

Irradiation Dose Limits & Data Interpolation vs Extrapolation

- Code language change addressing irradiation fluence limits is pending final approval by the std committee. (R19-2805)
  - All neutron dose limits expressed in dpa (displacements per atom).
  - Fluence references changes to damage dose.

- Data interpolation (HHA-3142)
  - Collective agreement that data interpolation is required:

"Since properties can only be determined for a number of (fixed) fluences and temperatures, the Code should allow a technically justifiable linear or nonlinear equation to interpolate between (data-known) fluence and temperature over allowable component lifetime." - *NUMARK Associates. Inc., Dec 2020*

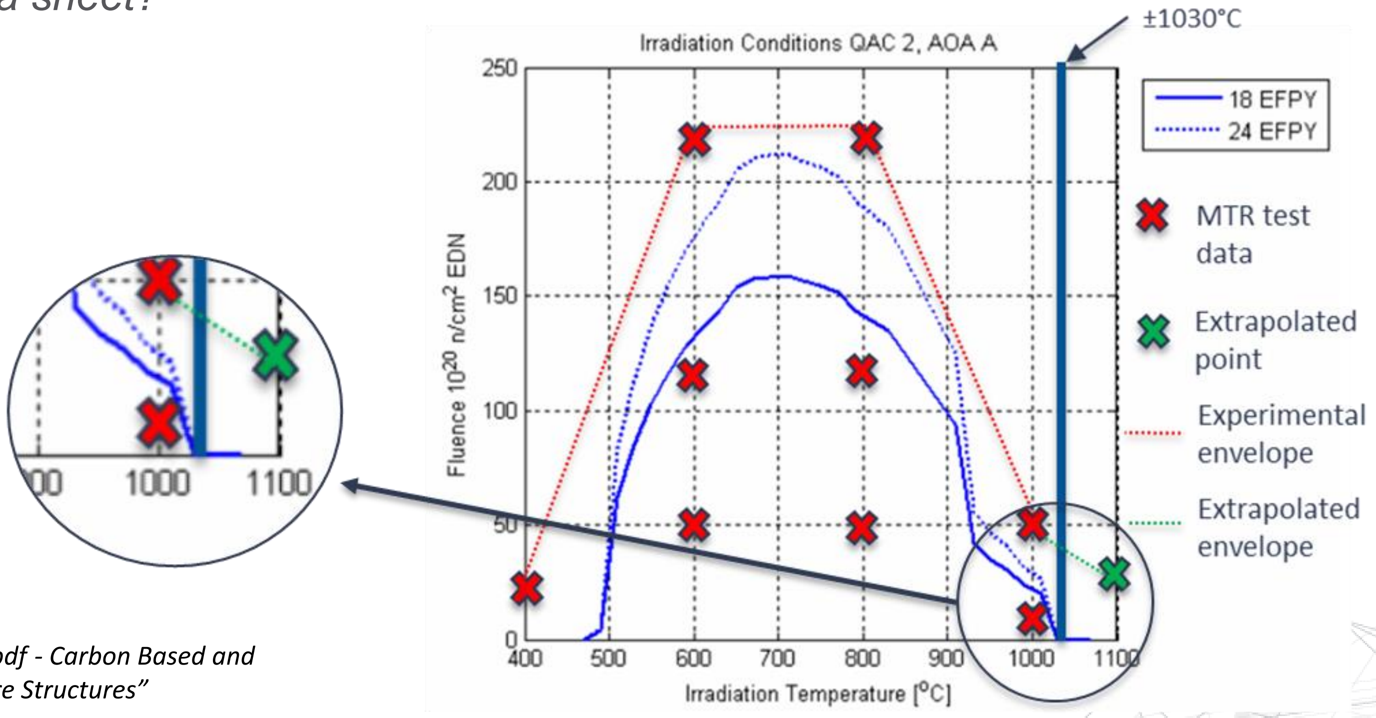


Irradiation Dose Limits & Data Interpolation vs Extrapolation

- Inquiry on data extrapolation (R21-557)

Question: *"When generating irradiated material properties for a Material Data Sheet for a graphite grade, as required in HHA-2200(a) in accordance with the requirements of mandatory appendix HHA-II-4000, is it permissible to use **limited** extrapolation from experimental data with **justification** to the temperature-fluence envelope of the material data sheet?"*

Answer: ***"Yes"***



Irradiation conditions Image from "https://www.nrc.gov/docs/ML0525/ML052580342.pdf - Carbon Based and Ceramic High Temperature Materials in the PBMR Core Structures"

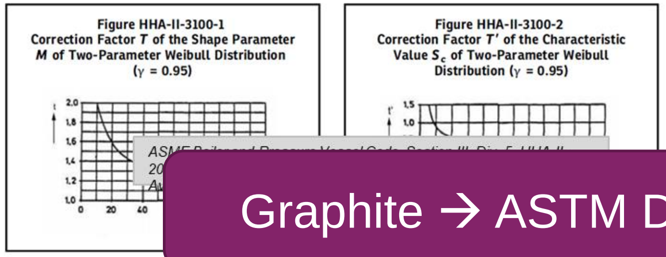
Optimization efforts on Weibull implementation and allowable stress calculation

Allowable stress calculation

- Optimize equations for two parameter simple assessment
- Update the 95% confidence limits: 5% lower bound of the shape (characteristic strength) and scale (Weibull modulus) parameters

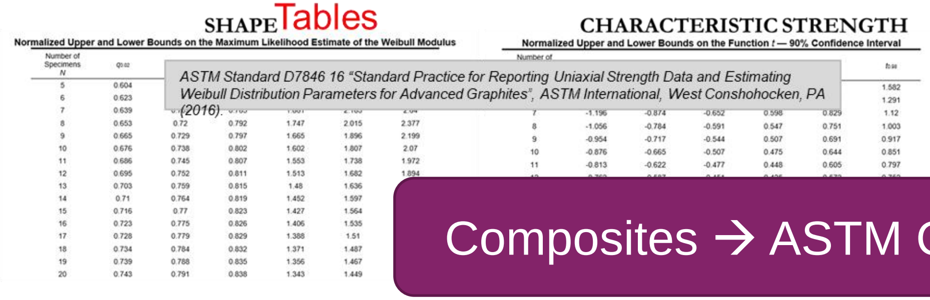
Integrate code with ASTM standards

Replace this:



Graphite → ASTM D7846

With this: Pivotal Quantity Functions: ASTM Tables



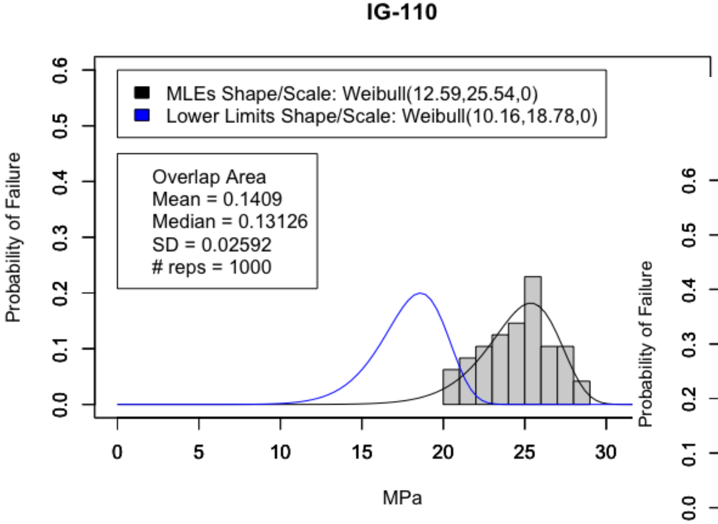
ASTM Standard D7846 16 "Standard Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Graphites", ASTM International, West Conshohocken, PA (2016).

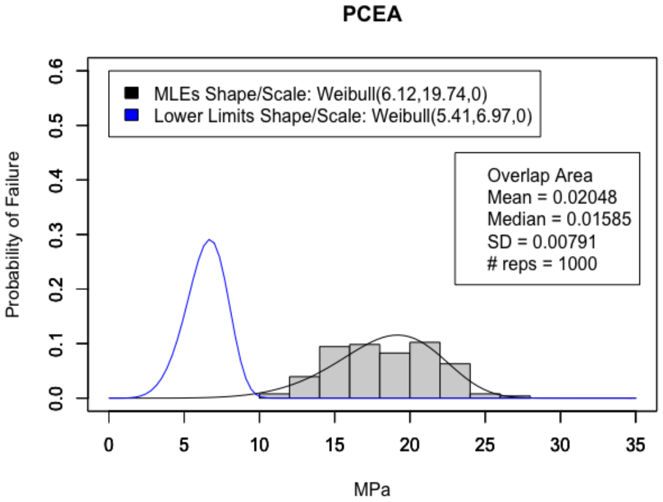
Composites → ASTM C1239

*Tables shown are top 20 rows. ASTM tables go up to sample sizes of 120.

Additional questions being reviewed by Weibull Task Group:

- The code provides a method to always use a conservative stress distribution, but the current process is not a quantifiable conservatism.
- Uncertainty is determined from the Weibull parameters derived from the material strength which varies between graphite grades.
- Should the absolute level of uncertainty be controlled?





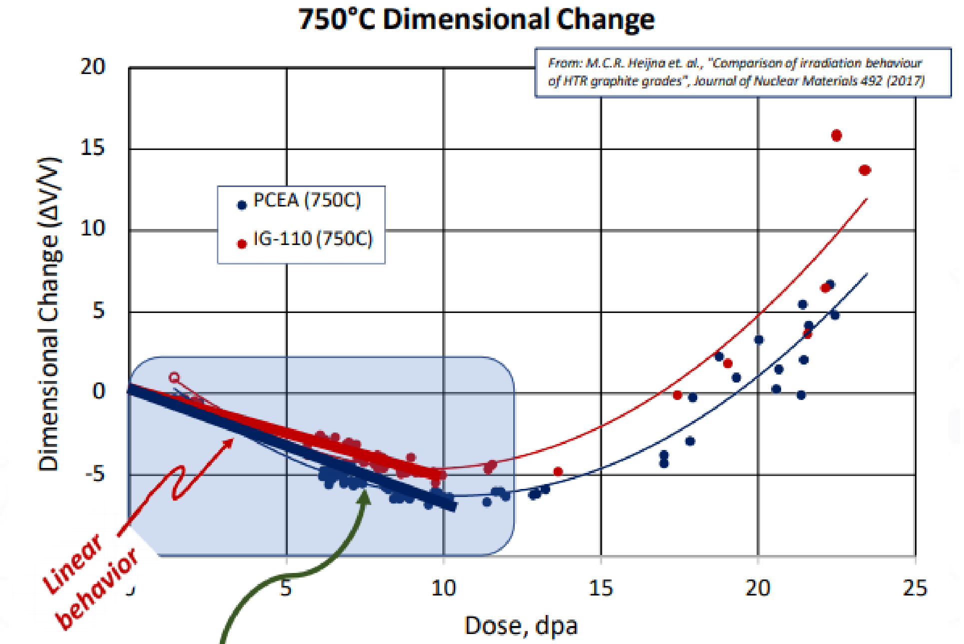
Graphs with permission from A. Mack

Irradiation Data Integration

Existing data for grades with similar density, grain size, and fabrication method will be analyzed (fabrication parameters) to derive a common response.

Aim: To revise code to require an applicant to provide limited irradiation data to ascertain similar behavior

	Temp. (°C)	Dose (dpa)
AGC-1	600	0.5 - 7
AGC-2	600	0.5 – 7
AGC-3	800	0.5 – 3.5
AGC-4	800	3 – 8.5
HDG-1	600	7 – 15
HDG-2	800	7 – 15



- Larger grain grades (PCEA) demonstrate longer life
- Small grain grades (IG-110) demonstrate less change

But both exhibit linear response

Behavior models

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

W. Windes

Molten Salt Code Integration

The current HHA does not address any coolant salt interactions with graphite.

Chemical attack, salt infiltration and retention as well as wear and erosion aspects need to be incorporated in the design rules.

The different reactor concepts share common challenges to graphite presence in the core.

Effect of fast neutron irradiation and its relationship with microstructure

- ➢ Dimensional changes, structural damage
- ➢ Change in mechanical and thermal properties
- ➢ Change in chemical resistance to environmental effects

Chemical environment effects and surface reactivity

Gas-cooled reactors

- ❖ Chronic oxidation
- • Moisture in coolant will cause slow by continuous oxidation during normal operation – will always happen
- ❖ Acute oxidation
- • Air or water ingress (accident conditions) – should never happen

Fluoride salt-cooled reactors

- ❖ Chemical Interactions: Salt-graphite interaction that may affect structural or physical properties of graphite
- ❖ Salt infiltration in graphite: May cause structural changes, hot spots in graphite
- ❖ Wear and erosion
- ❖ Tritium control: May accumulate in graphite

Further ddevelopment of ASTM standards for molten salt (ASTM D8091)

Ongoing Code Changes / Additions

- R20-1307 - Inclusion of C/C specific nonmandatory appendices
  - Record created and include general information on the composition, architecture, manufacture and properties of carbon-carbon composites as well as information on the effects of fast neutron irradiation on carbon-carbon composites
  - Ballot for review
- R21-989 – Errata in HHB – Ceramic Matrix Composites
  - Revised for 2021 edition.
- R19-2805 – Elimination on the use of fluence and historical dose units
  - Final ballot review by standards committee

FY21 ASME and ASTM Meetings and Presentations

Development of the design ASME BPV code and ASTM standards for graphite as well as ceramic composite core components were discussed and coordinated at several ASME and ASTM meetings that were held during FY21.

Meeting Date	Organization: committees	Location
10-13 Nov 2020	ASME: WG-NDM, SG-HTR, BPVIII	Virtual (Zoom), NY
25 Jan 2021	ASTM C28.07	WEBEX Meeting
26-29 Jan-2017	ASTM	Daytona Beach, FL
8-11 Feb 2021	ASME: WG GR GCCCA, WG-NDM, SG-HTR, BPVIII	Virtual (Zoom), NY
11-14 May 2021	ASME: WG GR GCCCA, WG-NDM, SG-HTR, BPVIII	Virtual (Zoom), NY
16 Jun 2021	ASTM D02.F	WEBEX Meeting
28 Jul 2021	ASTM C28.07	WEBEX Meeting
25-30 Jul 2021	ASME: WG GR GCCCA, WG-NDM, SG-HTR, BPVIII	Virtual (Zoom), NY

- W. Windes, “ASME Nonmetallic Considerations for Graphite and Composite Components”, ASME BPVC Sec III Div 5 Virtual Workshop on High Temperature Reactors, Nov 8-9, 2020.
- J.W Geringer, “ASME Code rules and ASTM standards integration for ceramic composite core materials and components”, HTR2021 virtual conference, June 2-5, 2021.