Xe-100 Graphite Engagement: ASME Service Level Definition, LBE Mapping, and Design Loadings for Graphite Core Assembly

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Agenda & Objectives

Agenda

Open Portion:

- Graphite Core Assembly Safety Functions
- Introduction to Structural Reliability Class definitions
- Introduction to analysis sequence for Design Loadings

Closed Portion:

- Xe-100 Licensing Basis Event mapping to ASME Service Levels
- Development of Design Loadings

Objectives:

Share X-energy's approach for the Xe-100 to:

- Identify relevant safety functions for the Graphite Core Assembly (GCA)
- Identify and categorize loading mechanisms
- Categorize appropriate ASME Service Levels.
- Map LBEs to the service levels
- Discuss methodology for determining limits associated with graphite degradation.
- Discuss process for assigning ASME Structural Reliability Classes (SRCs)
- Introduce the plans for cross-disciplinary analyses related to development of design loadings for evaluation of the structural evaluation of the GCA

Introduction | Background

- Physical Component Terminology:
  - Graphite Core Assembly (GCA, also expressed sometimes as graphite reflector): *the assembly of all permanently installed graphite core components in the reactor (i.e., excluding pebbles)*
  - Graphite Core Component (GCC, also expressed sometimes as graphite core structure or graphite block): *A single machined graphite item complying with [Subsection HA, Subpart B] and Subsection HH, Subpart B* - ASME BPVC Section III Division 5, HAB-9200
- As indicated by ASME BPVC Section III, Division 5 (HHA-3100):
  - Graphite core components (GCCs) are designed using semi-probabilistic methods
  - It is not possible to ensure a complete absence of cracks from graphite components
  - Undetectable manufacturing defects may exist
  - Damage tolerance of the design of the GCA must be demonstrated
- The GCA has important safety functions (detailed later in this presentation)
- The graphite reflector determines the geometry of the pebble bed and control rod channels and is relied upon to conduct heat away from the pebble bed in certain accident conditions, maintaining acceptable fuel temperatures
- In normal operation, the graphite reflector directs the flow of helium through the reactor

ASME BPVC III-5 Definitions

- Plant Conditions: general categories of conditions the GCA may experience, ranked from most to least frequent (1 to 5)
- ASME Service Loadings: types of loads that are experienced by the GCA, categorized for each Plant Condition. Service levels are defined from A to D, from most to least likely. Level A applies to normal operation and common occurrences, while level D applies to extreme and rare events.
- ASME Service Limits: allowable reliability target limit values (cracking; deformation) applied to each loading level A to D in the structural assessment of individual graphite core components
- Structural Reliability Class: graded level of reliability assigned to graphite core components, where SRC-1 signifies the highest mechanical reliability, as compared to SRC-2 or SRC-3

Design Basis of the Graphite Core Assembly

- As noted in the ASME BPV Code III-5, HAB-2141, Design Basis:

  *"(b) The definition of plant and system operating and test conditions and **the determination of their significance to the design and functionality of Core Components of a nuclear power system are beyond the scope of this Subpart and Subsection HH**. Appropriate guidance for the selection of plant or system operating and test conditions, which may be determined to be of significance in the selection of Core Component Design and Service Loadings, the combinations thereof, and **the corresponding acceptable limits, may be derived from systems safety criteria documents** for specific types of nuclear power systems and may be found in the requirements of regulatory and enforcement authorities having jurisdiction at the site."*

- Significance in ASME BPV Code III-5, HAB-2141 links back to HHA-3111 "important to safety"

  *"The allocation of Graphite Core Components to these Structural Reliability Classes **is the responsibility of the Owner and shall be justified in the system safety criteria for the nuclear power system**. The classes are to be indicated in the Design Specification. Interfaces between components of different classes shall be designed to ensure that any failure in a component classified in a lower class will not propagate to a component in a higher class."*

Design Basis of Graphite Core Assembly (cont.)

Therefore, the requirements for the design basis are derived from systems safety criteria.

- The systems safety criteria for the Xe-100 reactor design are developed using the Risk-Informed Performance-Based methodology of NEI 18-04, based on internationally-accepted Fundamental Safety Functions, and ultimately derive from a top-level objective to ensure acceptably low offsite dose consequences.
- The functional requirements of the Graphite Core Assembly are derived from applicable Principal Design Criteria for the Xe-100 reactor design which form the system safety criteria described in ASME III-5.
- Of these, the **Required Functional Design Criteria (RFDC) associated with the Required Safety Functions (RSFs)** are those functional requirements for the Graphite Core Assembly which are important to safety as defined in the code.
- There are additional functional requirements called Complementary Design Criteria (CDC) derived from Non-Safety-Related with Special Treatment (NSRST) Probabilistic Risk Assessment (PRA) safety functions (PSFs).
- The functional requirements apply to the Graphite Core Assembly as a whole.

RG 1.87 R2 has a footnote that "Important to safety SSCs perform the functions required by the General Design Criteria in Part 50, Appendix A, or other substantive regulations, and may or may not be safety related."

- The Xe-100 interpretation of important to safety may not align with the NRC interpretation implied by the footnote.
- Question: Does NRC consider our definition of "important to safety" in code space to be a deviation from RG 1.87 R2?

Required Safety Functions (RSFs)

Xe-100 Principal Design Criteria (PDC)[1], RFDC, and CDC address relevant RSFs and PSFs for the plant. The GCA design and analysis must conform to the following RSFs and PSFs, and their associated PDC

- Control Reactivity
  - RSF 1.1.1 (PDC-RFDC 11) – Control reactivity with inherent reactivity feedback. The reactor core and associated systems shall be designed with sufficient negative reactivity feedback characteristics such that, in the power operating range, the net effect compensates for a rapid increase in reactivity, adequately controls heat generation, and ensures that fuel and radionuclides release limits are not exceeded during DBEs and DBAs
  - RSF 1.1.2 (PDC-RFDC 26) – Control reactivity with movable poisons. The reactor shall be designed to include movable poisons that can insert and maintain safe shutdown during DBEs and DBAs.
- Control Heat Removal
  - RSF 1.2.1.1 (PDC-RFDC 34) – Transfer heat from fuel to vessel wall. The reflector structures shall be designed to transfer sufficient heat via conduction, convection, and radiation from the fuel to the reactor vessel wall to assure that fuel and radionuclide release limits are not exceeded during a DBE or DBA
- Maintain Core Geometry
  - RSF 1.4.1.2 (PDC-RFDC 70) – Limit stress to acceptable levels. The core reflector graphite shall be designed to withstand stresses developed during DBEs and DBAs and ensure acceptable geometry is maintained to control reactivity and heat removal.

1 - X Energy, LLC Xe-100 Principal Design Criteria Licensing Topical Report, Revision 2, ML23181A172, under review

NSRST PRA Safety Functions (PSFs)

- Control (Active) Heat Removal
  - PSF 1.2.2 (PDC-CDC 34) - Control heat removal with active means. The plant shall be able to transfer fission product decay heat and other residual heat from the reactor core to an ultimate heat sink using active means at a rate such that specified acceptable system radionuclide release design limits are met during AOOs.
- Control Reactivity (by Radionuclide Retention)
  - PSF 2.3.3 (PDC 10) - Inherent retention of radionuclides in reflector graphite. The reflector graphite shall be designed in a manner that ensures radionuclides released from the fuel during normal operations are inherently retained and that specified acceptable radionuclides release design limits are met in AOOs.

    Note: This is not meant to imply that the GCA will retain all radionuclides; however, the graphite is a part of the defense in depth effort to retain radionuclides.

Loading mechanisms and ASME service levels

- The Graphite Core Assembly must continue to perform the RSFs when subject to a range of different loading mechanisms
- Different loading mechanisms occur with different frequencies and severities, ranging from those expected to occur during continuous operation through to very unlikely events
- Loading mechanisms are identified and assigned to ASME Service Levels based on their expected frequency-consequence. Service Level A (most frequent: normal operation) to Service Level D (least frequent: Design Basis Accidents)
- In general, graded allowable limits will apply to each ASME Service Level, with more stringent limits for graphite core components whose reliability is important to safety [ASME definition], or which are subjected to environmental degradation. The different allowable limits are established through assignment of a Structural Reliability Class (SRC) to each graphite core component.

Component Cracking: ASME SRC Categories

- Structural Reliability Class: graded level of reliability assigned to graphite core components
- SRC-1 is defined as, "The Structural Reliability of components in this class is important to safety. These parts may be subject to environmental degradation." (HHA-3111)
- SRC-2 is defined as, "The Structural Reliability of components in this class is not important to safety. These parts are subject to environmental degradation during life." (HHA-3111)
- SRC-3 is defined as, "The Structural Reliability of components in this class is not important to safety. These parts are not subject to environmental degradation during life." (HHA-3111)

In this context, *Structural Reliability* is interpreted as a measure of the probability of an individual component containing a crack. For the Xe-100 design of SRC-1 components, the term 'important to safety' is taken to mean the necessity of a Graphite Core Component to support an RSF , i.e., cracking of one component would meaningfully degrade the ability of the reactor to meet a safety function.

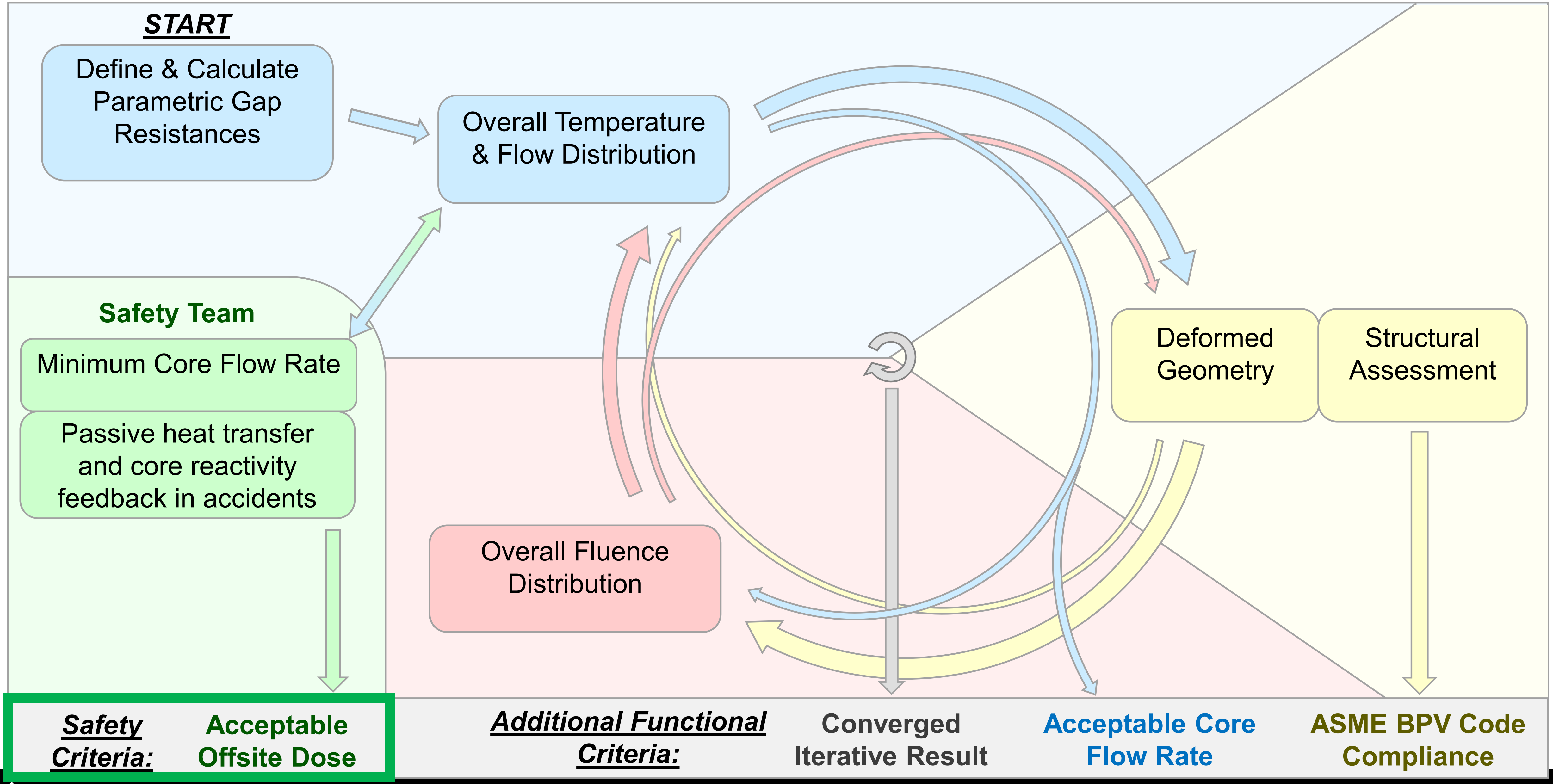
ASME Service Level (Limits & Loadings) Definitions

- The end state attributes of the Graphite Core Assembly vary by service level
- Level B: “the Core Component must withstand these loadings without damage requiring repair” (HAB-2142.4(b)(2))
  - As analogous to the metallic component definition (HBB-3113.4), these limits are applied to those loadings from incidents of moderate frequency
- Level C: “large deformations in areas of structural discontinuity that may necessitate the removal of the Graphite Core Component from service for inspection or repair of damage” (HAB-2142.4(b)(3))
  - As analogous to the metallic component definition (HBB-3113.5), these limits are applied to those loadings from infrequent incidents
- Level D: "permit gross general deformations with some consequential loss of dimensional stability and damage requiring repair, which may require removal of the Graphite Core Component from service” (HAB-2142.4(b)(4))
  - As analogous to the metallic component definition (HBB-3113.6), these limits are applied to those loadings from limiting faults

ASME Service Level (Limits & Loadings) Definitions

- Design Loadings: "The Design Loadings are the distributions of pressure, temperature, fast neutron flux or damage dose rate, and various forces applicable […]. These are defined as the enveloping Service Level A Loadings for the Graphite Core Component in the core" (HHA-3123).
- Level A: "Level A Service Limits are those sets of limits that must be satisfied for all Level A Service Loadings identified in the Design Specifications to which the Graphite Core Component may be subjected in the performance of its specified service function" (HAB-2142.4(b)(1))
  - As analogous to the metallic ASME BPVC level definition in Section III Division 5 (HBB-3113.3), these limits are generally applied to those loadings from system startup, operation in the design power range, hot standby, and system shut-down, excepting those loadings covered by Level B, C, and D
- The Design Loadings are developed by performing system-level multiphysics analyses which account for helium flow in the core, temperature, pressure, fluence, and graphite structural deformation / dimensional change

Analysis Sequence for Development of Design Loadings



Closed Portion

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Part 1: LBE Mapping to ASME Service Levels

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Allowable Limits for Graphite Core Assembly and Components

- The RSFs relate to performance in DBAs and DBEs. It is generally not possible to measure the safety functionality of the Graphite Core Assembly directly.
- Instead, allowable limits are derived that can be related to quantities that are easily modeled and/or measured (stress used in calculating probabilistic reliability target limits and deformation limits)
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- The limit for frequency of cracking can be conservatively addressed through the ASME III-5 methodology, which sets limits for the Code reliability targets described as Probability of Failure (physically represented as the probability of cracking) based on the Structural Reliability Class and Service Level
- Limits relating to the Graphite Core Assembly and/or Graphite Core Components will similarly be defined for the other categories (distortion, material degradation)
- Compliance with limits may be demonstrated through some combination of modelling, testing, monitoring and/or in-service examination

ASME Service Levels

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Plant Loading Mechanisms by Service Level

- The GCA and its constituent GCCs may be subject to a wide range of loading mechanisms. Some of these are active in all conditions and for all service levels (e.g., weight) but others only need to be considered in certain service levels. Loading mechanisms definitions are based on HHA-2122.
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Analysis Route for Structural Assessment of Graphite

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ASME Service Levels – Loading Mechanisms (1 of 3)

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ASME Service Levels – Loading Mechanisms (2 of 3)

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ASME Service Levels – Loading Mechanisms (3 of 3)

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ASME SRC Categories

- The Structural Reliability Class (SRC) is defined on a per-component basis
- For each Service Level, each SRC defines a maximum acceptable Probability of Failure (probability of crack initiation) for that component when subject to the loads applicable to that Service Level
- For example, an SRC-1 component must have a Probability of Failure of below 1E-4 (0.01%) over the reactor lifetime for all events at Service Levels A, B, and C
- The ASME code (HHA-3100) recognizes that in practice there may be disparate flaws such that use of the Probability of Failure values as design targets may not be precisely accurate for the actual rate of cracking of Graphite Core Components in service
- The effects of some amount of cracking must be assessed for all Graphite Core Components

Probability of Failure

- Noting the definition of Probability of Failure (POF) for Graphite Core Components (HHA-3100): “The design approach selected is semi probabilistic, based on the variability in the strength data of the graphite grade. Due to the nature of the material, it is not possible to ensure absolute reliability, expressed as an absence of cracks, of Graphite Core Components. This is reflected in the setting of POF targets.”
- Therefore, the physical implication of the POF limit is taken as the point at which there is nontrivial probability of cracking in a single Graphite Core Component
- HHA-3100 continues: “The Designer is required to evaluate the effects of cracking of individual Graphite Core Components in the course of the design of the Graphite Core Assembly and ensure that the assembly is damage tolerant.”
- This is in part addressed by the designation of appropriate service limits based on the end state attributes necessary for the events which result in loadings on the Graphite Core Assembly (e.g., ‘no damage requiring repair’ of Level B vs ‘large deformations’ of Level C vs ‘gross deformations’ of Level D)

Damage Tolerant Design

- The ability of Graphite Core Components to perform an RSF is not inherently linked to the presence of cracks
- This has been readily demonstrated in graphite cores of power reactors in the United Kingdom (e.g., Metcalfe 2023, “Damage tolerance in the graphite cores of UK power reactors and implications for new build”)
- Graphite Core Components (GCCs) are designed using probabilistic methods. Reliability targets are set to minimize cracking when this is important, but some frequency of cracked components must be acceptable to achieve a damage tolerant design
- The Graphite Core Assembly (GCA) consisting of many hundreds of GCCs, has important safety functions generally preserved by maintaining the core geometry within the limits of achievable mechanical reliability. However, degradation by crack initiation in individual GCCs might or might not affect the safety functions of the GCA, depending on many factors unique to the design.

Discussion of SRC Assignments by Component Group

- The POF limits for each component vary with the service level as well as the Structural Reliability Classification (SRC). Note that SL-A is split into two classifications: unirradiated (before initial startup, for damage dose < 0.001 dpa per HHA-3142.1(a)), and after irradiation. A more stringent POF applies in the pre-irradiation state for SRC-2: all Graphite Core Components must meet a POF of 1.0E-4 when subject to the design & level A/B loads for 'Pre-Ops'.
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Summary

- The ability of the GCA to perform safety functions is informed by the end state characterized by the ASME service levels
- The service levels for graphite are defined with reference to the degree of degradation and, at the assembly level, discontinuities and/or large or gross deformations for more severe/infrequent events
- The severity/frequency of the events is determined by the risk-informed, performance-based methodology described in NEI 18-04 for LBE categorization and categories associated with plant conditions
- Plant conditions 1-5 are mapped from NEI 18-04 terminology for normal operations, AOOs, DBEs, and DBAs. The ASME Service Levels associated with the loadings in these plant conditions is also mapped to the NEI 18-04 terminology.
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Questions for the NRC

- As noted in the ASME BPVC HAB-2141(b),
  - *"Appropriate guidance for the selection of plant or system operating and test conditions, which may be determined to be of significance in the selection of Core Component Design and Service Loadings, the combinations thereof, and the corresponding acceptable limits, may be derived from systems safety criteria documents for specific types of nuclear power systems and may be found in the requirements of regulatory and enforcement authorities having jurisdiction at the site."*
- X-energy has selected the NEI 18-04 methodology to inform selection of SRC reliability targets for different graphite core components based on the end state attributes of whether probabilistic crack initiation would affect the assembly safety functions
- Q: Does the NRC have any concerns or clarifying questions on how X-Energy is using NEI 18-04 to derive acceptable limits for core graphite components?

Part 2: Development of Design Loadings

Design Loadings

- Design Loadings are the enveloping Service Level A loadings which consist of design fast neutron flux distribution, design temperature distribution, design sustained mechanical load (deadweight and loads transferred from adjacent GCCs or other components), and design pressure distribution (HHA-3123)
- This excludes short duration mechanical loadings such as impact or seismic
- For internal stresses due to irradiation, according to HHA-3142.3(c), "The stress analysis shall account for superposition of the stresses resulting from all of the loads that a Graphite Core Component is exposed to simultaneously."
- Therefore, the design loading combination for each GCC is taken as the fast neutron dose distribution, the design temperature distribution, the design differential pressure distribution, and the resultant sustained mechanical loading state, which results in the highest utilization of that GCC (HHA-3123.2)
- These are taken as the conditions experienced during steady state full power operation specific to that GCC through the design life [[

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Development of Design Loadings

- **Scope of this section**: Provides a road map for multiple interrelated cross-disciplinary analyses related to development of the Design Loadings and associated structural evaluation of the Graphite Core Assembly
- **Objectives**: To illustrate the design with high-level details of the flow of inputs and outputs affecting structural analysis of normal operating conditions at steady state power and to describe the basis for development of the design loadings

- **Background:** Core coolant flow, temperature, pressure, fluence, and graphite structural deformation exhibit complex cross-dependent behavior which requires iterative analysis
- The complex behavior is impacted by primary and secondary flow paths between graphite blocks and interfacing components from the inlet to the outlet of the reactor pressure vessel
- Secondary flow paths that are not part of the primary coolant flow path are hereafter termed as follows:

Leakage flow path	**Flow paths in the graphite blocks that, in an ideal state, are perfectly sealed. Engineered to be minimized.**
Bypass flow path	**Flow paths in the graphite blocks that do not transit through part or all of the pebble bed because of a cooling or other flow requirement. Engineered to an optimized nominal condition, which may include gap minimization or flow restrictor sizing.**

- The analysis plans are informed by historical work for other reactors, especially PBMR

Background – Primary Flow Paths in the Xe-100 GCA and Core

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Background – Primary Flow Paths in the Xe-100 GCA and Core

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Design to Optimize Total Flow Behavior

- Graphite blocks follow a "single column principle" to prevent tension loading of the graphite as it undergoes shape changes during its lifetime
  - Resultant channels form between each column, at all elevations – [[ ]]P
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  - Reactivity is also a function of graphite temperature and material properties
- Characterization of graphite aging behavior requires **time-dependent system level analysis of primary and secondary flows / temperatures**

Approach to System Level Analysis for Graphite Aging Behavior

See illustration on following slide for a visual representation

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Multiphysics Analysis Sequence – Detailed Inputs/Outputs

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Iteration Until Convergence and All Criteria Met

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Questions for NRC Staff on the System Model Approach

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