Xe-100 Graphite Engagement: Transient, Fatigue, and Seismic Assessment Methodology

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Agenda & Objectives

Agenda (Open Portion):

- Transient & fatigue methodology - motivation / background
  - Rules considered and Homologous Stress definition
  - Effects of temperature, volume, irradiation
  - Statistical model
- Seismic methodology - qualification framework

Agenda (Closed Portion):

- Transient methodology details
- Fatigue methodology details
  - Data sources
  - Methodology plan & implementation
- Seismic methodology details
  - Seismic demand analysis
  - Software dedication
  - Seismic model testing & acceptance criteria

Objectives:

- Provide an overview of cyclic fatigue methodology applied by X-energy for use of graphite analysis
- Provide preliminary fatigue assessment formulations that will be implemented in future analysis performed by X-energy
- Summarize sources of data use for the development of theory and results
- Present seismic qualification framework for the Graphite Core Assembly (GCA)
- Describe roles of potential testing and software Commercial Grade Dedication (CGD)
- Discuss plans and methodologies to demonstrate that seismic analysis captures the response of the structure

Graphite Transient, Seismic, & Fatigue Methodology - Motivation

- Graphite core components are subjected to cyclic loading caused by varying temperatures and thermal gradients during transient events such as:
  - Reactor start-up
  - Load-following operations
  - Reactor trips
  - Cold pressurized shutdowns
  - Cold de-pressurized shutdowns
- Other cyclic stresses:
  - Seismic activity
  - Coolant flow fluctuations
- Low and high-cycle fatigue may exist under these conditions which can cause propagation of cracks from inherent graphite flaws
- There is a need for a methodology to qualify fatigue life of graphite core components and assess the effects of transient and seismic events on the GCA

Graphite Fatigue: Introduction

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Graphite Fatigue: What is in the Code

- Per ASME BPVC III.5 HHA-3144, guidelines for fatigue qualification, testing, or evaluation methods are not provided
- The NRC PIRT and additional Technical Letters points to the need for reliable cyclic data of unirradiated and irradiated graphite
- A technical report by NUMARK Associates[1] supporting assessment of the ASME BPVC III.5 sections on graphite materials suggests:
  - a) Reliable cyclic fatigue data on the graphite used for design
  - b) The data should be bounding operational envelope of dose, temperature, and oxidation conditions
  - c) Analysis of fatigue data to determine conservatism for stress versus number of cycles curves use for design
  - d) Data on graphite "static fatigue" or slow crack growth
  - e) Analysis of fatigue influence in ASME equivalent stress S_g
  - f) Recommended statistical analysis of data with 99% specimens' survival with 95% confidence

HHA-3144 Graphite Fatigue[2]

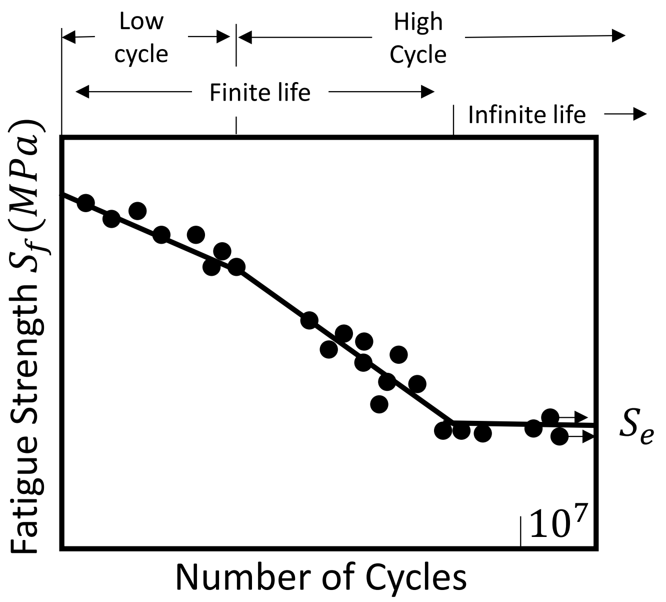
In the course of preparation.

1 – NUMARK Associates, Inc., TLR/RES/DE/CIB-2021-07, 'Additional Technical Information in Support of the U.S. Nuclear Regulatory Commission Review of the 2017 Edition of ASME Code, Section III, Division 5, "High Temperature Reactors," Subsection HH, "Class A Nonmetallic Core Support Structures," Subpart A, "Graphite Materials."' May 2021. ADAMS Accession No. ML21109A123.

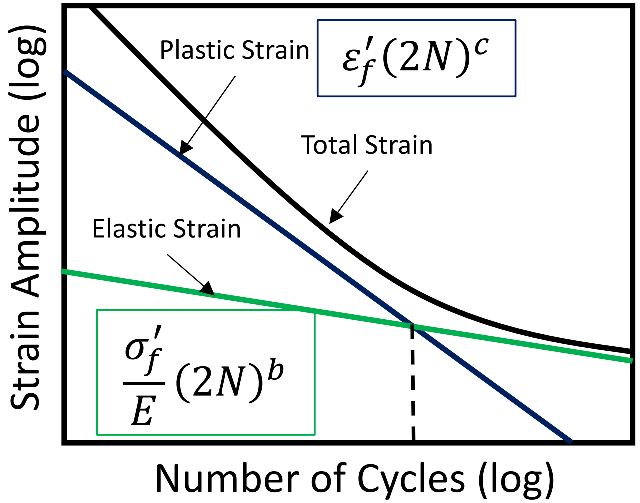
2 - ASME Boiler & Pressure Vessel Code, Section III, Division 5, "High Temperature Reactors – all Editions 2017 through 2023.

Introduction & Background

- Existing fatigue life theories are available for metals but are not directly applicable to graphite core components
- Methods of fatigue analysis are typically stress-life, strain-life and linear elastic fracture mechanics
- These methods are not entirely applicable to graphite because:
    - Graphite has an inherent scatter and does not necessarily yield to an endurance limit
    - Graphite shows little plasticity
    - Under irradiation graphite exhibits nonlinear changes in material properties
- **The concept of homologous stress is introduced as an alternative method analogous to the stress-life method**



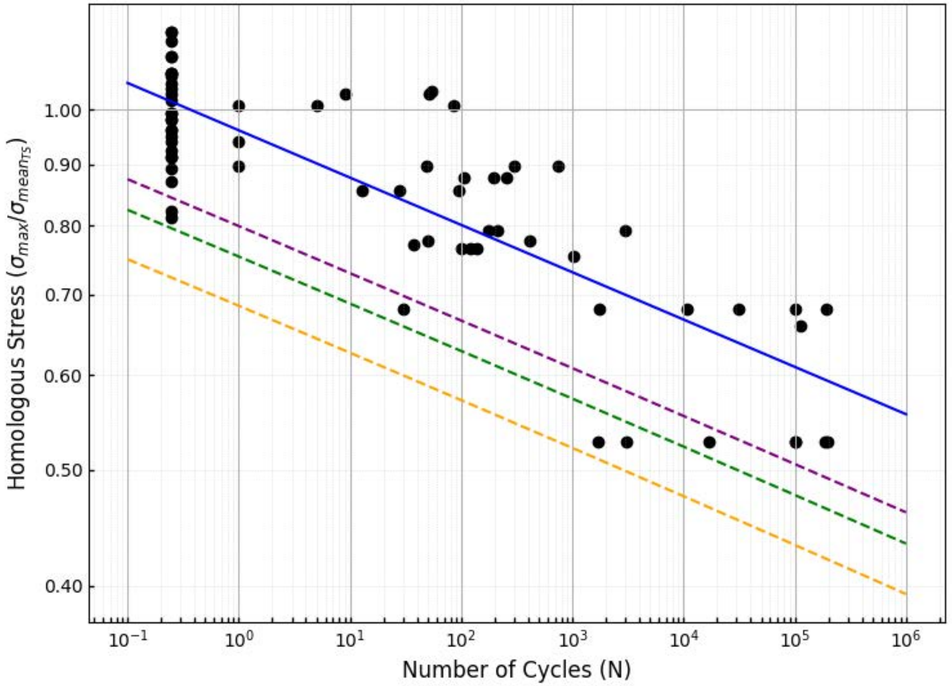
a) Stress-Life method for metals with endurance limit. Graphite has a probabilistic nature which results in scatter even at the endurance limit, therefore this method is not directly applicable.



b) Strain-life approach for typical schematic for metals. Graphite shows little to no plastic strain, from a different mechanisms than in metals, therefore not suitable.

Homologous Stress Introduction

$$\sigma_H = \frac{\sigma_{max}}{\sigma_{mean}}$$

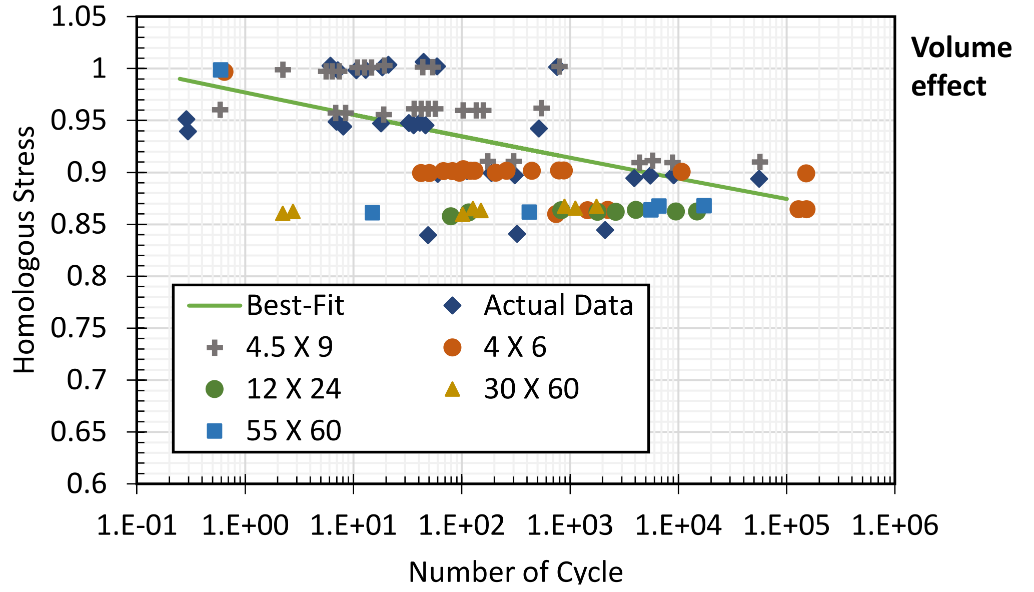


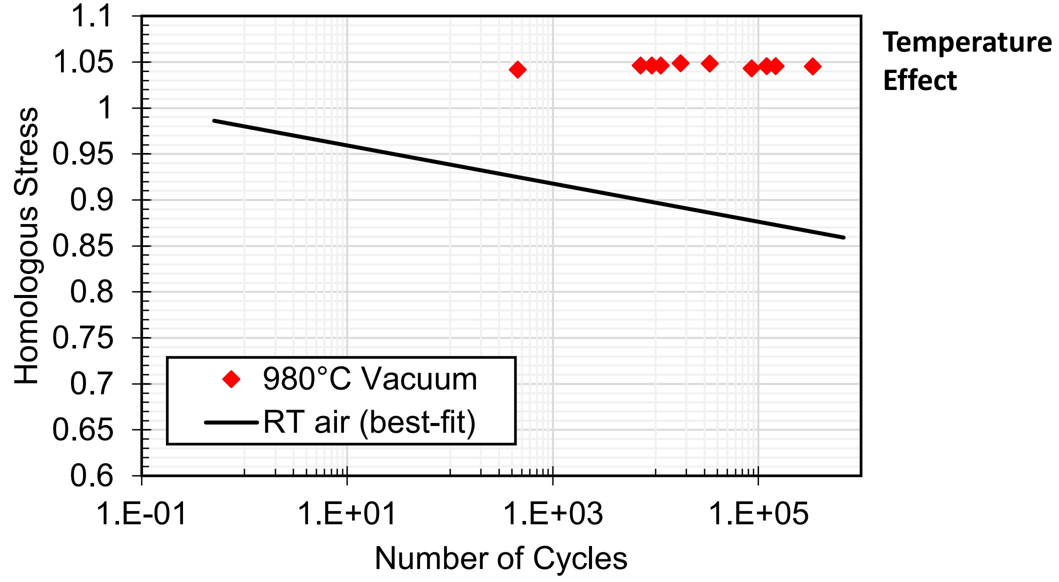
a) Typical homologous stress versus number of cycles plot for some graphite grade with lower tolerance limits. Notice Y axis is the homologous stress.

- The homologous stress (σ_H) is a ratio of the maximum applied stress normalized by the mean strength at the first-cycle
- This ensures that a randomly selected specimen survives the first cycle:
  - This captures the variability of strength, as at high stresses failure can occur at first cycle
  - Fatigue life is then the probability that an arbitrary specimen will have sufficient static strength to survive the first cycle and the probability that some cycle number will be exceeded
- Note the first cycle is given at N=0.25 cycles in the figure to the left
- The homologous stress eliminates the effects of specimen volume and temperature

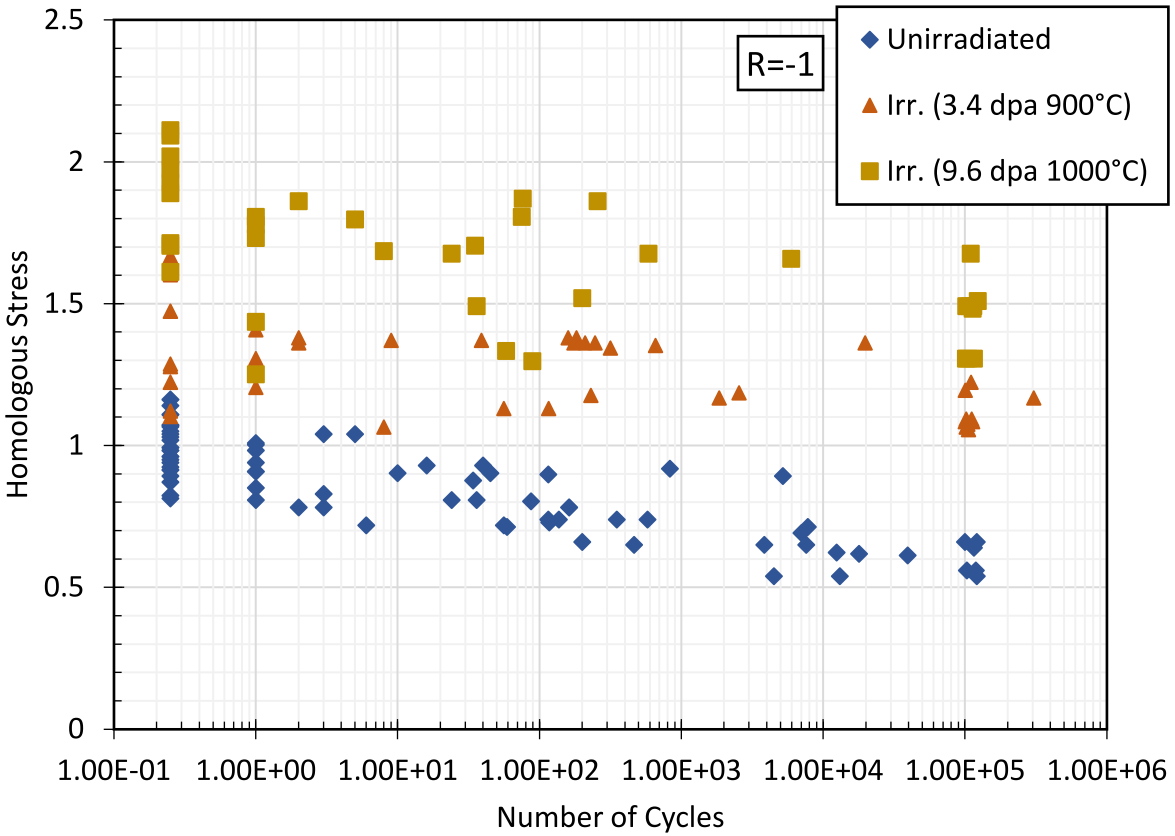
Effect of Temperature and Volume

- Effect of volume:
  - Multiple sizes of specimens are observed
  - Constant R ratio
  - Best-fit from the standard specimen data
  - No remarkable size effect on fatigue strength is found
- Temperature effect:
  - A comparison between fatigue life at room temperature and at air (solid line) to high temperature fatigue life in a vacuum (data points)
  - It has been concluded that at higher temperatures fatigue strength increases in vacuum conditions





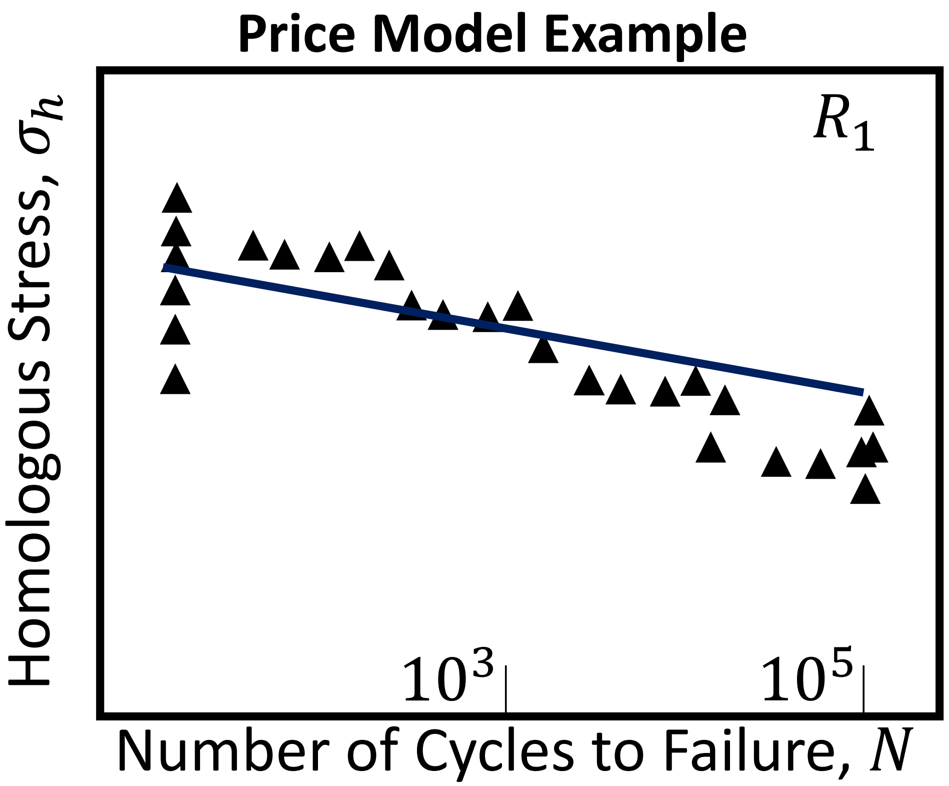
Effect of Irradiation



Effect of irradiation, comparison between some unirradiated graphite grade to two neutron fluence irradiated graphite. Note it is the same stress ratio.

- Irradiated data is normalized using the unirradiated mean strength
- Three sets are shown for a constant stress ratio of R=-1
- Fatigue strength increases with irradiation at least up to dimensional change crossover:
  - Densification caused by neutron irradiation increased fatigue strength
  - It is observed that as dose increases fatigue strength increases as well
  - An increased static strength is shown to relate to an increase in fatigue strength

Statistical Model Fatigue



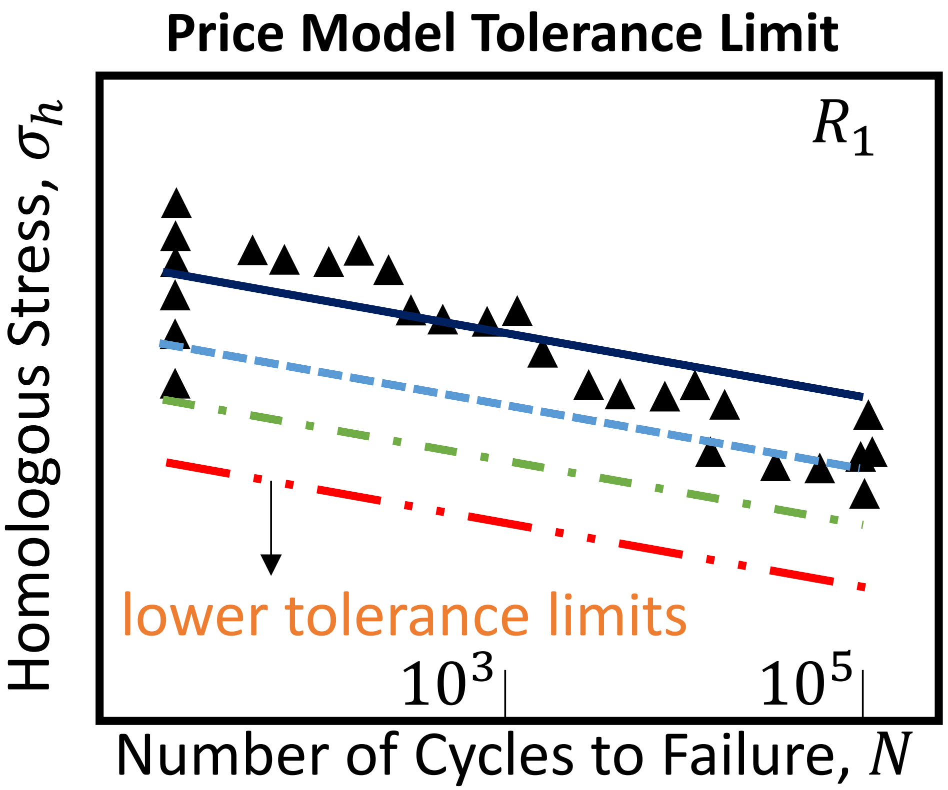
Schematic of the price model as a log-log plot of number of cycles to homologous stress. Note data is not from an actual graphite grade.

- Previous practice was to deduce the number of cycles corresponding to some failure probability from the dispersion of log(N) at a given stress:
  - This assumes either a Weibull distribution or a Gaussian distribution
  - A disadvantage to this approach is that it provides no information on low failure probabilities in high-cycle fatigue
- Therefore, the Price Model was introduced

$$\log\left(\frac{\sigma_{max}}{\sigma_{mean}}\right) = \alpha + \beta \log N + \varepsilon$$

- σ_{max} Maximum applied stress
- σ_{mean} Mean tensile or compressive strength
- α & β Constants
- ε Random variable distributed normally with mean of zero and a standard deviation

Statistical Model Fatigue



Schematic of the Price Model with tolerance limits representation.

- The Price Model approach assumes that for a constant life the failure stresses follows some distribution
- The statistical model is used in conjunction with lower tolerance limits
- Tolerance limit are given in x/y combinations:
  - x represent a percentage of the population
  - y represents the confidence level
- E.g., assuming the first dotted line (blue line) is a 90/95 combination. Therefore, it is concluded with 95% confidence, that the 90% of specimens would survive under a specific life cycle.

Conclusion | Next Steps for Graphite Fatigue

- Graphite core components can be subjected to fatigue which can cause propagation of cracks
- Typical methods of evaluation such as the Stress-Life and Strain-Life are not entirely applicable for graphite
- The homologous stress is used to evaluate fatigue and ensures survivability during the first fatigue cycle
- The volume of specimen has little to no impact on fatigue life
- An increase in irradiation and/or temperature results in an increase in fatigue strength
- The Price Model is considered as an alternative to evaluate the fatigue life of components

Transient & Seismic Loadings & Fatigue Considerations

- Fatigue assessment would be carried out for applicable loading scenarios where cyclic loading behavior might exist such as in transient events or in response to an earthquake
- Per NUMARK report comments on for HHA-3122 (d), seismic loads are likely to be the "need push" or the energy causing a dormant crack to begin propagating, as arrested crack to restart its slow growth, or an unstable crack to propagate catastrophically. Thus:
  - User should provide technical data on how the design considers the effects of both low-cycle and high cycle fatigue in maintaining S_g value for structural integrity
  - User should provide information on how the calculations resolve the seismic loads into fatigue-type loads and stresses for the components, and how they account for any potential damping effects
- Thus, a framework should be provided for assessing seismic loadings *(next section)*

GCA Seismic Qualification Framework

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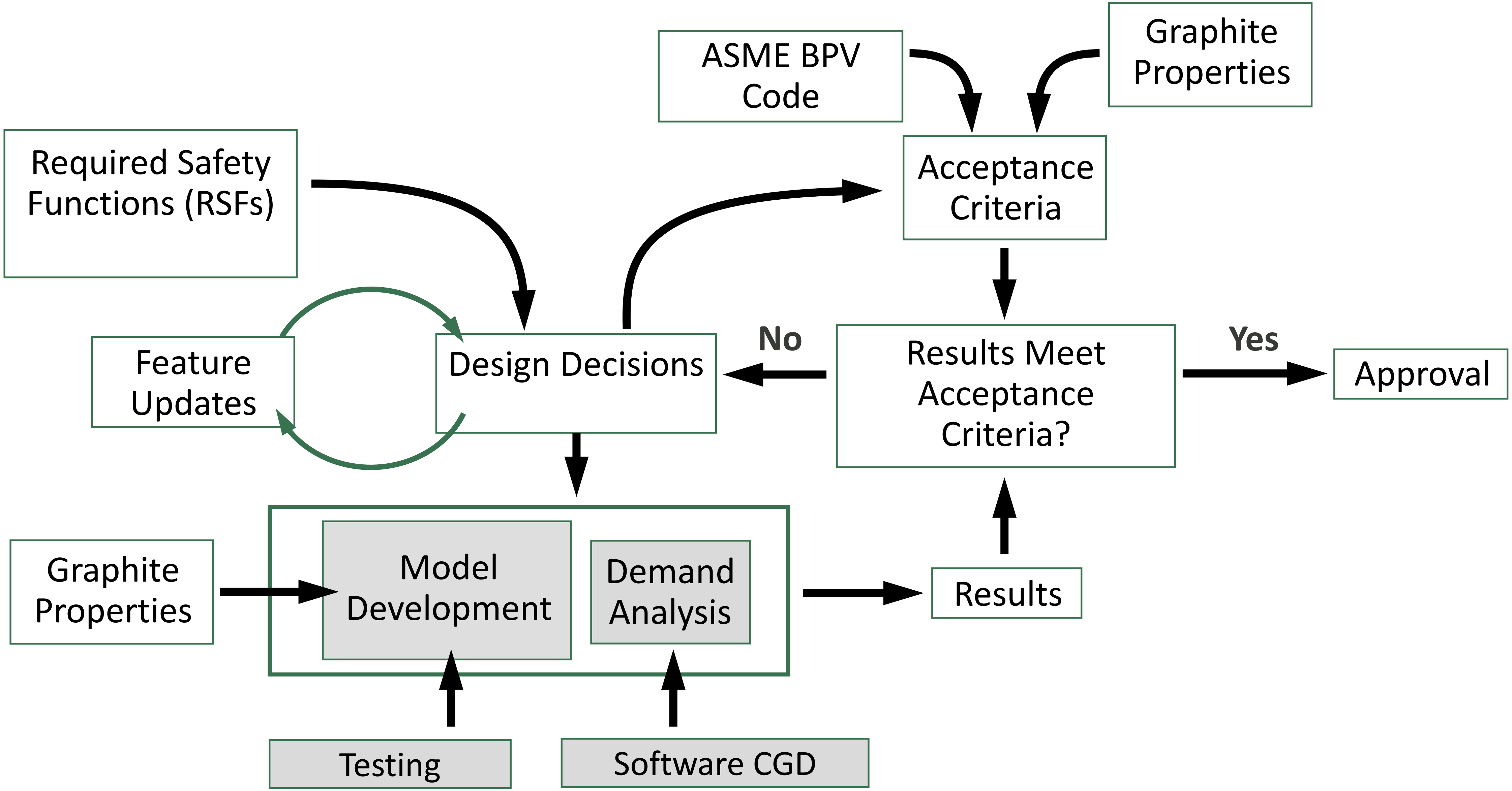
Introduction & Background

- **Objective**: demonstrate reasonable assurance that the Xe-100 Graphite Core Assembly (GCA) will continue performing its Required Safety Functions (RSFs) during and after a seismic event:
  - *ASME Boiler & Pressure Vessel Code, Section III, Division 5, HHA-3122, 2023 Edition: "The loadings that shall be taken into account in designing the Graphite Core Components include… (d) earthquake loads or other loads that result from motion of the reactor vessel"*
  - *This clause is unchanged from the 2017 Edition as endorsed with limitations in RG 1.87 Rev. 2, as pertains to regulation 10 CFR 50.34(a)(1)(ii)(B) A*
- **Approach**: Calculate seismic demands (loads, displacements, etc.) using dynamic analyses in LS-DYNA supported by custom pre/post-processor and geometry generation script, XECORE, and assess the stress state in Ansys Mechanical
- Confidence in the demands produced by analysis is established using a combination of:
  - Software Commercial Grade Dedication (CGD) to qualify the software for the range of use
  - Testing of the analysis models to investigate sensitivities (e.g., different initial gap configurations)
  - Potential physical testing to confirm the expected physical behavior and inform design features

Graphite Seismic Qualification Framework



Ensure Demands are Correct

Testing (both of the analysis models and as supported by potential physical testing) and software CGD together provide confidence in demands.

Are we solving the correct problem? — **Testing**

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Are we solving the problem correctly? — **Software CGD**

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Design features that support the GCA RSFs in a seismic event

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Assurance that analysis is yielding correct demands

Demand Analysis → Computed by Software, Validated by CGD Physical Behavior → Confirmed by Testing

- Testing and software CGD work together to ensure that modeling and analysis yield correct demands
- Testing reveals structural behaviors, which are checked against the dynamic model
- Important behaviors identified during testing are incorporated into the model

Model Development

- Implement current iteration of the graphite core design as a dynamic model
- Model should capture important structural behaviors

- Provides assurance that the important features of the response are accounted for in the dynamic model

Testing

Demand Analysis

- Guided by the evolving seismic analysis plan
- Analysis Plan is revised as open items are addressed and design changes are made
- Generates output to check against acceptance criteria

- Provides assurance that analysis software performs as intended by the software developer and model user

Software CGD

Model the Correct Problem

"Ensure that the analysis model accurately represents the physical structure."

Is the modeled load path representative of the actual load path? → <u>Design</u> the GCA and interfaces to enforce a load path through select components. This reduces the uncertainty in the load path.

Are the notable structural behaviors accounted for in the dynamic model? → <u>Test</u> models of subassemblies to demonstrate the preferential load path and identify unexpected behaviors. Potential physical testing can be performed after some initial analysis testing has supported confidence in the expected behavior.

Are the material and structural properties of modeled components correct? → <u>Analyze</u> modeled components using appropriate properties available in literature and historical data.

Closed Portion – GCA Transient and Fatigue Methodology

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Transient Analysis Methodology

- Introduction: Transient analysis are carried out to assess the structural integrity of GCCs under different Service Loadings that are identified considering all plant operating conditions

- Purpose: The GCC stresses due to transient loading will be used to assess the compliance of the GCCs design with the specified service limits as defined by the ASME BPVC Section III, Division 5, subsection HAB-2142

- Scope: The scope is to describe, for the different GCCs of graphite reflector, the transient thermal-structural methodology composed of:
  - Transient thermal analysis
  - Quasi-static structural analysis

Transient Analysis Methodology

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Overview of Graphite Fatigue Methodology Details

- The transient event analysis will provide inputs (e.g., maximum principal stresses and cycle count of events) that can be used in graphite fatigue assessment
- The purpose of this section is to provide an overview of the rules being considered for graphite fatigue assessment as there are no clear guidelines provided by ASME BPVC.III.5
- In this section, preliminary results for a graphite fatigue assessment method are provided using historical data
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Rules Considered

- NUMARK Technical Report comments on graphite fatigue:
  - **a) Reliable cyclic fatigue data on the graphite used for design**
  - b) The data should be bounding the operational envelope of dose, temperature, and oxidation conditions
  - c) Analysis of fatigue data to determine conservatism for stress versus number of cycles curves use for design
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Overall Data Available

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Assumptions on the Data (Oxidation, Temperature, Dose)

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Limitation of Strength Change

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Price Model and Lower Tolerance Levels

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Static Fatigue

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Allowable Stresses Two Parameter

- Per ASME BPVC III.5, HHA-II-3100
  - Two parameter Weibull distribution:

$$f(x) = \left(\frac{x}{S_c}\right)^{m-1} \cdot \frac{m}{S_c} \cdot \exp\left[-\left(\frac{x}{S_c}\right)^m\right]$$

$$p(x) = 1 - \exp\left[-\left(\frac{x}{S_c}\right)^m\right]$$

$$L(x) = 1 - p(x)$$

$$\ln\left(-\ln\left(L(x)\right)\right) = m \cdot \ln x - m \cdot \ln S_c$$

  - Calculate lower limit factors:

$$m_{0.05} = \frac{m^*}{t(n; 0.95)} \qquad S_{c\,0.05} = S_c^* \times \exp\left[-\frac{t'(n; 0.05)}{m^*}\right]$$

  - Thus, the allowable stress can be obtained from the following:

$$S_g(POF) = S'_{c\,0.05}(-\ln(1 - POF))^{\frac{1}{m_{0.05}}}$$

Lower Tolerance Limits for Allowable Stresses

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Steps of Methodology

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Overview of Results for [[ ]]P

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Example Results for [[ ]]P

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Overview of Statistical Model

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Modified Goodman Diagram [[

- Modified Goodman diagrams are used in design as it relates interdependent parameters (max stress, min stress, mean stress, etc.)
- Modified Goodman Diagram are plots of maximum stress versus minimum stress both divided by the mean tensile or compressive strengths
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- Goodman diagrams are constructed using the tolerance limit:
  - E.g., the homologous stress level that ensures with 95% of confidence that 99% of specimens would survive 10^5 cycles
- Multiple stress ratios are needed for the generation of Modified Goodman Diagrams

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Example Results of Modified Goodman Diagrams

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Example Results of Modified Goodman Diagrams

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Fatigue Methodology Application with FEA Tools

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Conclusions | Graphite Fatigue

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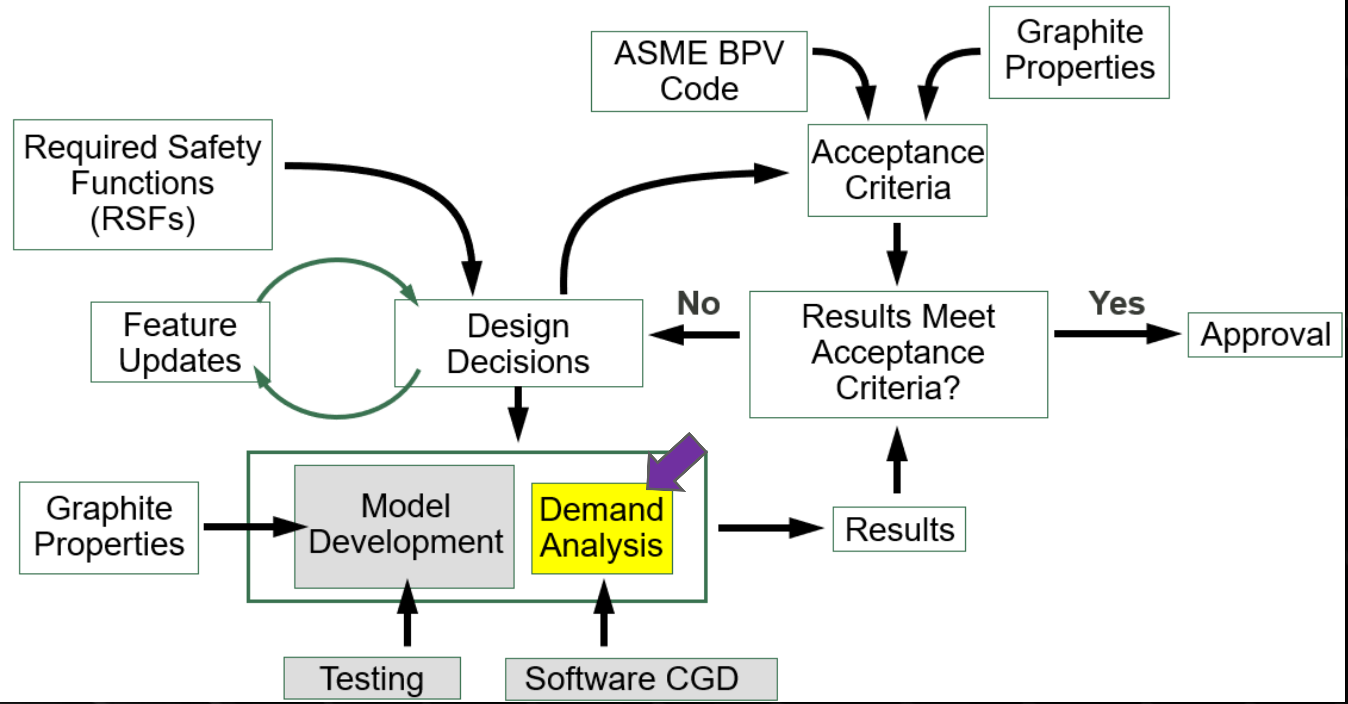

GCA Seismic Demand Analysis

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Seismic Demand Calculation Using Software

- The Graphite Core Assembly response to a seismic event is simulated in analysis performed in LS-DYNA, an explicit, dynamic, non-linear finite-element program that is well-suited to the physics being represented and has been used for similar applications (e.g., AGR)
- X-energy is developing a supporting software in Python called XECORE:

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- The analysis is in a preliminary stage. It is currently being used to inform development of design features such that the graphite core assembly can perform its safety functions.

Analysis Model Scope

- **Components**

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- **Outputs**

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Preliminary Modeling Approach

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Preliminary Modeling Approach

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Seismic Loading Considerations

Per NUMARK report comments for HHA-3122 (d) Loadings:

- *“the user should provide technical data on how the design considers the effects of both low-cycle and high-cycle fatigue”* → Fatigue methodology as presented in the preceding slides

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Analysis Plan Phases

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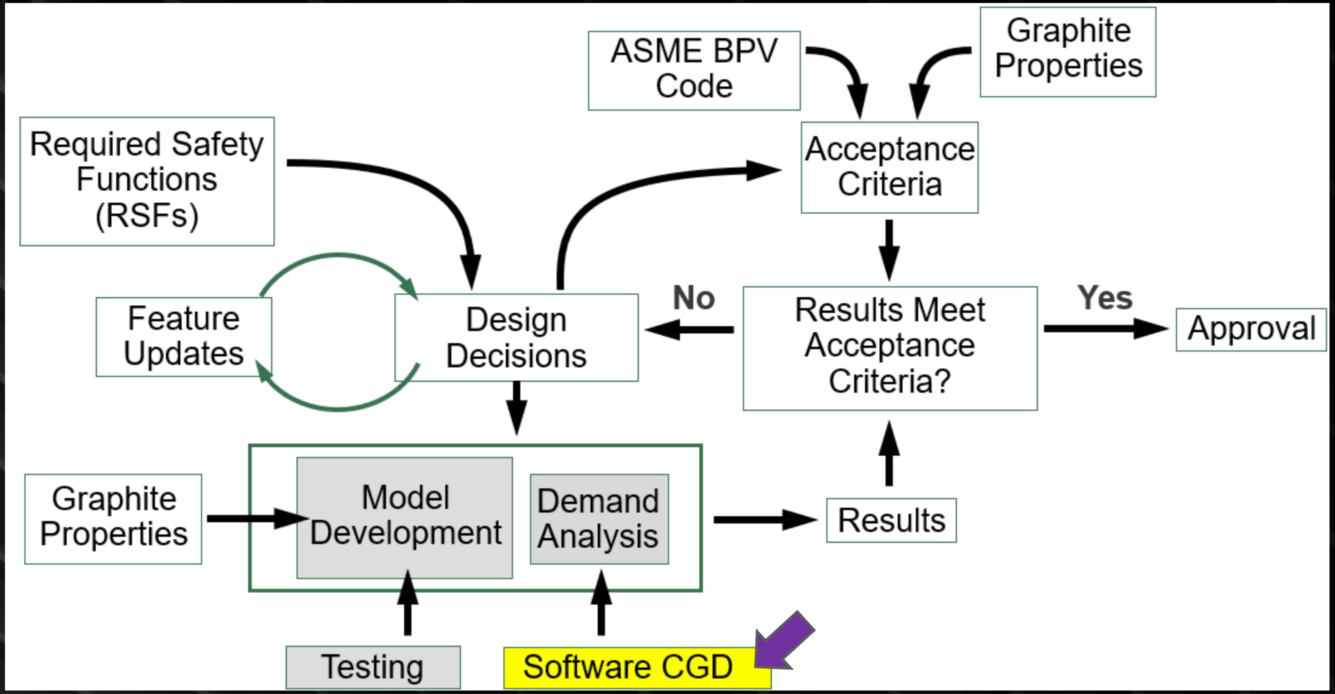

GCA Seismic Software Dedication

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Software Commercial Grade Dedication (CGD)

"Ensure the problem is being solved correctly as modeled."

- Qualification of LS-DYNA and XECORE software is planned by use of commercial grade dedication:
  - *Four CGD methods are identified in NQA-1, Part II, Subpart 2.14 and discussed in EPRI 1025243 Rev. 1, "Guidelines for the Acceptance of Commercial-Grade Design and Analysis Computer Programs Used in Nuclear Safety-Related Applications," as endorsed by the NRC in Regulatory Guide 1.231 Rev. 0*

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CGD Method for LS-DYNA

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Technical Evaluation of LS-DYNA

Prior to the CGD process:

- Document that the software is:
  - Performing a safety function
  - Being procured as a Commercial Grade Item (CGI) rather than a basic component
- Identify the software's critical characteristics
- Document the software's safety functions, Failure Mode and Effects Analysis (FMEA), and critical characteristics
- Establish acceptance methods to confirm critical characteristics are met

CGD Method for XECORE

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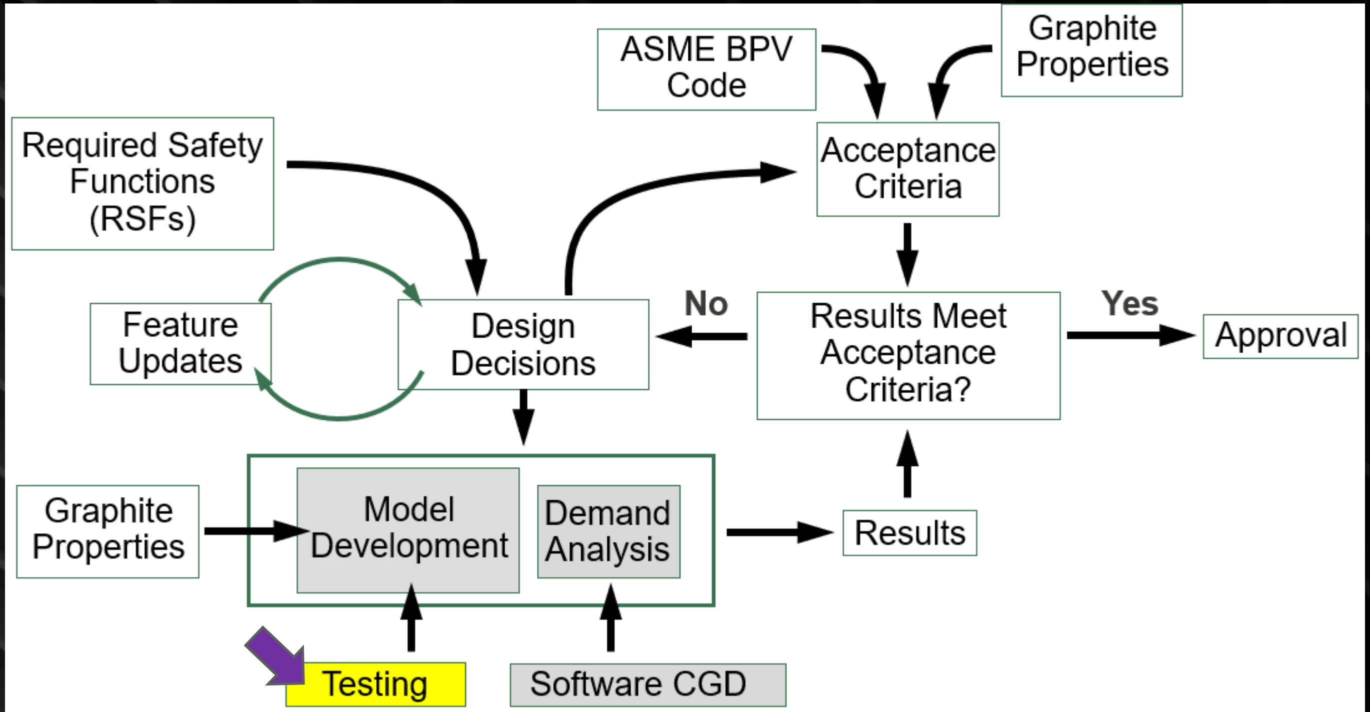

GCA Seismic Model Testing

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Overview of Planned & Potential Testing

- As noted above, a phased plan is outlined for GCA seismic analysis and qualification

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Phased Testing

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Testing Objectives and Outputs

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Follow-on Testing

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Scaling Approach

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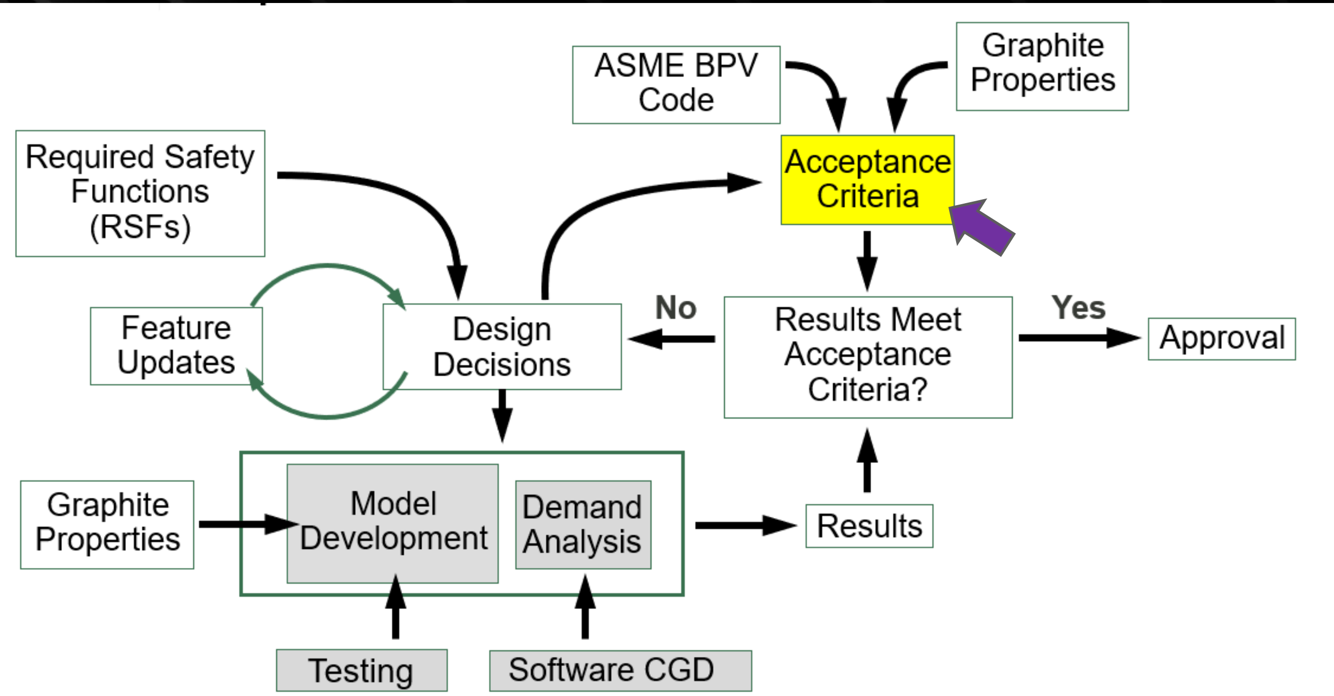

GCA Seismic Acceptance Criteria

GCA Seismic Acceptance Criteria

- The approach will be to identify how safety functions are adequately maintained at the assembly level so as to ensure that dose consequence thresholds aren't exceeded, and demonstrate this by applying appropriate acceptance criteria in the analysis that support keeping dose consequences below these thresholds
- For the seismic demand, structural components considered in the load path must have sufficient capacity if their reliability is necessary to support the safety function by the assembly
- Feature updates and design decisions will be informed by the design analysis as demands from seismic analysis are considered:
  - The design features can be further developed to ensure transfer of loads along the desired load path
  - Component dimensions and clearances can be specified to allow the graphite core assembly to fulfill its safety functions under the considered load cases

Required Safety Functions

Example - 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"

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Example Acceptance Criteria

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Required Safety Functions (RSFs)
Reproduced for Quick Reference

As previously shared, and reproduced for convenience - The GCA design and analysis must conform to the following RSFs, and their associated PDC (Principal Design Criteria)

- 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

Discussion & Questions

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