INL/MIS-21-63470-Revision-0

ART Graphite R&D Introduction

July 2021

Changing the World's Energy Future

William E Windes

Idaho National Laboratory

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ART Graphite R&D Introduction

ART
Advanced Reactor Technologies

ART Graphite Team

Researcher	Expertise
Andrea L. Mack andrea.mack@inl.gov	ASME Code
Austin C. Matthews austin.matthews@inl.gov	Material property testing, ASTM, PIE, Oxidation
Anne Campbell campbellaa@ornl.gov	PIE, Irradiation damage, Irradiation behavior
Cristian Contescu contescuci@ornl.gov	Oxidation, microstructure
David T. Rohrbaugh david.rohrbaugh@inl.gov	Unirradiated and Irradiated material properties
Martin Metcalfe martin.p.metcalfe@gmail.com	HTR operations, ASME, ASTM
Jose' D. Arregui-Mena arreguimenjd@ornl.gov	Microstructure, irradiation damage
Joseph L. Bass Joseph.Bass@inl.gov	Behavior Modeling

Researcher	Expertise
Michael E. Davenport michael.davenport@inl.gov	Irradiation experiments
Nidia C. Gallego gallegonc@ornl.gov	Molten salt technical lead, irradiation damage
Paul, Ryan paulrm@ornl.gov	Oxidation, graphite manufacturing
Philip L. Winston philip.winston@inl.gov	Irradiation experiments
Rebecca E. Smith rebecca.smith@inl.gov	Irradiated and unirradiated graphite oxidation
Steve Johns stevejohns@u.boisestate.edu	Irradiation damage
William Windes william.windes@inl.gov	Technical lead, irradiation behavior, ASME
Yuzhou Wang Yuzhou.Wang@inl.gov	Characterization, XRD, Raman

Dr. Tim Burchell (ORNL) has retired on 1 October 2020

Five different research areas

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

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

Graphite R&D Program
Defines the safe working envelope for nuclear graphite and protection of fuel

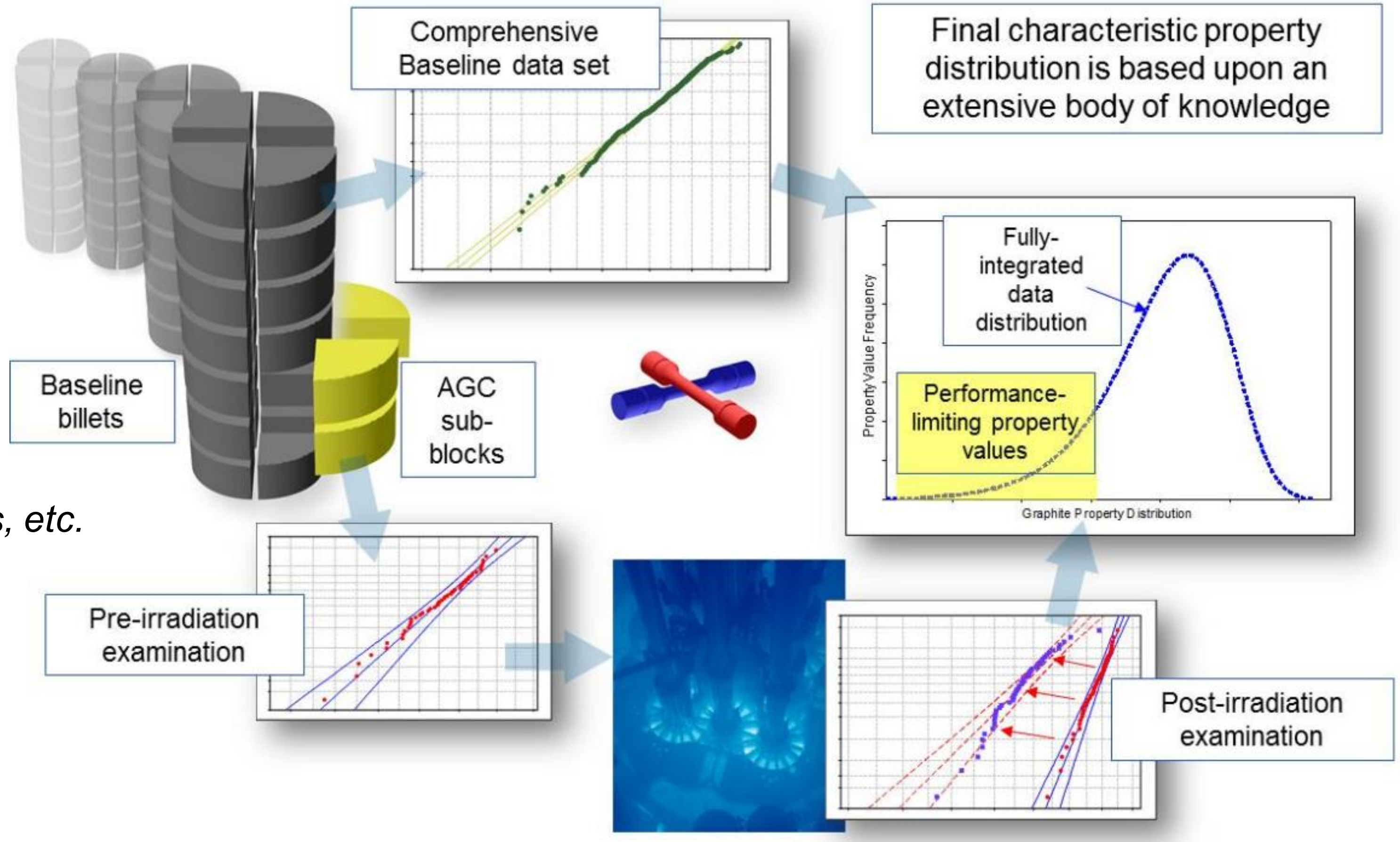
Virgin Properties
- (Statistically) Establishes as-received material properties
- Baseline data used to determine irradiation material properties

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

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

As-Fabricated Properties (Baseline) *(Matthews)*

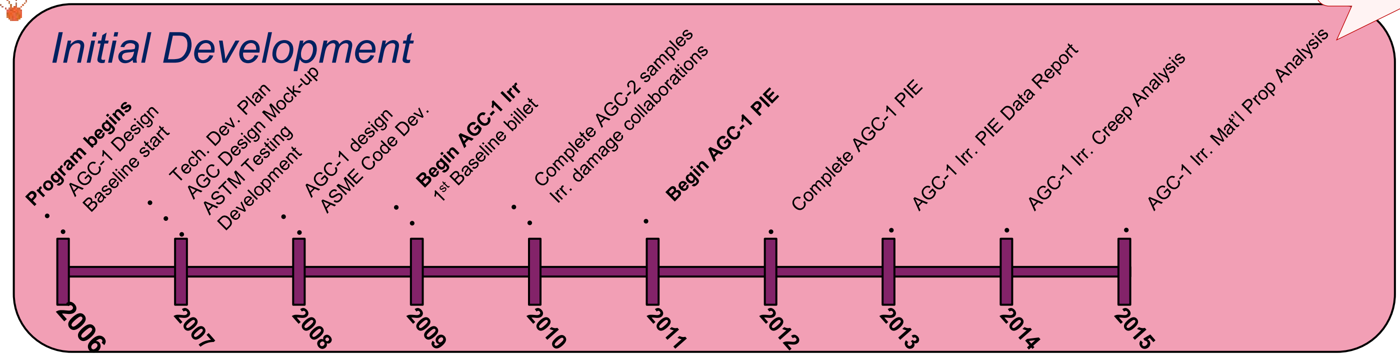
- Baseline (unirradiated) material properties
  - As-manufactured material property data for all major AGC graphite grades
    - *Provides a "baseline" of material property values*
    - *Compare to changes resulting from irradiation, oxidation, molten salt interaction*



- New uses for Baseline data everyday
  - Data for NRC degradation model
  - Testing conservatism of ASME code
    - *Sample pop., location, degradation effects, etc.*
  - Elevated temperature mechanical testing
    - *Per ASME requirements*
  - Split-disk testing critical for:
    - *Irradiation changes*
    - *Molten salt effects*
    - *Combination effects*
  - Limited testing of new **super fine** grades

AGC Experiment (Irradiation) *(Windes)*

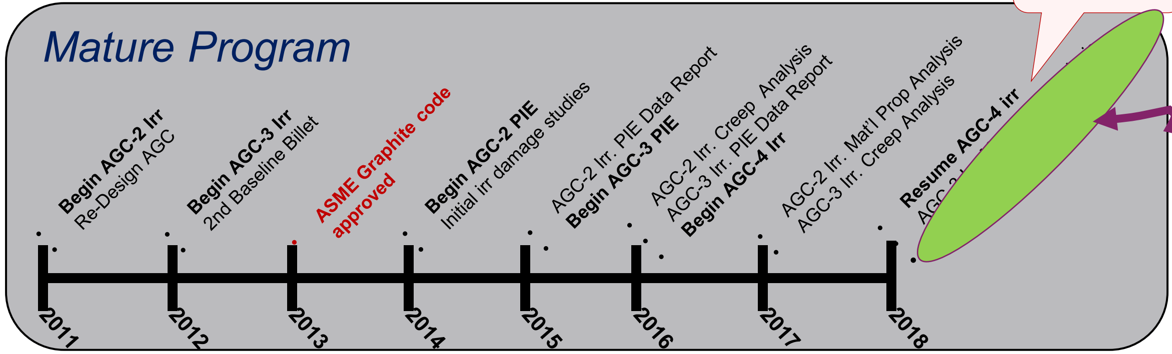
Micro and Prismatic dose range (600°C)



- **Program starts 2006**
- **Large initial investment**
- **AGC-1**
  - Prototype test train
  - Lessens learned from design & irradiation

Initial validation of ASME Code

- **Improved/Final AGC Design**
- **Initial data allows:**
  - Initial irr. analysis
  - Collaborations
  - Model development
- **High Dose Graphite**



Decision to increase AGC irradiation dose

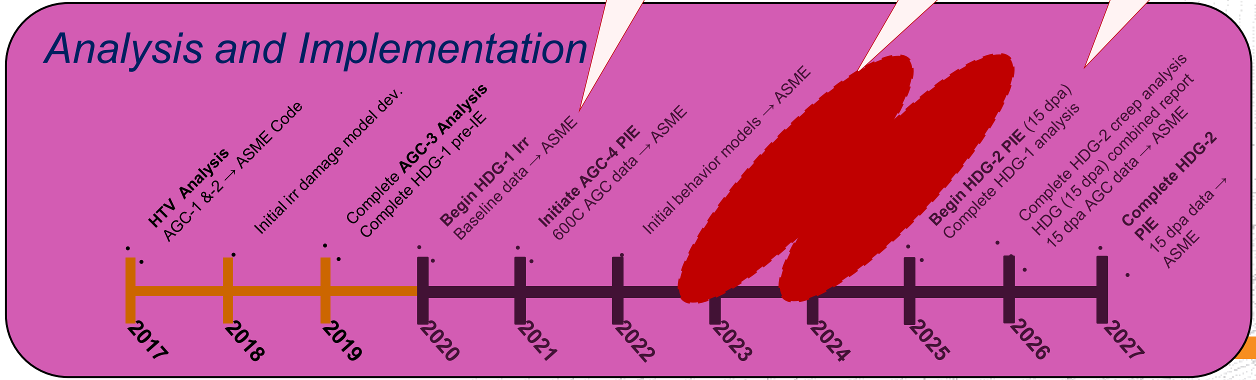
- High Dose Graphite (HDG) capsules
- Reuse VHTR capsules AGC-5 and AGC-6 (1100ºC)
- Pertinent to current commercial HTR designs

Micro and prismatic dose range (800°C)

Large PB & MSR dose range (600°C)

Large PB & MSR dose range (800°C)

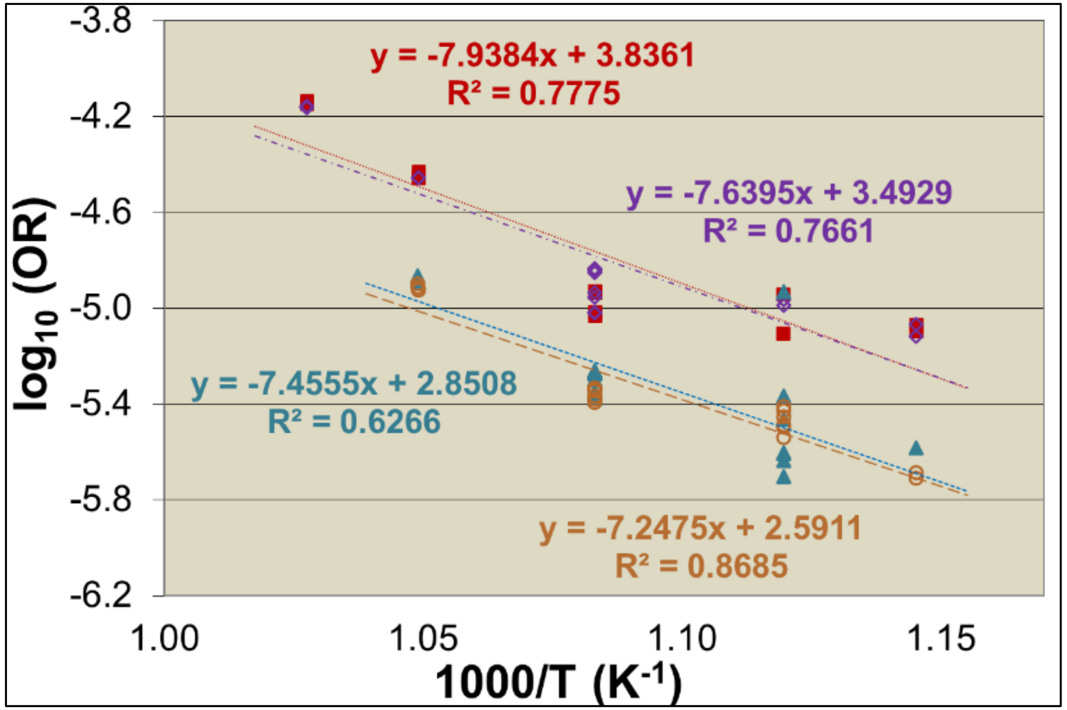
- **Data analysis:**
  - Baseline data → **ASME**
  - Mechanism studies data → AGC data
  - AGC data → **ASME**
  - Behavior Models → **ASME**
  - **ASME Code complete**



Oxidation testing *(Smith)*

Wrapping up irradiated oxidation

- Oxidation of irradiated specimens
- Oxidation rate increases
- Dose dependency
  - *Increasing rate with increasing dose?*



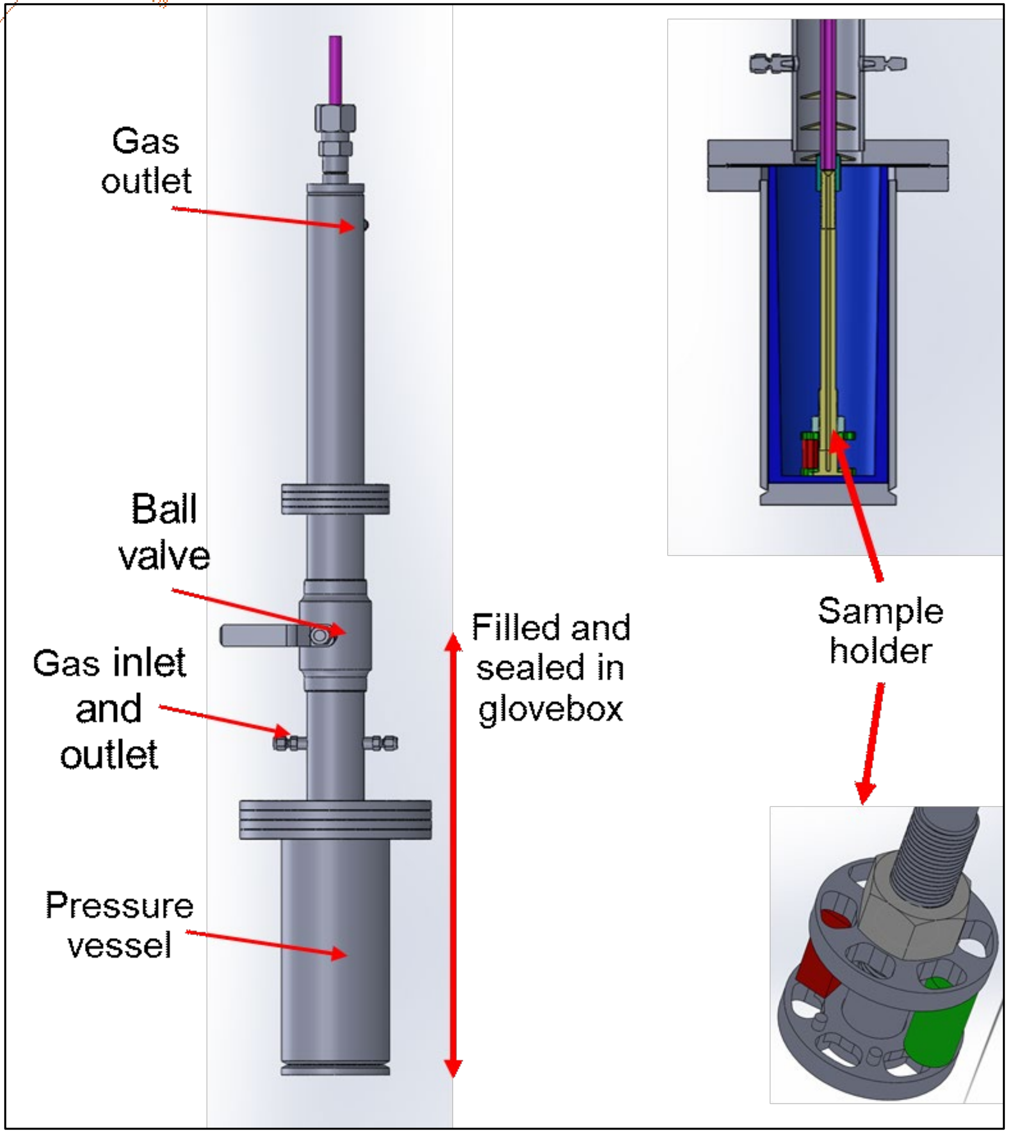
GIF oxidation report

- Summary of all oxidation results for all GIF contributors
  - *USA, EU, China, Japan, N. Korea*
- GIF High Level Deliverable (HLD)

Continuing effects on material properties

- Mechanical strength changes from oxidation
  - *Modifications to ASME code rules*
- Material property changes due to increasing oxidation
  - *Strength, CTE, modulus, thermal diffusivity*
- Fine grain and moderate grain size materials

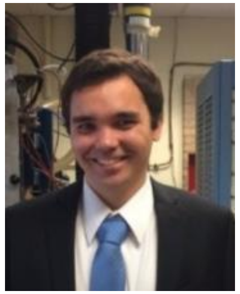
Molten Salt Studies *(Gallego)*



Molten Salt testing

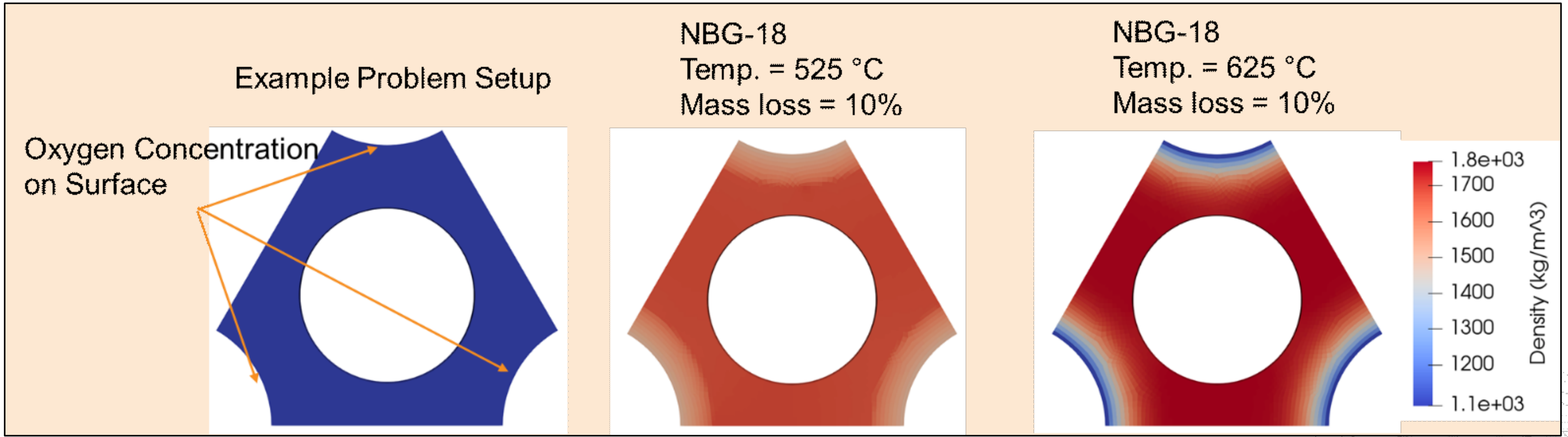
- Salt impregnation into graphite pores
  - Physical damage/cracks
  - "Hot spots" from fueled molten salt
- Wear/abrasion/erosion
  - Molten salt has higher density than graphite
  - Liquid flow over soft graphite has potential
- Chemical coupling with metallic systems
  - Graphite – MS is inert
  - There are questions when a metallic component is added

Behavior Models *(Bass)*



Behavior Models: Answering core design and degradation behavior

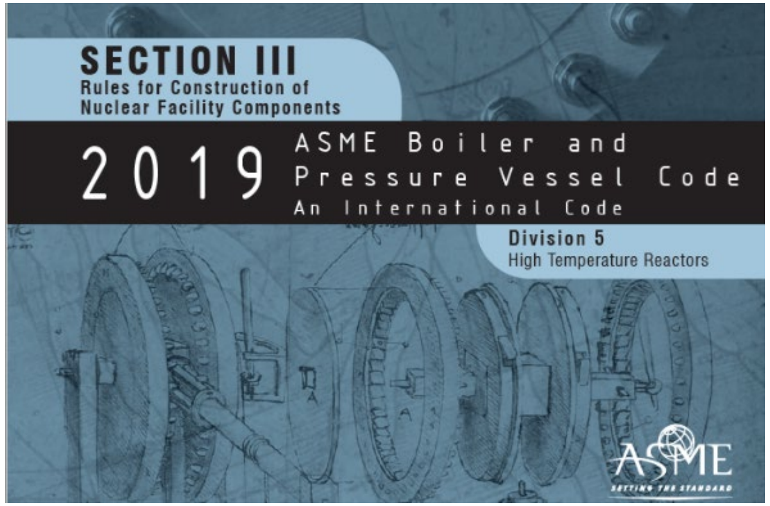
- New developments in graphite behavior models addressing:
  - Oxidation behavior in large core components
  - Irradiation effects on structural integrity of components
  - Molten salt effects anticipated
- Adding ASME code rules/methodology to determine core component integrity



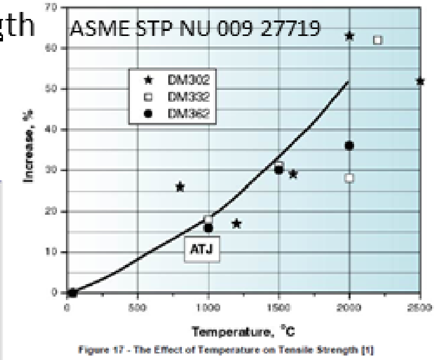
Graphite Code Development *(Geringer)*

Progress in ASME Code development

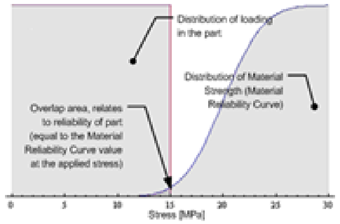
- Latest updates on ASME graphite and composite code development
- Laundry list of new areas of optimization from NRC assessment (Task Groups)
  - Defining failure criteria
  - Oxidation rate and effects on structural performance
  - Clarification of probability of failure (POF) assessment
  - Addition of irradiation data and trends to code rules
  - Assessment of molten salt



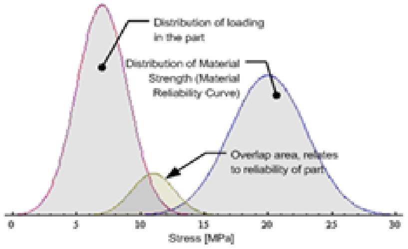
Graphite strength



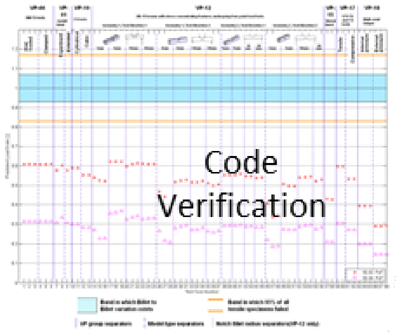
Weibull



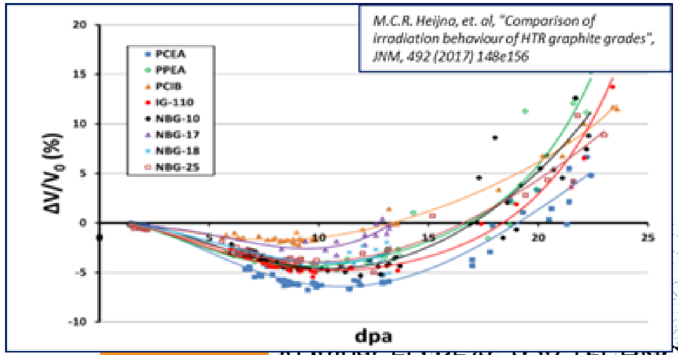
Simplified Assessment



Full Assessment



Code Verification



Collaborations (domestic and international)

Irradiation damage

- Oxford
- Leeds
- Wisconsin
- ANSTO
- Manchester
- KAERI
- Boise State
- MURR

NDE

- John Hopkins (NEUP)

Oxidation

- Boise State
- China (INET)
- KAERI

Thermal Creep

- Manchester

Behavior Analysis

- Irradiation changes
- Dimensional/creep response
- Oxidation – Exper. & modeling
- Modeling mechanical strength
- Microstructure changes/effects
- Testing and code development

Mechanical changes

- Oxford
- Manchester
- U. Minnesota
- Boise State

ASME, ASTM, IAEA

- Gen IV (GIF)
- Japan
- EU
- Korea
- U.K.
- China
- NEUP
- ANSTO

Modeling

- Manchester
- U. Wisconsin
- RPI

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