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Project No. 99902071

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555-0001

Submittal of X Energy, LLC (X-energy) Slides for Xe-100 White Paper, "Graphite Material Qualification"

The purpose of this letter is to submit the slides for the public meeting scheduled for 24 April 2023.

Enclosure 3 contains commercially sensitive, proprietary information and, as such, we are requesting that this information be withheld from public disclosure in accordance with 10 CFR 2.390, "Public inspections, exemptions, request for withholding," paragraph (a)(4). Enclosure 2 provides an affidavit with the basis for this request.

This letter contains no commitments. If you have any questions or require additional information, please contact Ingrid Nordby at inordby@x-energy.com.

Sincerely,

DocuSigned by:
F053E736949E4C3...
Travis A. Chapman
Director, Reactor Licensing & Regulatory Affairs, Xe-100 Program
X Energy, LLC

cc:

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Stephanie Devlin-Gill
Michael Orenak

U.S. Department of Energy
Jeff Ciocco
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Enclosures:

1) X Energy, LLC Xe-100 White Paper Slide Deck, "Graphite Material Qualification Open Session" (Public)

2) Affidavit Supporting Request for Withholding from Public Disclosure (10 CFR 2.390)

3) X Energy, LLC Xe-100 White Paper Slide Deck, "Graphite Material Qualification Closed Session" (Non-Public)

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Enclosure 1
X Energy, LLC
"Graphite Material Qualification Open Session" Slides for April 24, 2023, Public Meeting
(Public)

Xe-100 Graphite Material Qualification Open Session

S Baylis

April 24, 2023

Objectives, Scope and Outline of Presentation

Objective:

- Introduce X-Energy's proposed approach to qualifying graphite for use in the Xe-100 reactor

Scope:

- Discuss graphite material for top and bottom reflectors, and inner and outer side reflector
- No discussion of pebble material.
- Focus on work to qualify the material under ASME III-5
- No discussion of detailed component design, structural performance (e.g., seismic response), or safety analysis

Outline:

- Introduction to graphite – historical context and material structure
- Graphite response to irradiation
- Effects of oxidation
- ASME III-5 code requirements

Objectives, scope and outline of presentation

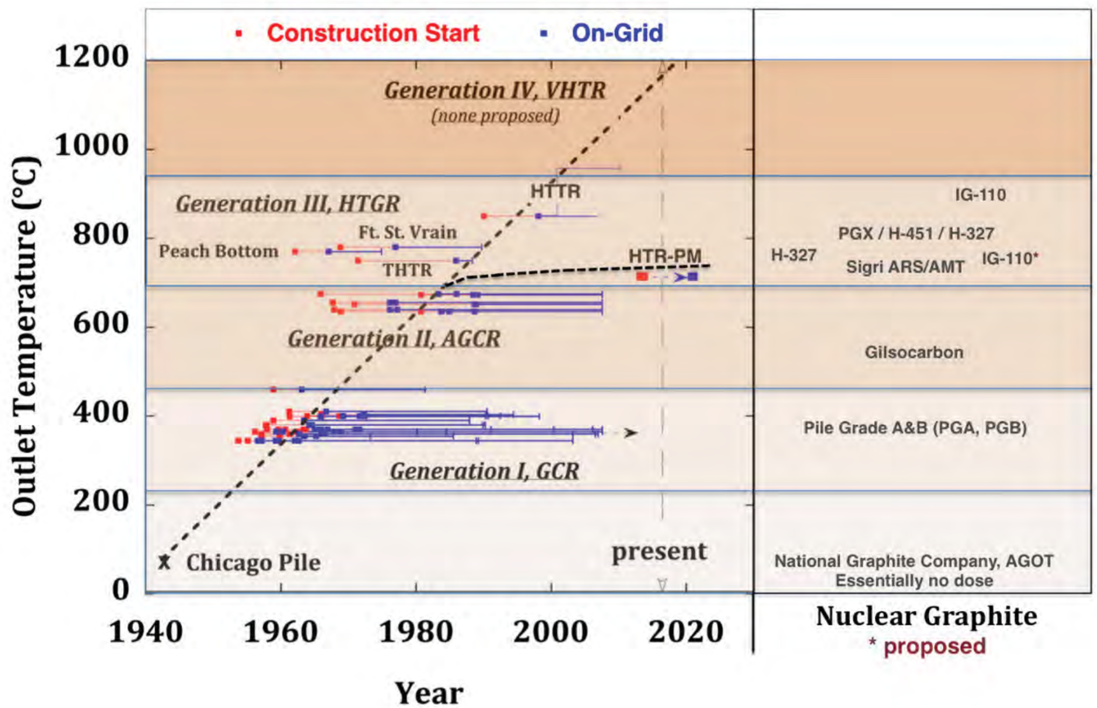
Objective: introduce X-Energy's proposed approach to qualifying graphite for use in the Xe-100 reactor

Scope of presentation:
- Will discuss graphite material for top and bottom reflectors, and inner and outer side reflector. Will not be discussing pebble material.
- Will focus on work to qualify the material under ASME III-5. Will not discuss detailed component design, structural performance (e.g., seismic response) or safety analysis.

Outline:
- Introduction to graphite – historical context and material structure
- Graphite response to irradiation
- Effects of oxidation
- ASME III-5 code requirements

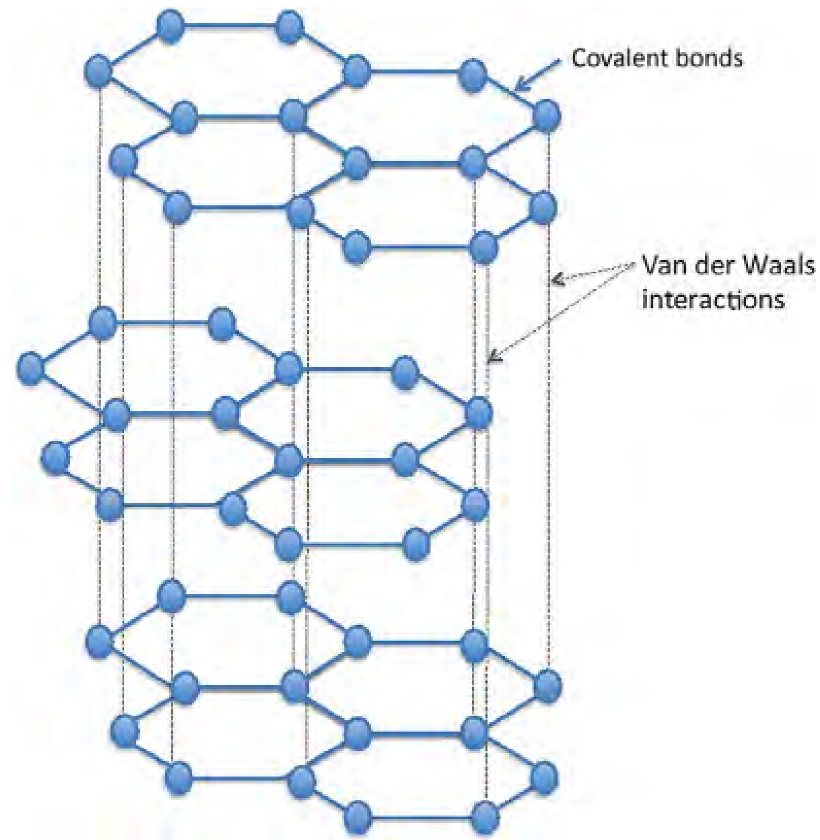
Introduction to Graphite – Operating Experience

- Graphite pioneered the way into the Nuclear Age
- Graphite was first used in CP-1
- Higher temperature gas reactors were designed and built, leading to a great deal of operating experience in the temperature range of interest for the Xe-100
- Xe-100 is fortunate to have a team with members who worked on several previous HTGRs



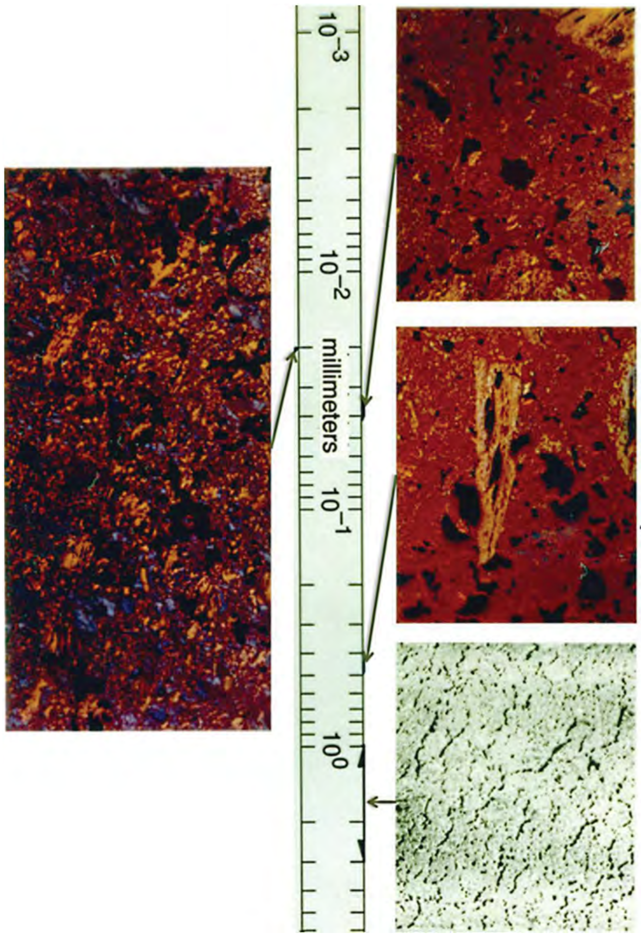
Introduction to Graphite

- Graphite has a layered structure where the carbon atoms in each layer are bonded in hexagonal arrays with covalent bonds (effectively graphene)
- The layers are bonded to each other by weaker Van der Waals interactions
- The weak bonds among the layers determine weak shear strength



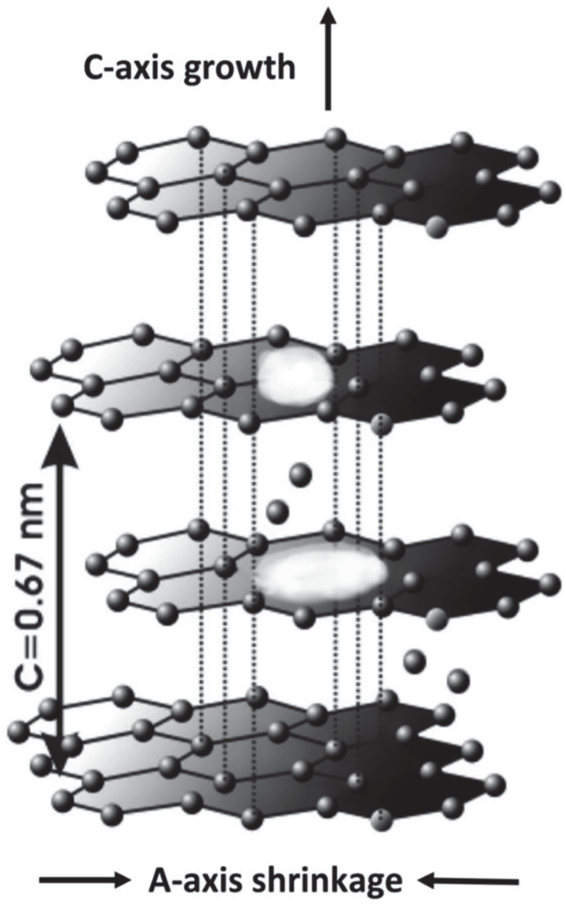
Introduction to Graphite (cont'd.)

- Graphite crystals are anisotropic, as properties depend on the direction of force application
- Bulk graphite is very porous from the formation process
- Bulk anisotropy depends on average orientation of crystals



Graphite Aging with Irradiation – Crystal Dimensional Change

- Neutron irradiation displaces atoms and creates vacancies (Frenkel Defects)
- Most displaced atoms return to lattice positions, but they may lodge at interstitial sites, vacancies or, at grain boundaries
- At low temperature, when mobility is also low, the distance between the displaced atom and its resulting vacancy is small. Consequently, Wigner energy builds up
- At elevated temperature (>250°C), mobility is high enough
- The preferential interstitial site is in the weaker Van Der Waals inter-planer area rather than in the covalent-bonded, graphene planes
- ‘Standard’ model: mobile vacancies aggregate to form line defects and heal, shrinking basal planes. Interstitials aggregate to form new graphene sheets. Swelling in C-axis and shrinkage in A-axis
- ‘Buckle, ruck and tuck’ model: at low temperature (<250°C), pinning of dislocations by defects leads to buckling of planes. At higher temperatures, dislocations interact and pile up, leading to folding of planes



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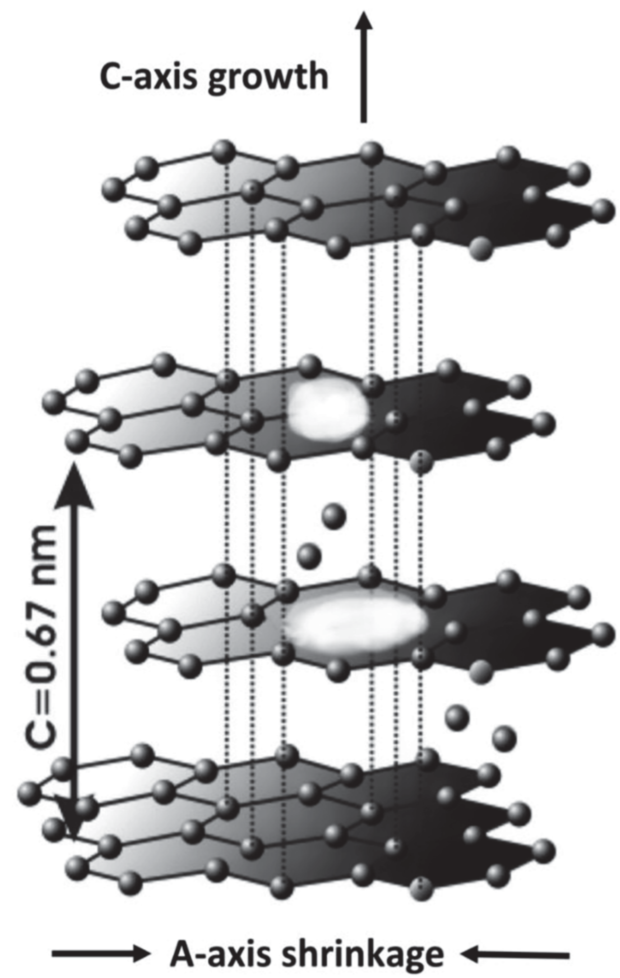
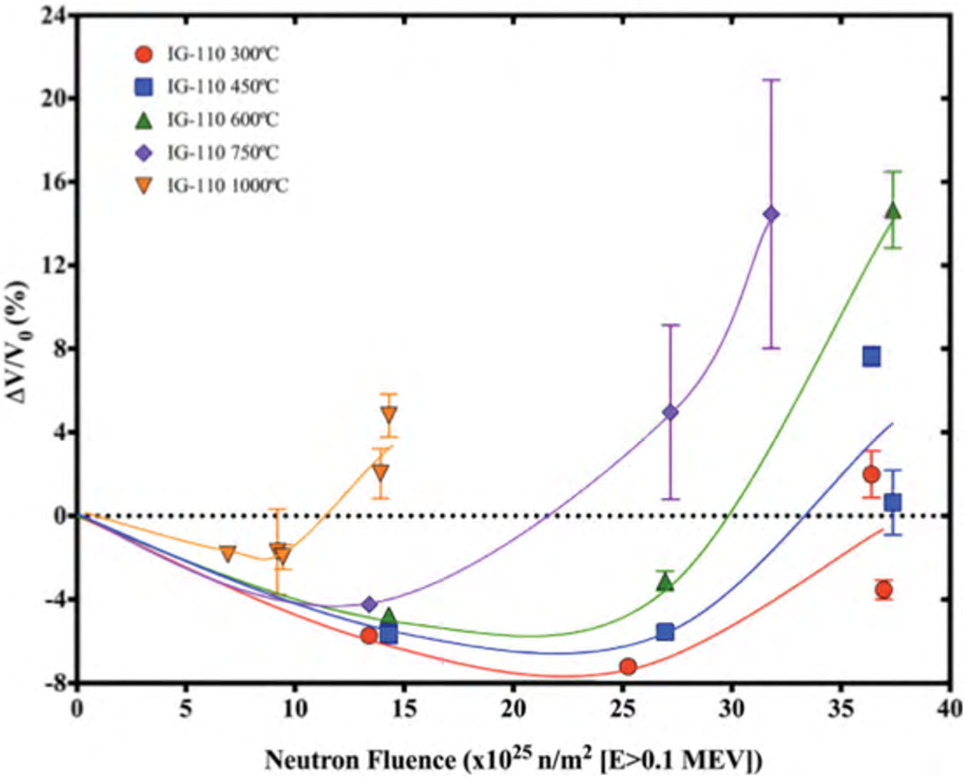


Graphite Aging with Irradiation

- As graphite is irradiated at temperature it initially becomes denser. This is a result of C-axis expansion filling porous voids while A-axis contraction leads to net shrinkage
- Simultaneously, crystal strain leads to new pore generation. When the rates of densification and pore generation are equal the process undergoes **Turnaround**
- Beyond this point, the graphite swells
- A key point, known as **Crossover ('nullity', 'unity', 'nil swelling')**, is reached where the graphite has the same size as when it started
- With an increase in irradiation temperature, turnaround occurs at a lower dose



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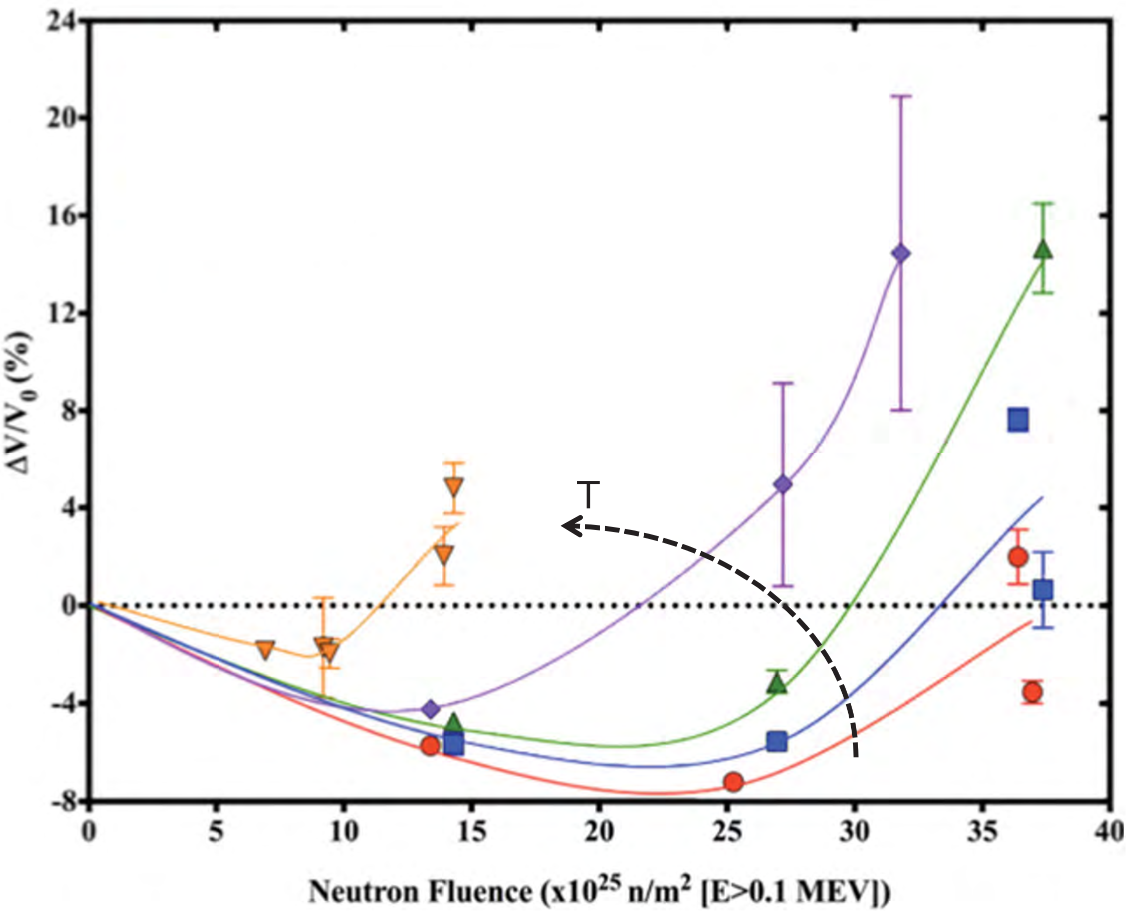

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Irradiated Material Properties

The processes behind dimensional change drive changes in material properties. Shape of curves depend on irradiation temperature.

- Low dose (~1dpa): rapid increase in elastic modulus, strength and CTE, rapid decrease in thermal conductivity (‘pinning’ effects)
- Moderate dose: continued increase in elastic modulus and strength, CTE and thermal conductivity fall to plateau (‘structure’ effects)
- High dose (beyond turnaround): modulus and strength begin to fall, further reduction in thermal conductivity: pore generation effects

Irradiation creep

- Rate of dimensional change depends on applied load. Difference in strain between stressed and unstressed material referred to as irradiation creep
- ‘Primary creep’: rapid initial strain on similar dose scale to pinning, magnitude roughly equal to elastic strain. Fully recoverable – strain anneals out with further irradiation if load is removed. Initial rate depends on elastic modulus and stress.
- ‘Secondary creep’: slower, permanent strain. Rate depends on elastic modulus, stress and temperature.
- Details are complex.
- Strong evidence for significant influence of creep strain on CTE. Weaker evidence for small influence of creep strain on elastic modulus.

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Graphite oxidation - context

In addition to neutron irradiation, the other major physical phenomenon affecting graphite material properties is oxidation

- The majority of current and historic gas-cooled reactors use(d) CO_2 coolant (Magnox, UNGG, AGR): significant radiolytic oxidation in all reactors, maximum graphite temperatures limited by potential for thermal oxidation.
- Modern HTGR designs use helium coolant: much lower rates of oxidation in normal operating conditions, allows operation with graphite at higher temperatures.
- Potential for limited chronic oxidation by coolant impurities (water, hydrogen, CO, CO_2 etc.): will be evaluated but not expected to challenge component integrity.
- Acute oxidation: steam and/or air ingress in postulated accident conditions could cause rapid oxidation of graphite.
- ASME code recommends simplified, conservative treatment of oxidation (HHA-3141):
    - Account for strength reduction at >1% weight loss
    - Scope of code does not include simultaneous (chronic) oxidation >1% and irradiation >0.25dpa (but does include acute oxidation of irradiated material)
    - Any region with strength reduction >50% is not credited in stress evaluation
    - Any region with weight loss >30% is regarded as removed from geometry

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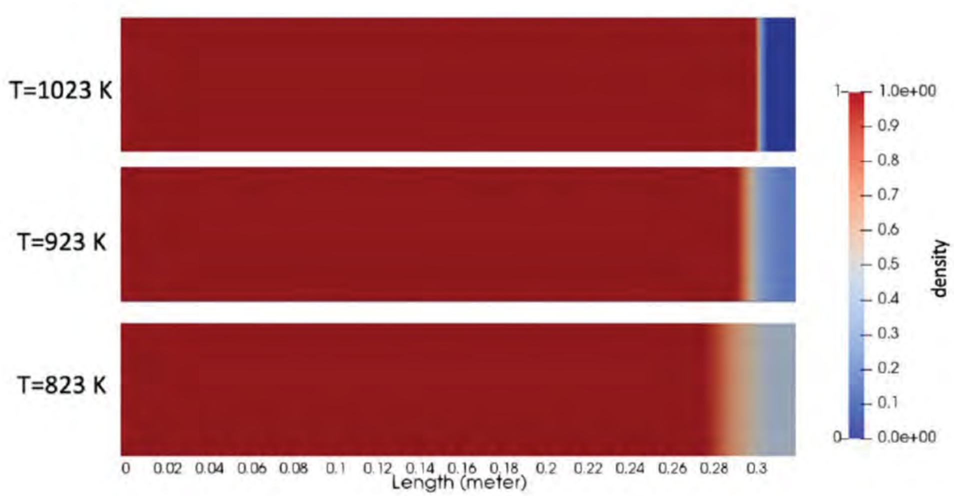
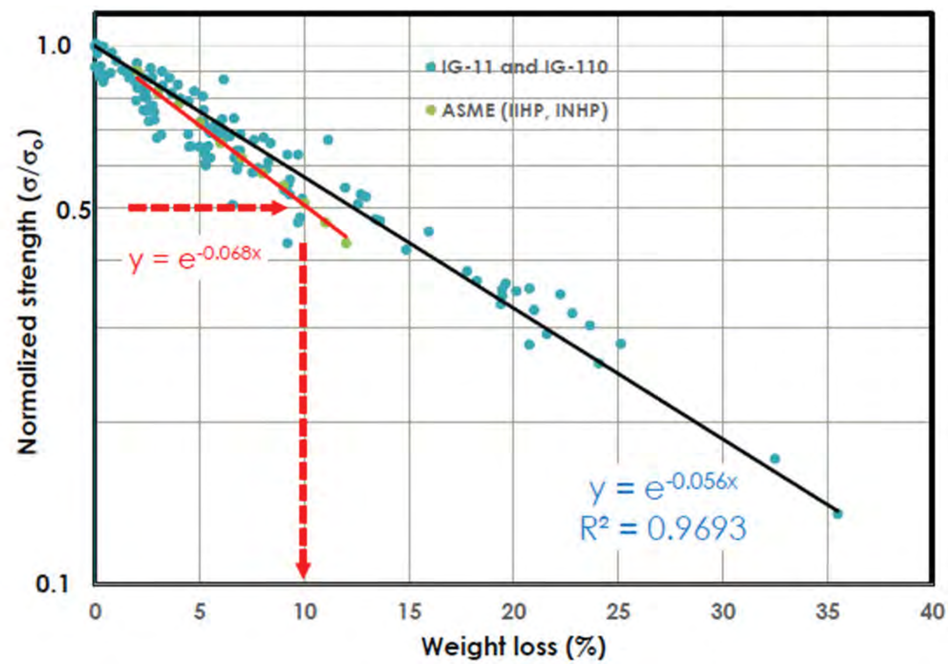
Changes with Oxidation – Chronic vs Acute





- Uniform Bulk Oxidation at lower temperature causes more strength loss than surface-localized oxidation at high temperature considering the same amount of Oxygen.
- Oxidation is much faster at higher temperatures, causing more to occur on the surface than the bulk
- Acute Oxidation at high temperatures leads to faster dimensional change
- Barring specific data, generally, 10% weight reduction is around 50% strength reduction.

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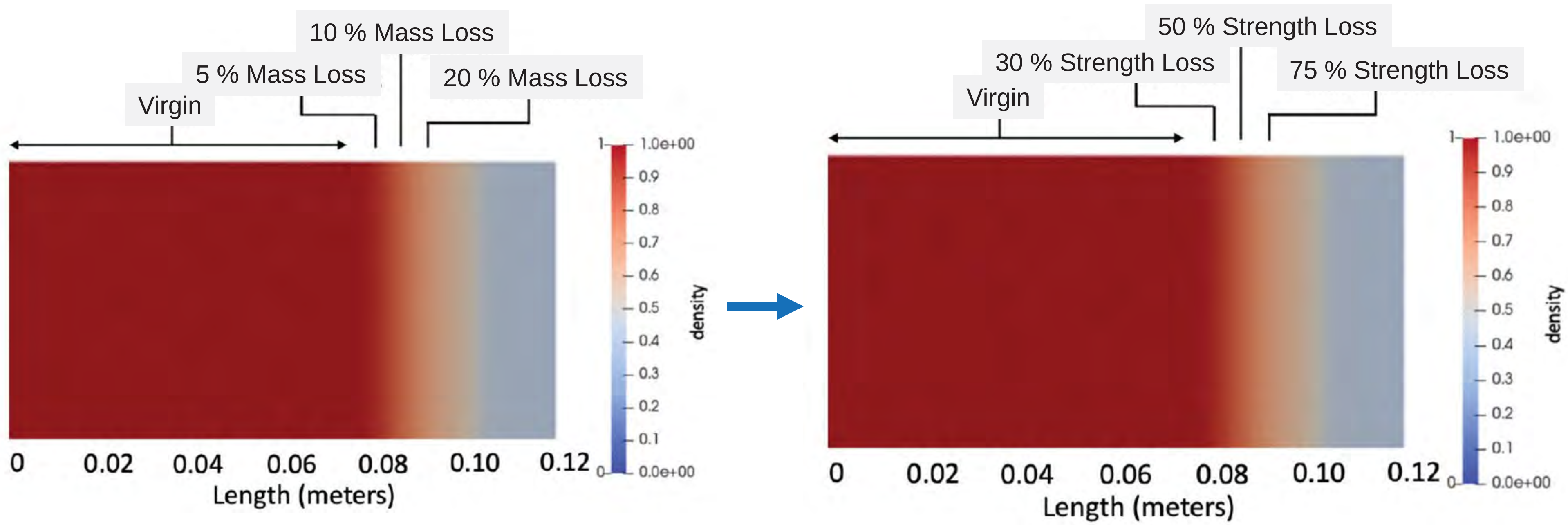
Oxidation- from Models to Strength Reduction Estimates



- Calculating an expected oxygen partial pressure, time and temperature allows for an estimate of weight reduction
- This weight reduction translates to a strength reduction
- Strength reduction can be considered with structural analysis and PoF calculations.

The Code Requirements

The main governing code of Concern is the ASME B&PV Code, Section III, Division 5. The code provides standards and guidance on the **Qualification of the Material**:

- Irradiated Material Properties (HHA-2220 and HHA-III-3300)
- Qualification Envelope states maximum of 200°C Temperature increments for damage dose and any properties that are temperature dependent.
- Properties of interest are:
  - Dimensional Change
  - Strength
  - Elastic Modulus [Dynamic Young’s Modulus]
  - Creep Coefficient [Use appropriately validated and calibrated model for relevant range of dose, temperature and stress]
  - Coefficient of Thermal Expansion [in relevant temperature range, including effect of creep strain, HHA 3142.3]
  - Thermal Conductivity [in relevant temperature range]
- Material being tested for qualification use must be representative (HHA-III-4200)
- Historical Data must be shown to be applicable if used (HHA-III-5000)
- Reporting Requirements for Material Data Sheets (HHA-II-4000)
- Material Specification and use of ASTM standards (HHA-III-1000 and HHA-I-1110)
- Etc.

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The Code Requirements

The main governing code of Concern is the ASME B&PV Code, Section III, Division 5. The code provides standards and guidance on the **Irradiation Limits**:

- Irradiation Fluence Limits (HHA-3142.1)
  - < 0.001 dpa the effects of neutron irradiation are negligible and may be ignored
  - >0.001 dpa the effect of neutron irradiation on thermal conductivity shall be taken into account
  - > **0.25 dpa** all effects of neutron irradiation (described in HHA-2200) shall be considered, and a viscoelastic analysis applied
- Stored (Wigner) Energy (HHA-3142.2) for graphite irradiated:
  - To significant fluence [> 0.25 dpa]
  - And at a temperature < 200°C,

Then the effect of stored (Wigner) energy buildup shall be accounted for during thermal transient evaluation.

The Code Requirements – Design of Components

The main governing code of Concern is the ASME B&PV Code, Section III, Division 5. The code provides standards and guidance on the **Design of Graphite Components and Assemblies**
Graphite Core Components are to be designed such that (HHA-3212):

- *All mechanical loads that occur shall be transferred to the adjacent load-carrying or supporting structures within allowable limits.*
- *Displacement or deformation of adjacent Graphite Core Component in opposing directions do not cause constraint and thus hinder expansion or shrinkage due to temperature or irradiation.*
- *Changes in the shape of a Graphite Core Component due to irradiation do not adversely affect the stability or functionality of the core assembly.*
- *The compensation of the differential strains inside the Graphite Core Assembly and in the surrounding structures does not lead to stresses exceeding the HHA-3211 limits in the Graphite Core Components.*
- *Movement of blocks and the accumulation of gaps inside the Graphite Core Assembly are within allowable limits.*
- *Changes in shape of the Graphite Core Component due to radiation and temperature effects are within allowable limits and do not affect the function and stability of the core assembly.*
- *Design channels for the gas flow through Graphite Core Components are such that the shielding effect of the graphite internals is within allowable limits.*
- *Grooves, keyways, dowel holes, and other recesses in the blocks are to be blended. The minimum fillet radius shall be five times the maximum grain size as documented in the Mandatory Appendix HHA-II Material Data Sheet.*
- *External edges of Graphite Core Components shall be chamfered.*

The Code Requirements - Certification

The main governing code of Concern is the ASME B&PV Code, Section III, Division 5. The code provides standards and guidance on the **Designer and Supplier Certification**:

- G – certificate (HAB-330):
  Designer of Graphite Core Components must have a G-Certificate (HAB-3320). The Designer is responsible for designing the components and assemblies, preparing the Design Specification, Design Report, Design Drawings and Construction Specification
- GC – certificate (HAB-3430):
  Holder is responsible for construction and assembly of components, prepares the Construction Report, tests components (HAB 3420)
- G Quality System – certificate (HAB-3800):
  Holder is a Graphite Material Organization (GMO), and the certification is provided by ASME or a GC-certificate holder, based on the GMO's quality system program. The holder is responsible for material manufacture, graphite core component machining and installation (HAB-3830)

- All machining (HHA-4220), examination (HHA-4230, HHA-5220, HHA-5400, HHA-5500), testing (HHA-4240), packaging (HHA-4250) and installation (HHA-5300) must be done by a responsible party (G-certificate, GC-certificate or G Quality System-Certificate holder)

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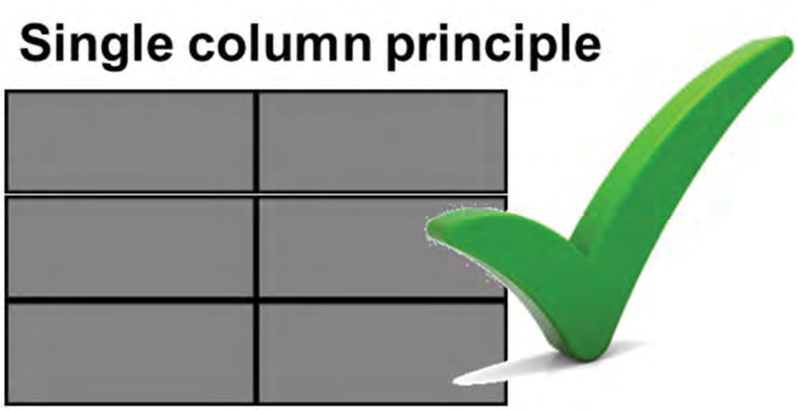
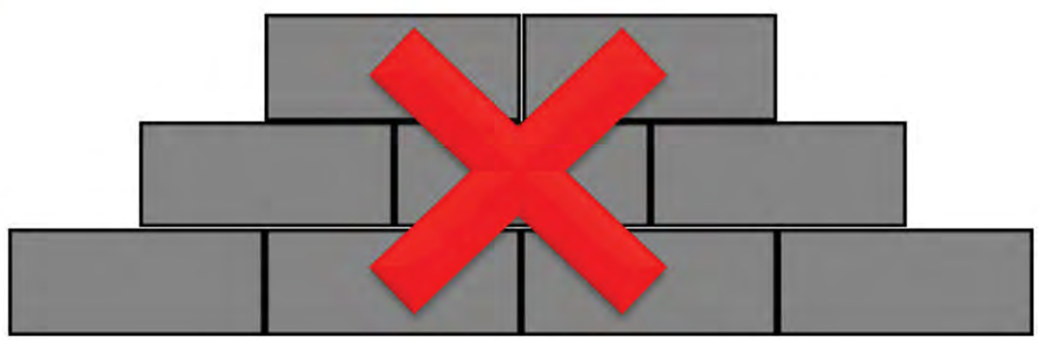
The Xe-100 Graphite Reflector System - Design

Graphite Design Challenges:

Graphite blocks are merely stacked one on top of the other and cannot be cemented or bonded together in any way due to high temperatures and neutron irradiation.

All block stacks must conform to the "**single column principle**". This means that blocks in the vertical can only be supported by block directly beneath. There may thus be no areas where the potential can develop for bridging to occur as this will place the blocks under a tensile stress condition which could result in block cracking and ultimately failure.





Questions

?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Enclosure 2
Affidavit

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Affidavit Supporting Request for Withholding from Public Disclosure (10 CFR 2.390)

I, Travis A. Chapman, Director, Reactor Licensing & Regulatory Affairs, Xe-100 Program, of X Energy, LLC (X-energy) do hereby affirm and state:

1. I am authorized to execute this affidavit on behalf of X-energy. I am further authorized to review information submitted to or discussed with the Nuclear Regulatory Commission (NRC) and apply for the withholding of information from disclosure. The purpose of this affidavit is to provide the information required by 10 CFR 2.390(b) in support of X-energy's request for proprietary treatment of certain commercial information submitted in the slides for a requested meeting regarding X-energy's Graphite Qualification. Specifically, the slide deck entitled, "Graphite Material Qualification Closed Session" contains proprietary information and have been marked appropriately.

2. I have knowledge of the criteria used by X-energy in designating information as sensitive, proprietary, confidential, and export-controlled.

3. Pursuant to the provision of paragraph (b)(4) of 10 CFR 2.390, the following is furnished for consideration by the NRC in determining whether the information sought to be withheld from public disclosure should be withheld.

> a. The information sought to be withheld from public disclosure in the slide deck entitled, "Graphite Material Qualification Closed Session" is owned by X-energy. This information was prepared with the explicit understanding that the information itself would be treated as proprietary and confidential and has been held in confidence by X-energy.
>
> b. The information sought to be protected in the slide deck entitled, "Graphite Material Qualification Closed Session" is not available to the public.
>
> c. The information contained in the slide deck entitled, "Graphite Material Qualification Closed Session" is of the type that is customarily held in confidence by X-energy, and there is a rational basis for doing so. The information X-energy is requesting to be withheld from public disclosure includes technical information related to the design, analysis and operations associated with our Xe-100 high-temperature, gas-cooled, pebble bed advanced reactor design that directly impact our business development and commercialization efforts. X-energy limits access to this proprietary and confidential information in order to maintain confidentiality.
>
> d. The slide deck entitled, "Graphite Material Qualification Closed Session" contain information about the planned activities of X-energy related to the development of the Xe-100 design bases and relate to the commercialization strategy for our Xe-100 advanced reactor. Public disclosure of the information contained in the slide deck entitled, "Graphite Material Qualification Closed Session" would create substantial harm to X-energy because it would reveal valuable technical information regarding X-energy's design development, competitive expectations, assumptions, current position and strategy. Its use by a competitor could substantially improve the competitor's

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position in the design, manufacture, licensing, construction and operation of a similar competing product.

e. The Proprietary Information contained in the slide deck entitled, "Graphite Material Qualification Closed Session" is transmitted to the NRC in confidence and under the provisions of 10 CFR 2.390; it is to be received in confidence by the NRC. The proprietary slides are marked.

I declare under the penalty of perjury that the foregoing is true and correct. Executed on April 14, 2023.

Sincerely,

DocuSigned by:
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Travis Chapman
Director, Reactor Licensing & Regulatory Affairs
Xe-100 Program
X Energy, LLC

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