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U.S. Nuclear Regulatory Commission

Fuel Qualification for Advanced Reactors (Draft)

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CONTENTS

1. INTRODUCTION

1.1 Purpose

The objective of nuclear fuel qualification is the demonstration that a fuel product fabricated in accordance with a specification behaves as assumed or described in the applicable licensing safety case, and with the reliability necessary for economic operation of the reactor plant [1]. Advanced reactor designs are being proposed that utilize fuel designs and operating environments (e.g., neutron energy spectra, fuel temperatures, neighboring materials) that are outside of the large experience base available for traditional light-water reactor fuel. Nuclear fuel effects many aspects of the overall nuclear power plant design, and qualification of nuclear fuel has traditionally involved long development times. The purpose of this report is to provide a fuel qualification assessment framework that would satisfy regulatory requirements. This framework constitutes a top-down approach where high level regulatory requirements are supported by lower level objective goals. The bases for the identified goals and clarifying examples for the expected evidence used to satisfy those goals are provided.

1.2 Safety Case

The role of nuclear fuel in the safety case can vary significantly between different reactor designs. For example, facilities that utilize traditional oxide fuels with metal cladding have been designed with robust barriers (e.g., a containment building) to protect against the release of radioactive material under accident conditions whereas a facility that utilizes tristructural-isotropic (TRISO) fuel may credit a series of barriers (including barriers within the fuel itself) to protect against the release of radioactive material (i.e., a functional containment [2]). Specifying the fission product retention functions of the nuclear fuel is an essential step in nuclear fuel qualification.

1.3 Scope

Many aspects of nuclear safety are impacted by nuclear fuel including neutronic performance, thermal-fluid performance (e.g., margin to critical heat flux limits), fuel mechanical performance, reactor core seismic behavior, fuel transportation, and storage. The scope of this report focuses on the identification and understanding of fuel life-limiting failure and degradation mechanisms that occur as a result of irradiation during reactor operation. Additionally, the assessment criteria developed in Section 3 of this report are informed by regulatory experience licensing solid fuel reactor designs (particularly light water reactor designs). An attempt has been made to develop generically applicable criteria. However, it is recognized that some criteria may not applicable to liquid metal forms (e.g., Molten Salt Reactors) and that additional or alternate criteria may be required to address the safety case for those reactor fuel forms.

2. BACKGROUND

2.1 Regulatory Basis

Nuclear fuel qualification to support reactor licensing involves the development of an evidentiary basis to support findings associated with higher level regulatory requirements that are attributed to the nuclear facility. These requirements and their relationship to this report are discussed below. Note that, for several regulatory criteria, the descriptions clarify that satisfying the goals under this fuel qualification framework “partially addresses” those requirements which are associated with the nuclear facility. The reason that satisfying the goals of the fuel qualification framework provides a partial fulfillment of those requirements is because the framework provides a means to identify the safety criteria for the fuel, which are used in the analysis of structures, systems, and components (SSCs) of the facility. It is the description and analysis of the SSCs of the facility that are ultimately used to address the requirements.

- 10 CFR 50.43(e)(1)(i) requires that the performance of each safety feature of the design has been demonstrated through either analysis, appropriate test programs, experience, or a combination thereof. The assessment framework developed in Section 3 of this report attempts to (1) identify the safety features of the fuel that support the overall safety-case of the nuclear facility (see G2, “Safety Criteria” in Section 3.2 of this report), and (2) clarify the types of evidence (e.g., analysis, testing, experience) typically expected to demonstrate those safety features. In accordance with the scope of this report, the safety features assessed in the framework developed in Section 3 of this report are associated with the identification and understanding of fuel life-limiting failure and degradation mechanisms that occur as a result of irradiation during reactor operation.

- 10 CFR 50.43(e)(1)(iii) requires that sufficient data exist on the safety features of the design to assess the analytical tools used for safety analyses over a sufficient range of normal operating conditions, transient conditions, and specified accident sequences, including equilibrium core conditions. The sufficient range of normal operation, transient conditions, and specified accident sequences are included as G2.1.1, “Definition of fuel performance envelope,” and discussed in Section 3.2.1.1 of this report. Additionally, criteria for the assessment of analytical tools are addressed by the evaluation model assessment framework discussed in Section 3.3 of this report, and the criteria for data adequacy are addressed by the experimental data assessment framework discussed in Section 3.4 of this report.

- General Design Criteria (GDC)/Advanced Reactor Design Criteria (ARDC) 2 require that systems, structures, or components (SSCs) important to safety be designed to withstand the effect of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions. The safety functions generally associated with nuclear fuel include reactivity control, heat removal, and radionuclide containment. The requirements associated with the consideration of natural phenomena are partially addressed by satisfying G2.3, “Ability to achieve and maintain a safe shutdown can be assured.” G2.3 is discussed in Section 3.2.3 of this report.

- GDC/ARDC 10 require that specified acceptable fuel design limits (SAFDLs) or specified acceptable radionuclide release design limits (SARRDLs) are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences (AOOs). This requirement can be partially addressed by satisfying G2.1, “Margin to design limits can be demonstrated under conditions of normal operation, including the effects of AOOs with high confidence.” G2.1 is further discussed in Section 3.2.1 of this report.

- GDC 27/ARDC 26 require, in part, the ability to achieve and maintain a safe shutdown under postulated accident conditions. This requirement can be partially addressed by satisfying G2.3, “Ability to achieve and maintain a safe shutdown can be assured.” G2.3 is discussed in Section 3.2.3 of this report.

- GDC/ARDC 35 require an emergency core cooling system that provides sufficient cooling under postulated accident conditions and that coolable geometry of the reactor core is maintained. This requirement can be partially addressed by satisfying G2.3, “Ability to achieve and maintain a safe shutdown can be assured.” G2.3 is discussed in Section 3.2.3 of this report.

- 10 CFR 50.34(a)(1)((ii)(D), 10 CFR 52.47(a)(2)(iv), and 10 CFR 52.79(a)(1)(vi) require an evaluation of a postulated fission product release. This requirement can be partially addressed by satisfying G2.2, “Margin to radionuclide release limits under accident conditions can be demonstrated with high confidence.” G2.2 is discussed in Section 3.2.2 of this report.

2.2 Related Guidance

Several guidance documents are available that address considerations in the area of nuclear fuel qualification. This guidance and it’s relationship to this report are discussed below.

2.2.1 NUREG-0800

NUREG-0800, Section 4.2, “Fuel System Design,” [3] provides acceptance criteria that are considered in a licensing review for a fuel system. The fuel system safety review considerations discussed in NUREG-0800 are captured in Section 3.2 of this report. Specifically, the purposes of NUREG-0800, Section 4.2 were captured as follows:

1. Assurance that the fuel system is not damaged as a result of normal operation and AOOs is addressed through G2.1, “Margin to design limits can be demonstrated under conditions of normal operation, including the effects of AOOs with high confidence,” and discussed in Section 3.2.1 of this report.
2. Assurance that the fuel system damage is never so severe as to prevent control rod insertion when it is required is addressed through G2.3, “Ability to achieve and maintain safe shutdown can be assured,” and is discussed in Section 3.2.3 of this report. The specific item of control element insertion is discussion in Section 3.2.3.2.
3. Assurance that the number of fuel rod failures is not underestimated for postulated accidents is addressed through G2.2, “Margin to radionuclide release limits under accident conditions can be demonstrated with high confidence,” and is discussed in Section 3.2.2.
4. Assurance that coolability is always maintained is addressed through G2.3, “Ability to achieve and maintain safe shutdown can be assured,” and is discussed in Section 3.2.3 of this report. The specific item of maintaining coolable geometry is discussed in Section 3.2.3.1.

NRUEG-0800, Section 4.2 is based upon existing knowledge regarding traditional light water reactor (LWR) fuel and the licensing bases for traditional LWR power plants. Specifically, NUREG-0800, Section 4.2 evaluates fuel system designs for known fuel failure mechanisms from traditional LWR fuel (i.e., uranium-dioxide fuel with zirconium-alloy cladding), identifies specific testing for addressing key LWR fuel phenomena, and includes empirical acceptance criteria based on testing of LWR fuel samples. Accordingly, the specific SRP acceptance criteria provided in NUREG-0800, Section 4.2, may not be applicable or sufficient to address advanced reactor technologies that utilize different fuel forms or where the role of the fuel in the safety case and licensing basis is different. However, lessons learned from the development of the SRP acceptance criteria have been incorporated into this report. Specifically:

- The significant effect that fuel manufacturing parameters have on fuel performance is addressed through G1, "A fuel manufacturing specification controls the key fabrication parameters that significantly affect fuel performance," and is discussed in Section 3.1 of this report.
- Limitations on test facilities and the risks associated with obtaining irradiated fuel data need to be considered. These considerations are discussed in the Experimental Data Assessment Framework discussed in Section 3.4 of this report and are also mentioned in Section 3.2.2.3.1.

2.2.2 ATF-ISG-2020-01

ATF-ISG-2020-01, "Supplemental Guidance Regarding the Chromium-Coated Zicronium Alloy Fuel Cladding Accident Tolerant Fuel Concept," [4] provides supplementary guidance to NUREG-0800, Section 4.2, "Fuel System Design." The guidance was developed using a phenomena identification and ranking table (PIRT) process and is specific to applications involving fuel products with chromium-coated zirconium alloy cladding. Similar to the discussion for NUREG-0800, Section 4.2, the specific phenomena identified may not be applicable to advanced reactor technologies. However, the use of the PIRT process to identify failure mechanisms and identify necessary features of an evaluation model are discussed in the Evaluation Model Assessment Framework in Section 3.3 of this report.

2.2.3 RG 1.233

Regulatory Guide 1.233, "Guidance for a technology-inclusive, risk-informed, and performance-based methodology to inform the licensing basis and content of applications for licenses, certifications, and approvals for non-light-water reactors," provides guidance for a modern risk-informed approach to licensing reviews [5]. This approach places emphasis on assessing the risk of the facility as determined through the quantification of event frequency and the associated radiological consequences. The consequence evaluation aspect of the risk assessment is addressed, in part, by G2.2., "Margin to radionuclide release limits under accident conditions can be demonstrated with high confidence," and is discussed in Section 3.2.2.

Additionally, Regulatory Guide 1.233 discusses the need to accomplish fundamental safety functions. Fuel qualification partially addresses the fundamental safety functions of reactivity control, heat removal, and radioactive material retention by G2, "Safety Criteria," and is discussed in Section 3.2 of this report. Specifically, (1) radionuclide retention is partially addressed by G2.1, “Margin to design limits can be demonstrated under conditions of normal operation, including the effects of AOOs with high confidence,” and G2.2, “Margin to radionuclide release limits under accident conditions can be demonstrated with high confidence”, and (2) reactivity control and heat removal are partially addressed by G2.3, “Ability to achieve and maintain safe shutdown can be assured.”

2.2.4 Guidance in Development

NRC staff are pursing guidance in additional areas that impact fuel qualification. As discussed in Section 1.3 of this report, additional or alternative criteria to those identified in this report may be required to address the safety case for reactors that use non-solid fuel forms. To that end, NRC is supporting the development of a proposed methodology for molten salt reactor fuel salt qualification [6] [7].

Additionally, Section 1.2 of this report discusses the role of the fuel in the safety case which is further discussed under G2, “Safety Criteria,” in Section 3.2 of this report. G2 is supported by source term considerations. Specifically, G2.2.1, “Radionuclide retention requirements of the fuel under accident conditions is specified” and G2.2.3, “Radionuclide retention and release behavior of the fuel matrix under accident conditions is modelled conservatively,” are items that are associated with source term. Furthermore, G2.1, “Margin to design limits can be demonstrated under conditions of normal operation, including the effect of anticipated operational occurrences with high confidence,” discusses the SARRDL which involves the use of a source term. NRC is supporting the development of source term guidance for non-light-water-reactors which can impact this aspect of fuel qualification [8] [9].

2.3 Accelerated Fuel Qualification

Accelerated fuel qualification (AFQ) involves the use of advanced modeling and simulation to inform constituent and system selection and to enable integral fuel performance analyses [10]. The AFQ process may support the identification of important parameters and phenomena for targeted characterization through separate-effects tests. The information obtained through these analyses and separate effects tests could be beneficial in justifying the adequacy of the evaluation model as part of EM G3.3.1 and discussed in Section 3.3.1 of this report. Ultimately, the AFQ process produces integral irradiation tests to validate engineering scale fuel performance codes and to confirm the performance and safety of the fuel system under prototypic conditions. Accordingly, the integral test data produced as part of the AFQ process appears to be consistent with the data considerations discussed in the Experimental Data Assessment Framework discussed in Section 3.4 of this report.

2.4 Lead Test Specimens

Much of the data necessary to qualify fuel for use require the use of irradiated test specimens. However, a situation may be encountered where test specimens are not available at the desired burnups. The use of lead test specimens has been successfully used in operating reactors and are discussed in NUREG-0800, Section 4.2, “Fuel System Design. The use of lead test specimens is further discussed in Section 3.4.2 of this report.

2.5 Assessment Frameworks

The development of an assessment framework using a top-down approach is not a novel approach to the regulatory process. Similar types of assessment frameworks have been developed in the code scaling, applicability, and uncertainty (CSAU) evaluation methodology [11], the evaluation model development and assessment process (EMDAP) [12], and are similar to the “objectives hierarchy” discussed in NUREG/BR-0303, “Guidance for Performance-Based Regulation,” [13]. Another framework was developed to aid in the assessment of thermal margin evaluations for light water reactors that was based on many years of performing safety reviews [14]. The use of assessment frameworks have aided safety reviews and have been shown to increase transparency regarding information needs, efficiency by focusing attention on areas of recognized importance, and clarity in the logical framework supporting a decision.

3. FUEL QUALIFICATION ASSESSMENT FRAMEWORK

This section systematically identifies fuel safety criteria. The comprehensive list of safety criteria is referred to as a fuel assessment framework and is informed by existing regulatory requirements, regulatory guidance, and experience performing safety reviews for nuclear fuel in light water and non-light water reactors. The fuel assessment framework is developed using a top-down approach that’s starts with the high level goal (G) that the fuel is qualified for use. Consistent with the purpose of fuel qualification, which is discussed in Section 1.1, and with a regulatory focus on safety, *fuel that is qualified for use means that high confidence exists that the fuel fabricated in accordance its specification will perform as described in the applicable licensing safety case*. This statement is captured figuratively in Figure 3-1, which decomposes fuel qualification into two supporting goals. These goals are further decomposed into lower level supporting goals. This process is continued until objective criteria are identified which can be directly supported by evidence. The process, criteria, and associated evidence is described in the subsections that follow.

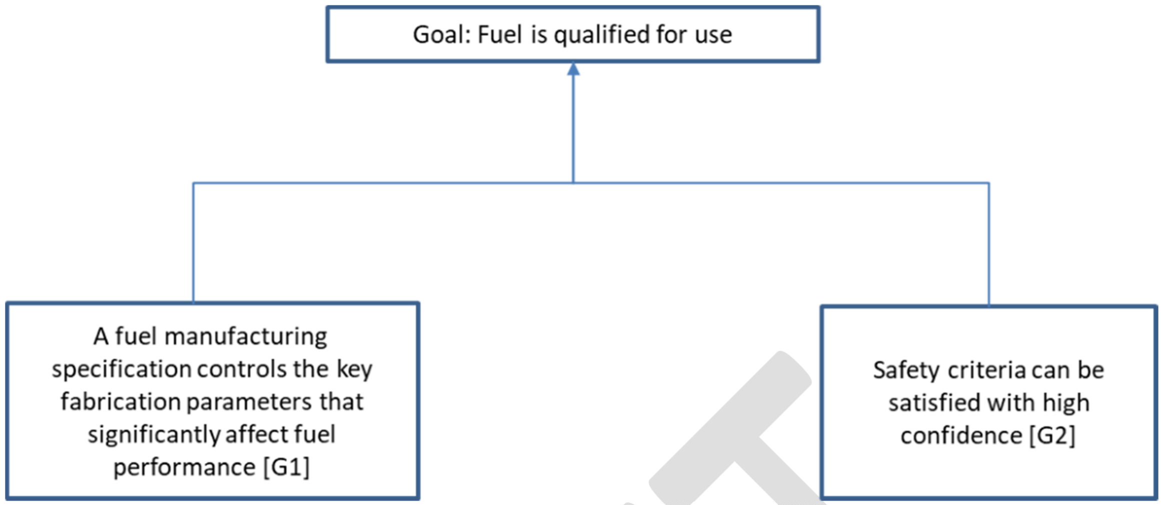

Figure 3-1. Decomposition of the main goal

3.1 G1 Fuel Manufacturing Specification

It is well known that fuel performance during normal operation and accident conditions can be highly sensitive to the fuel fabrication process. For example, failure criteria during reactivity induced accidents for light water reactors with zirconium-based cladding depends upon the heat treatment of the cladding (due to the impact on microstructure) [15], and key manufacturing parameters that must be controlled have been identified for TRISO fuel in order to ensure satisfactory performance [16]. It is recognized that manufacturing processes for a nuclear fuel product can evolve over the product life cycle, and therefore, a complete manufacturing specification is not expected to be included in licensing documentation. However, sufficient information should be included in the licensing documentation to ensure that key parameters affecting fuel performance are controlled during the manufacturing process. Accordingly, this goal is decomposed in Figure 3-2 to identify the type of information that should be included in licensing documentation.

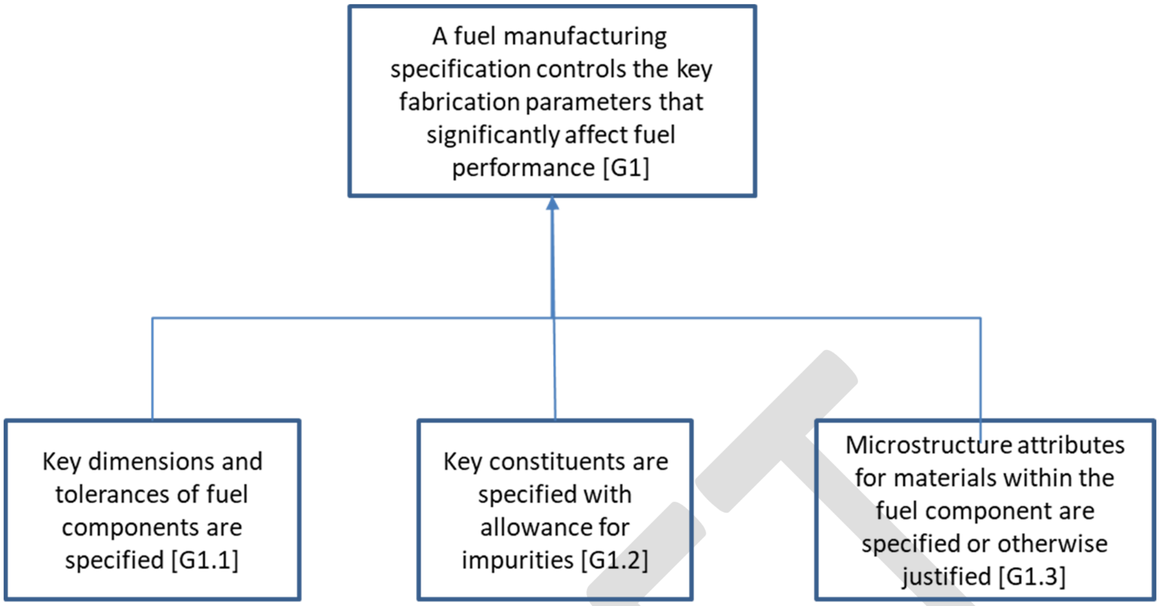

Figure3-2. Decomposition of G1 - Fuel Manufacturing Specification

3.1.1 G1.1 Dimension

Key dimensions and tolerances for fuel components that affect performance should be specified. Consistent with the scope of this report, as discussed in Section 1.3, these dimensions should be specific to components that impact fuel life limiting failure and degradation mechanisms that that occur as a result of irradiation during reactor operation (e.g., fuel pellet and cladding dimensions). This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.1.2 G1.2 Constituents

Key constituents of fuel components (e.g., UO_2 fuel, U-Pu-10Zr fuel, cladding material) should be specified along with allowances for impurities. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.1.3 G1.3 Microstructure

Attributes of the microstructure for the materials within fuel components should be specified or otherwise justified. It is noted that the microstructure of a material represents the desired end state of the material and this type of information may be captured in several ways. For example, specifying specific manufacturing processes (e.g., cold-working, heat treatments, deposition techniques, etc.) that are essential to create the desired end-state may be specified in lieu of specifying microstructure attributes. Additionally, if may be possible to demonstrate an insensitivity to microstructure such that specification of microstructure or the processes that affect microstructure are not needed in licensing documentation. Sufficient justification should be provided in licensing documentation for cases where an insensitivity to microstructure and manufacturing processes is present for a specific material. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.2 G2 Safety Criteria

An evaluation of the safety case involves an assessment against safety criteria, which are associated with the protection against the release of radioactive material. In general, there are many safety criteria associated with nuclear fuel that are dependent upon the event under which the fuel is subjected. Specifically, nuclear fuel is expected to retain its integrity under conditions of normal operation, including the effects of AOOs, but some degree of fuel failure can be accommodated for low frequency (i.e., not expected to occur during the life of the plant) design basis accident conditions. Accordingly, this goal is decomposed in Figure 3-3 to address the varying types of safety criteria associated with the range of events for which nuclear fuel must be qualified.

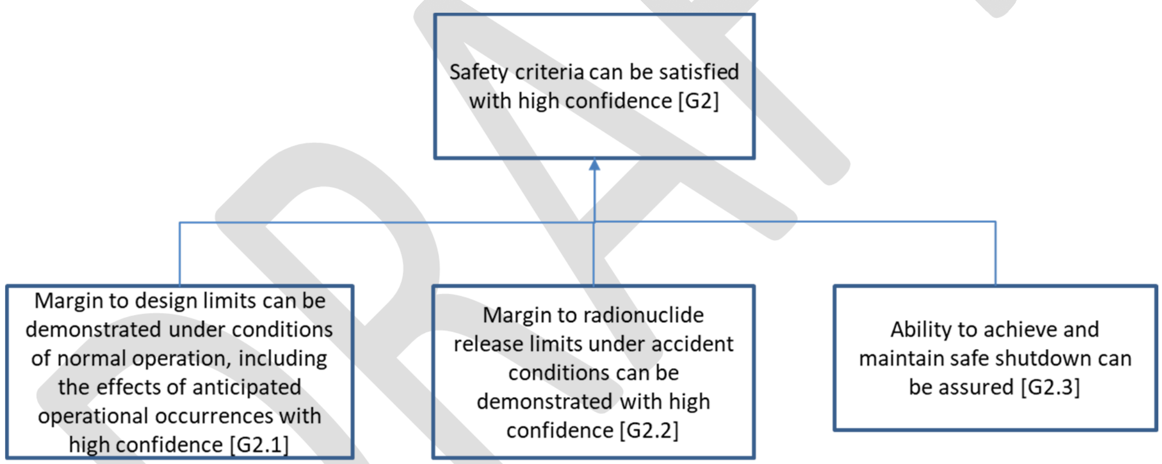

Figure 3-3. Decomposition of G2 – Safety criteria

3.2.1 G2.1 Design Limits Under Conditions of Normal Operation and AOOs

Fuel integrity is expected to remain intact under conditions of normal operation, including the effects of AOOs such that failure of a fission product barriers does not occur. Alternatively, some designs may propose to use the concept of a SARRDL which allows some small degree of radionuclides begin released from the fuel [17]. Multiple fuel failure and degradation mechanisms may exist, and limits need to be established to protect against those failure and degradation mechanisms. At the highest level, the assessment of a fuel against design limits for normal operation and AOOs requires knowledge of the conditions that the fuel is exposed to (i.e., the performance envelope) and a method to assess the fuel performance under those conditions (i.e., an evaluation model). These supporting goals are captured in Figure 3-3 and discussed in the subsections below.

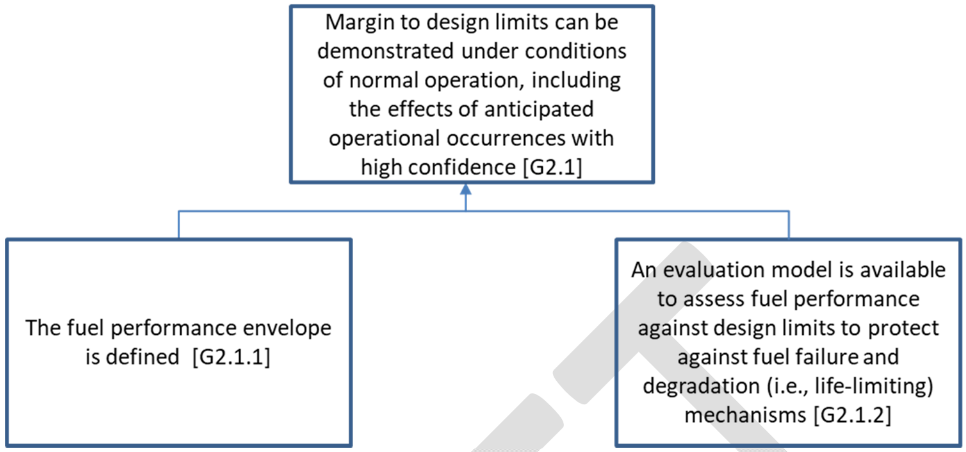

Figure 3-4. Decomposition of G2.1 – Margin to design limits under conditions of normal operation, including the effects of AOOs

3.2.1.1 G2.1.1 Definition of Fuel Performance Envelope

The fuel performance envelope specifies the environmental conditions and radiation exposure under which the fuel is required to perform. The envelope may be specified by fuel designers and provide constraints on the design of the reactor and associated systems. Alternatively, a reactor design can be proposed that places requirements on fuel performance. In support of G2.1, this goal is satisfied by specifying the environmental conditions (e.g., temperatures, pressures, power), exposure, and transient conditions that the fuel is expected to encounter under conditions of normal operation, including the effects of AOOs. Additionally, this goal supports G2.2 associated with the fuel contribution to source term during design basis accidents and is further discussed in Section 3.2.2.1. Accordingly, this goal is fully satisfied by specifying the environmental conditions the fuel is expected to encounter during normal operation, AOOs, and design basis accident conditions to which the fuel is subject. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.2.1.2 G2.1.2 Evaluation Model

An evaluation model is available to assess fuel performance against design limits to protect against fuel failure and degradation mechanisms requires the specification of the means by which fuel is evaluated for performance, failure, and degradation. Assessment of an evaluation model is an area of review that supports several goals and requires further decomposition into several supporting goals. Therefore, a separate assessment framework for evaluation models is provided in Section 3.4 of this report. G2.1.2 is satisfied by satisfying the supporting goals in the evaluation model assessment framework in Section 3.4 of this report for fuel performance during normal operation and AOOs.

3.2.2 G2.2 Radionuclide Release Limits

Radiological consequences under postulated accident conditions are an essential consideration regarding nuclear power plant licensing. Under postulated accident conditions some amount of fuel failure is possible and results in a contribution to the accident source term. As radionuclide inventory originates from the nuclear fuel, part of fuel qualification must involve characterizing the behaviour of the fuel under accident conditions such that the fuel contribution to accident source term can be determined in a suitably conservative manner. Accordingly, the ability to demonstrate margin to radionuclide release limits under accident conditions, as it relates to fuel qualification, is supported by three goals identified in Figure 3-5 that are related to characterizing the fuel contribution to accident source term. These three goals are discussed further below.

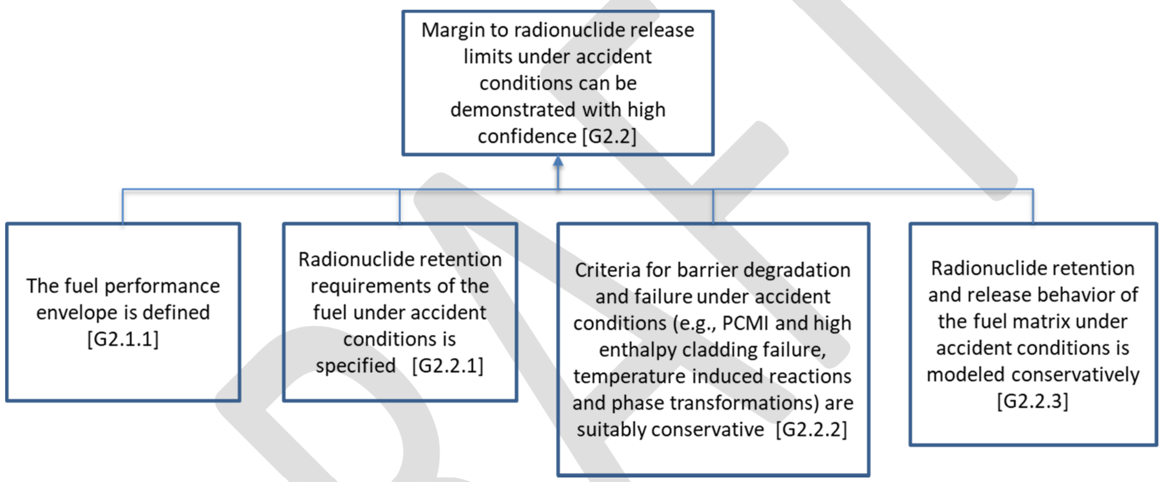

Figure 3-5. Decomposition of G2.2 – Margin to radionuclide release limits

3.2.2.1 G2.1.1 Definition of Fuel Performance Envelope

G2.1.1 is the same goal as was discussed in Section 3.2.1.1. In support of G2.2, this goal is satisfied by specifying the design basis accident conditions to which the fuel is subject. Design basis accident conditions are dependent on reactor design. However, as discussed in Section 3.2.1.1, the conditions to which the fuel is subject under design basis accidents may be specified independent of the reactor design resulting in constraints on the design of the reactor and associated systems. The types of design basis accident conditions that should be considered include transient overpower events (e.g., reactivity inducted accidents) and transient undercooling events (e.g. loss-of-coolant accident). This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.2.2.2 G2.2.1 Radionuclide Retention Requirements

The role that nuclear fuel plays in the safety case can vary between reactor designs and fuel types. For example, traditional light water reactor fuel that utilizes uranium dioxide pellets with zircalloy cladding is not expected to retain cladding integrity under large break loss-of-coolant accidents. Advanced reactor designs may propose to credit retention of radionuclides within the fuel under accident conditions. To satisfy this goal, the degree to which radionuclide retention within the fuel system should be specified. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.2.2.3 G2.2.2 Criteria for Barrier Degradation

Radionuclide barrier (e.g. fuel cladding) failure and degradation mechanisms under accident conditions need to be understood when retention of barrier integrity is credited (e.g., cladding integrity during reactivity induced accidents in light water reactors, fission product attack of SiC layer in TRISO fuel at high temperatures). This goal is decomposed into two supporting two goals in Figure 3-6.

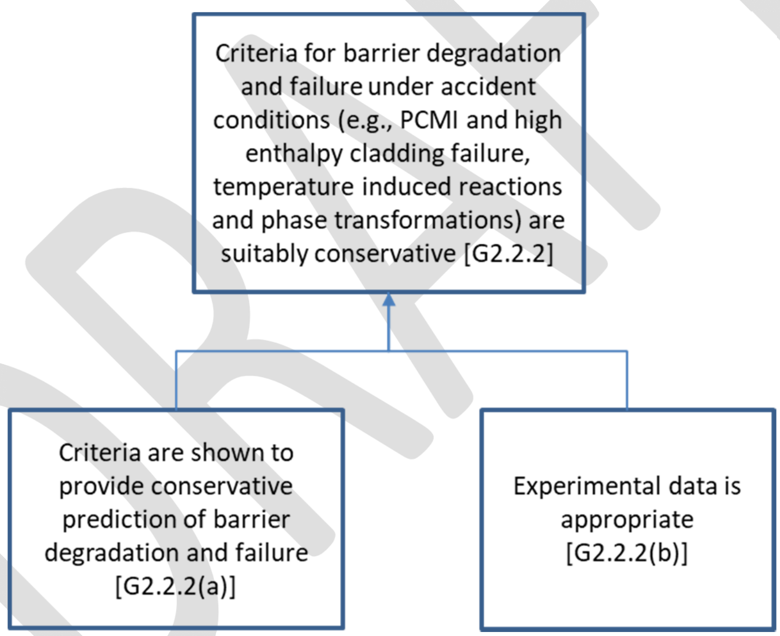

Figure 3-6. Decomposition of G2.2.2 – Criteria for barrier degradation

3.2.2.3.1 G2.2.2(a) Demonstration of Conservative Criteria

Criteria used to determine barrier degradation should be suitably conservative. These criteria are expected to be established based on transient testing and irradiated fuel samples which is further discussed under G2.2.2(b). Ideally, criteria would be established through a regression analysis using experimental data, and then validated by assessment against a separate and independent set of data (see Section 3.4.1, ED G1 for the discussion on data independence) in order to establish a statistical confidence level (e.g., 95/95). However, this ideal scenario may not be realized due to environmental, safety, and economic concerns associated with obtaining irradiated fuel samples and conducting transient testing in accordance with design basis accident conditions. Experience from transient overpower testing has shown that it may be acceptable to develop realistic criteria for barrier degradation using fewer data points [18]. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.2.2.3.2 G2.2.2(b) Experimental Data

This goal is satisfied through an evaluation against the assessment framework for experimental data provided in Section 3.4 of this report.

3.2.2.4 G2.2.3 Conservative Modeling of Radionuclide Retention and Release

Consistent with the radionuclide retention requirements specified as part of G2.2.1 and discussed in Section 3.2.2.2, radionuclide retention and release behavior of the fuel under accident conditions should be modeled conservatively. This goal is related to the barrier degradation criteria specified in G2.2.2 and discussed in Section 3.2.2.3, but is distinct in its focus on radionuclide retention within the fuel matrix.(e.g., UO_2 pellet or U-10Zr fuel ingot) or fuel particle (e.g., fuel compact for a TRISO based fuel). This goal is decomposed into two supporting goals in Figure 3-7.

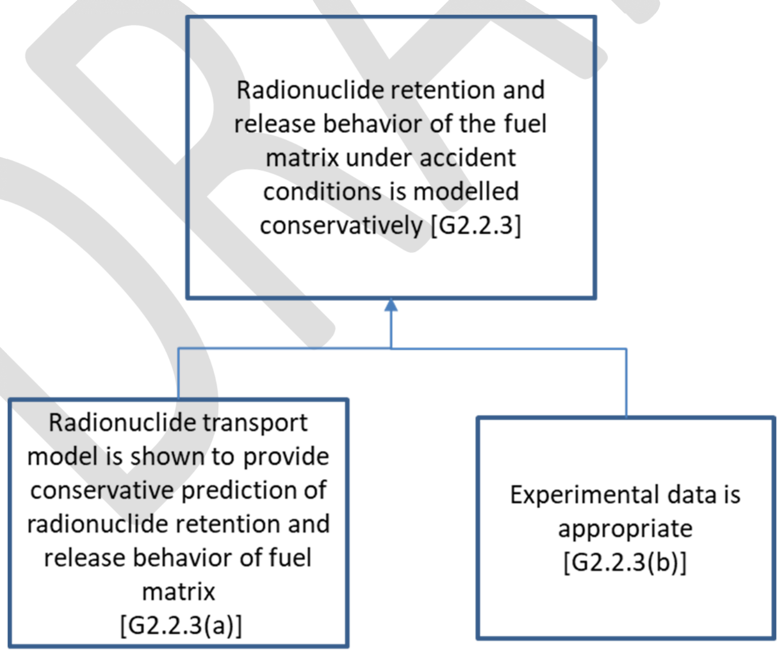

Figure 3-7. Decomposition of G2.2.3 – Radionuclide release modeling

3.2.2.4.1 G2.2.3(a) Demonstration of Conservative Transport Model

Radionuclide transport model from the fuel should be should to be conservative. Similar to the scenario discussed for barrier degradation criteria, discussed in Section 3.2.2.3.1, economic and environmental concerns may inhibit the ability to obtain significant amounts of data such that conservative or bounding estimates may be required. Additionally, experience with source term models for light water reactors have included some degree of expert judgement. A clarifying example of how a suitably conservative radionuclide transport model can be developed is available in regulatory guidance on accident source term [19]. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.2.2.4.2 G2.2.3(b) Experimental Data

This goal is satisfied through an evaluation against the assessment framework for experimental data provided in Section 3.4 of this report.

3.2.3 Safe Shutdown

Safe shutdown refers to a state of a nuclear plant where the reactor is subcritical, decay heat is being removed, and radionuclide inventory is contained. The ability to achieve a safe shutdown state under any scenario needs to be assured. In order to ensure that this safe shutdown state can be achieved, criteria need to be established to ensure that a coolable geometry is maintained under all scenarios and that fuel system damage is never so severe as to prevent control element (e.g., control rods) insertion when it is required. These supporting goals are captured in Figure 3-8 and discussed in the subsections below.

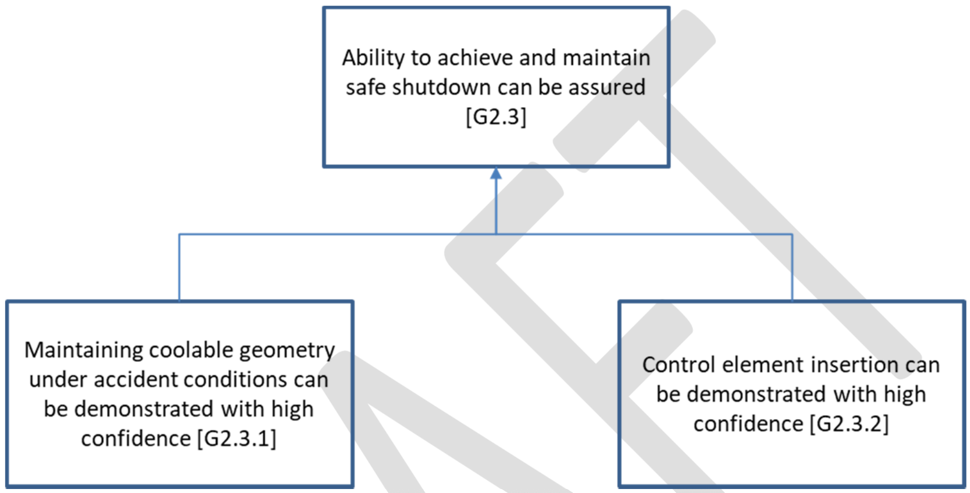

Figure 3-8. Decomposition of G2.3 – Safe shutdown

3.2.3.1 G2.3.1 Maintaining Coolable Geometry

Maintaining coolable geometry is identified as a supporting goal to achieving and maintaining a safe shutdown. Maintaining coolable geometry is further decomposed into supporting goals in Figure 3-9. These supporting goals are discussed in the subsections below.

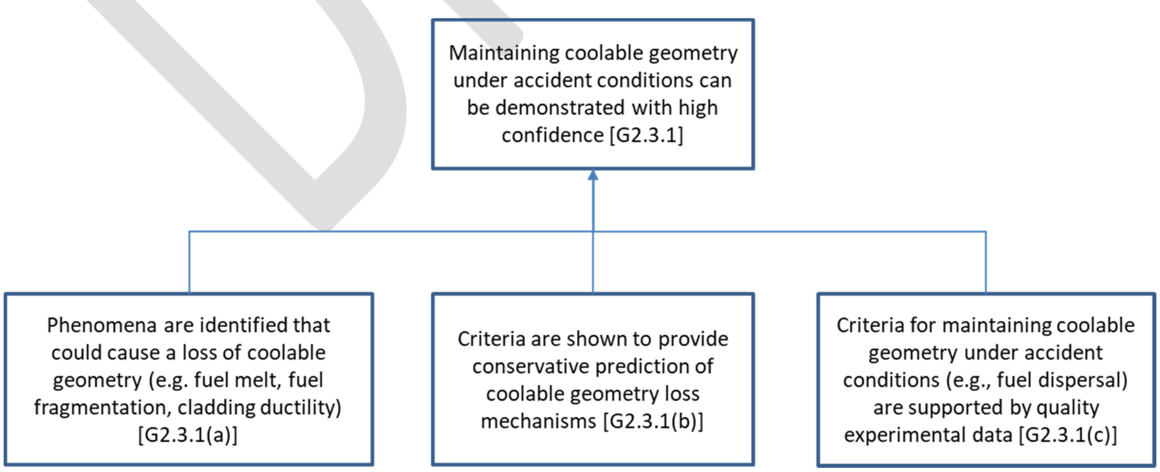

Figure 3-9. Decomposition of G2.3.1 – Coolable geometry

3.2.3.1.1 G2.3.1(a) Identification of Phenomena

Phenomena should be specified that could cause the loss of coolable geometry. Phenomena have historically been selected to ensure that core geometry is not significantly altered as a result of a design basis accident. Examples of phenomena that could cause the loss of coolable geometry include (1) centerline fuel melt and fuel fragmentation during transient overpower events, and (2) loss of cladding ductility or long-term cladding phase stability during loss-of-coolant accidents. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.2.3.1.2 G2.3.1(b) Conservative Criteria

Criteria used to ensure coolable geometry should be conservative. Evidence needed to satisfy this goal is dependent on the associated phenomena. For example, a conservatively chosen criteria such as the onset of fuel melting should not require integral testing, but an empirically based criterion such as energy deposition for fuel dispersal or peak cladding temperature for cladding embrittlement is expected to demonstrate appropriate margin against experimental data. Historical examples of acceptable empirical criteria include the criteria developed for transient overpower [18] and loss-of-coolant accidents [20]. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.2.3.1.3 G2.3.1(c) Experimental Data

This goal is satisfied through an evaluation against the assessment framework for experimental data provided in Section 3.4 of this report.

3.2.3.2 G2.3.2 Control Element Insertion

Control element insertion is identified as a supporting goal to achieving and maintain a safe shutdown. Control element insertion is further decomposed into supporting goals in Figure 3-10. These supporting goals are discussed in the subsections below.

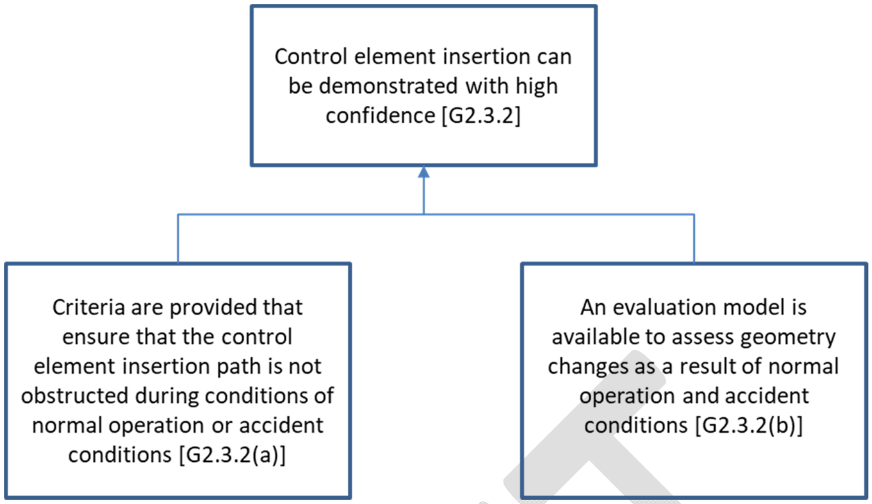

Figure 3-10. Decomposition of G2.3.2 – Control element insertion

3.2.3.2.1 G2.3.2(a) Identification of Criteria

Criteria should be specified to ensure that the control element insertion path is not obstructed during the conditions of normal operation or accident conditions. These criteria should consider loads from internal events and external events (e.g., seismic). An example of this criterion for traditional light water reactors is the stress limit imposed on the control rod guide tubes sufficient to inhibit distortion of the insertion path. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.2.3.2.2 G2.3.2(b) Evaluation Model

This goal is satisfied through an evaluation against the assessment framework for evaluation models provided in Section 3.3 of this report.

3.3 Assessment Framework for Evaluation Models (EM)

The term "evaluation model" here is used in the generic sense. Typically, an evaluation model is an analytical tool or computer code. However, use of a sophisticated tool, such as a computer code, may not be necessary. For example, a simple mathematical expression or set of data can be used as an evaluation model provided sufficient evidence exists to support its use. The assessment framework developed here is expected to be applicable generically.

The assessment framework developed here supports G2.1.2 and G2.3.2(b), which are associated with evaluating design limits under conditions of normal operation, including the effects of AOOs, and control rod insertion criteria, respectively. It is noted that there is conceptual overlap between the assessment framework for evaluation models presented here and the goals established to determine criteria for barrier degradation, radionuclide retention and release, and coolable geometry which are presented in Sections 3.2.2.3, 3.2.2.4, and 3.2.3.1.2, respectively. The goals to support criteria for barrier degradation, radionuclide retention and release, and coolable geometry are distinct in that they are associated with higher consequence events and have historically involved the development of empirical evaluation models based on destructive testing using irradiated nuclear fuel under accident conditions. Accordingly, goals presented in Sections 3.2.2.3, 3.2.2,4, and 3.2.3.1.2 were developed separate from the evaluation model assessment framework described here.

The top-level goal of an acceptable evaluation model is supported by the goals of (1) having adequate modelling capabilities, and (2) assessment against experimental data. This decomposition is shown in Figure 3-11 and discussed in the following subsections.

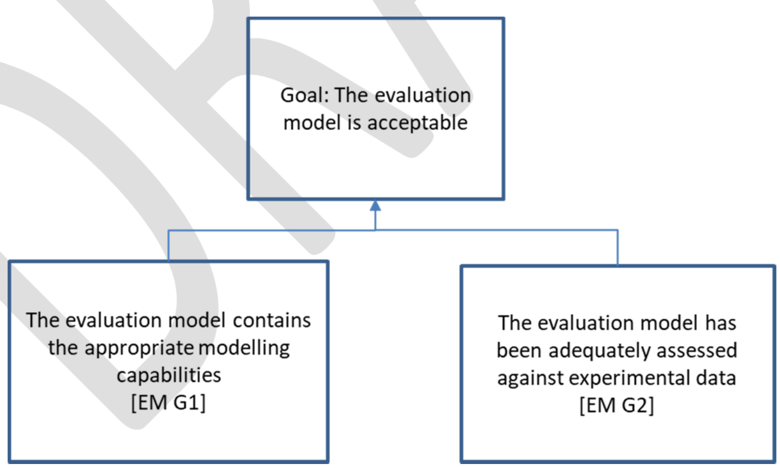

Figure 3-11. Decomposition of the main goal for evaluation model assessment

3.3.1 EM G1 Evaluation Model Capabilities

The evaluation model capabilities goal is decomposed into three supporting goals in Figure 3-12. This decomposition is informed by the Predictive Capability Maturity Model (PCCM) framework which identifies "Representation and Geometric Fidelity" and "Physics and Material Model Fidelity" as assessment elements [21]. Additional elements of PCCM framework are also considered in the evaluation model assessment framework. Specifically, "Model Validation" and "Uncertainty Quantification and Sensitivity Analysis" are addresses under the code assessment goal EM G2 and further discussed in Section 3.3.2. The remaining elements of the PCCM framework "Code Verification" and "Solution Verification" are expected to be addressed as part of a quality assurance program applicable to the design, analysis, and fabrication of a nuclear power facility. The goals supporting EM G1 are discussed in the following subsections.

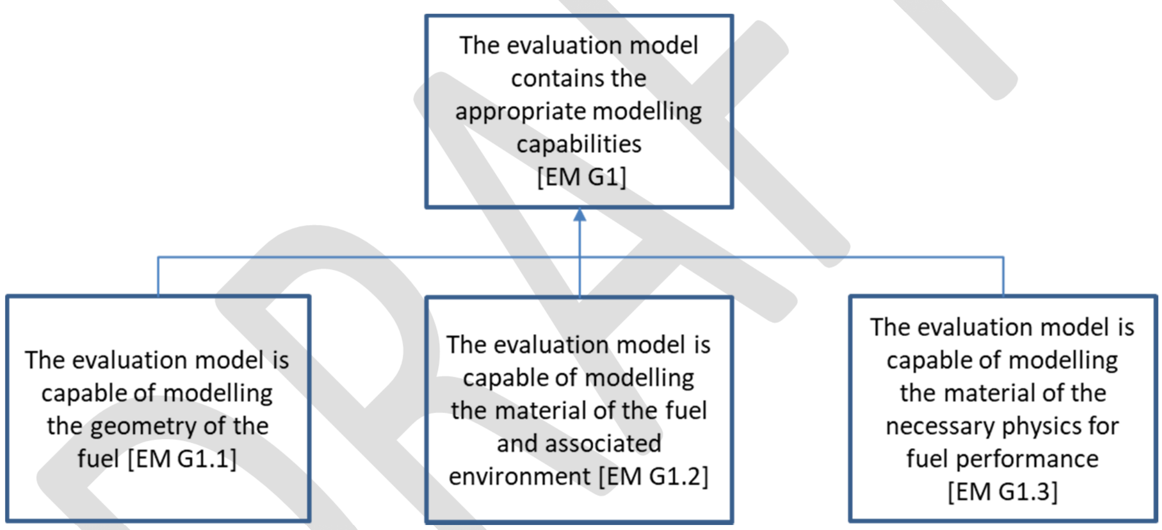

Figure 3-12. Decomposition of the EM G1 - Modelling Capabilities

3.3.1.1 EM G1.1 Geometry Modeling

The evaluation models should to be capable of modelling the geometry of the fuel system. Guidance of the levels of maturity to assess the geometry is provided in Table 3 of the PCCM, which includes the consideration of peer review [21]. It is recognized that some fuel designs may require simplifying assumptions to address geometric modelling difficulties. For example, TRISO based particulate fuel involves coupled phenomena occurring at different geometric scales (e.g., micro-scale within the TRISO particle, meso-scale within the fuel compact, and macro-scale within the reactor core). Geometric modelling for such particulate fuel is expected to involve simplifications and assumptions that may not be required for a fuel design with less heterogeneity. Additionally, the evaluation model should have the ability to capture geometric changes associated with irradiation and exposure to the in-reactor environment (e.g. fuel swelling, cladding creep, oxide layer growth). Irrespective of imposed simplifications, appropriate justification should be provided for the geometric modelling scheme, and validation of the integrated evaluation model is accomplished through the assessment process under EM G2. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.3.1.2 EM G1.2 Material Modeling

The evaluation model should be capable of modelling material properties of the fuel system and its surrounding environment. This also includes changes in material properties due to irradiation and exposure to the in-reactor environment (e.g., thermal-conductivity degradation in nuclear fuel, changes to melting temperature, eutectic formation, changes to Young's modulus). Guidance of the levels of maturity to assess the material modelling is provided in Table 3 of the PCCM, which includes considerations for model calibration against test data and peer review [21]. Justification should be provided for the material modelling scheme, and validation of the integrated evaluation model is accomplished through the assessment process under EM G2. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.3.1.3 EM G1.3 Physics Modeling

The evaluation model should be capable of modeling the physical processes that impact fuel performance. This goal requires knowledge of failure mechanisms, including changes due to irradiation and exposure to the in-reactor environment for the specified fuel, and fuel contribution to the SARRDL if applicable. The evaluation model is expected to have sufficient physics models to address known failure mechanisms type (e.g., cladding oxidation and hydrogen pickup, fuel rod internal pressure, cladding strain). Guidance on the levels of maturity to assess the physics modelling is provided in Table 3 of the PCCM, which includes considerations for model calibration against test data and peer review [21]. Justification should be provided for the physics models incorporated into the evaluation model, and validation of the integrated evaluation model is accomplished through the assessment process under EM G2. Means of justification include the use of an expert panel to develop a phenomena identification and ranking table (PIRT) [22], and internal review based on past experience and legacy data [23]. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.3.2 EM G2 Evaluation Model Assessment

Evaluation model assessment is an essential process that provides the confidence in the application of the evaluation model. To ensure that the evaluation model prediction is suitably conservative, any bias or uncertainty in the evaluation model prediction should be adequately quantified such that design and safety analyses can account for this uncertainty and bias. The assessment process in general involves comparing evaluation model predictions against experimental data. This process is illustrated in Figure 3-13 which decomposes evaluation model assessment into two supporting goals, which are discussed in the following subsections.

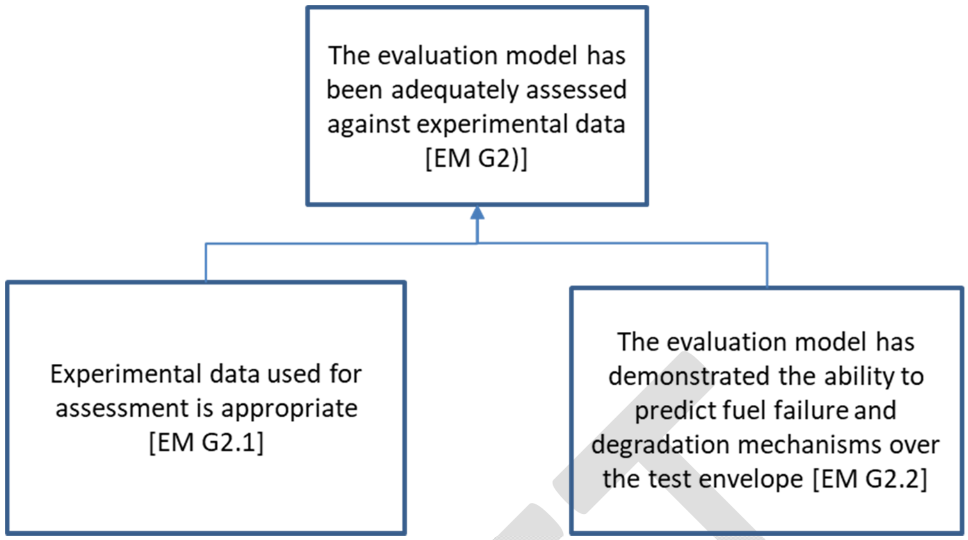

Figure 3-13. Decomposition of the EM G2 – Assessment against data

3.3.2.1 EM G2.1 Experimental Data

This goal is satisfied through an evaluation against the assessment framework for experimental data provided in Section 3.4 of this report.

3.3.2.2 EM G2.2 Demonstrated Prediction Ability over Test Envelope

Satisfying EM G2.2 involves comparing evaluation model predictions against experimental data. This comparison should establish evaluation model uncertainties and biases and identify limitations in the evaluation model applicability. EM G2.2 is satisfied by addressing the four supporting goals shown in Figure 3-14 and discussed in the subsections below.

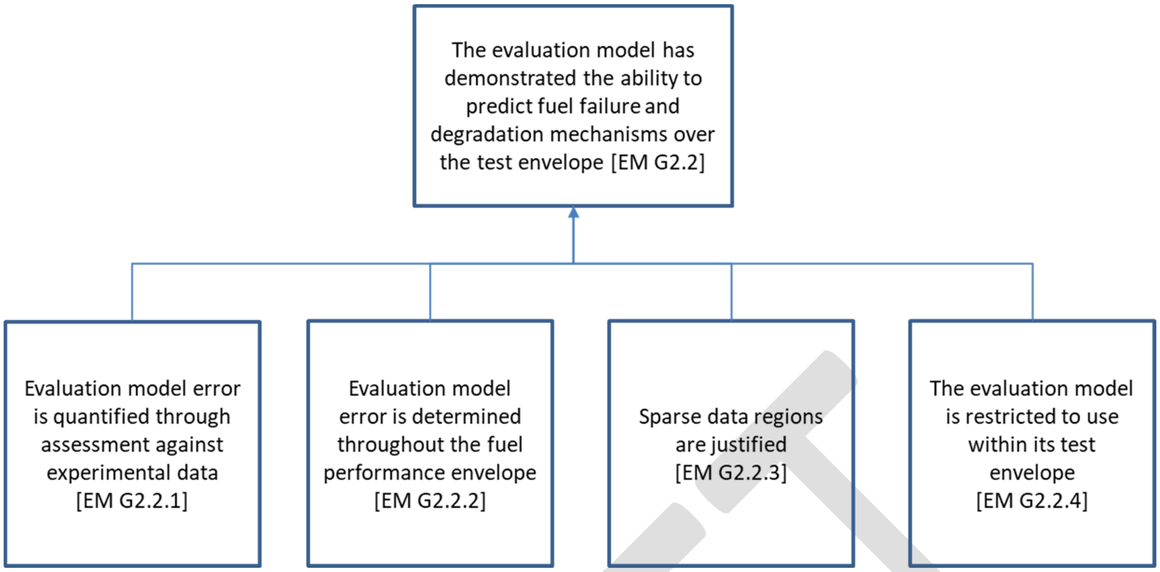

Figure 3-14. Decomposition of the EM G2.2 – Demonstrated ability

3.3.2.2.1 EM G2.2.1 Quantification of Error

Evaluation model uncertainties and biases for figures of merit need to be sufficiently understood in order to establish confidence in the evaluation model. It is expected that evaluation model predictions for assessment cases are compared against assessment data and the differences in measured-to-predicted values quantified in order to determine prediction biases and uncertainties. If sufficient data exists, then statistical confidence levels could be placed on the uncertainties of the evaluation model predictions. However, a more bounding or conservative approach can be taken (e.g., applying a bias or penalty to the model predictions, showing that evaluation model is inherently conservative). This goal is satisfied by a statement on the evaluation model biases and uncertainties along with justification through a quantification of predicted-to-measured values for assessment cases. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.3.2.2.2 EM G2.2.2 Span of Validation Data

Assessment data should to be distributed throughout the fuel performance envelope. The performance envelope, discussed in Sections 3.2.1.1 and 3.2.2.1, should be used to specify the test envelope. Accordingly, assessment data should be available to assess the evaluation model over the entire span of the performance envelope. However, it is recognized that regions of the fuel performance window may not require data. For example, post-irradiation examination of an integral test specimen may not be necessary for low burnup fuel. In such cases, it may be sufficient to provide justification that data in a specific region of the performance envelope is not required (e.g., limiting phenomena are known to not be present below a specified burnup). This goal is satisfied by demonstrating that assessment data is available over the entire performance envelope, and any gaps in assessment data are sufficiently justified. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.3.2.2.3 EM G2.2.3 Data Density

Assessment data should be appropriately distributed throughout the fuel performance envelope. As discussed in Section 3.3.2.2.2, it may be acceptable to have regions in the performance envelope where the evaluation model is not directly supported by assessment data from integral experiments. However, in regions where assessment data is needed to validate the evaluation model, a sufficient number of data points should be available to assess the evaluation model. It is reasonable to expect data density to be greater near conditions of normal operation as fuel designers may require additional data in order to satisfy fuel reliability targets. However, any sparse data regions (i.e., regions of low data density) in the fuel performance envelope need to be adequately justified. This goal is satisfied by justifying the data density throughout the fuel performance window. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.3.2.2.4 EM G2.2.4 Restricted Domain

Use of the evaluation model should be restricted to an application domain for which the model has been assessed. Application of an evaluation model outside of the supporting test envelope (see Section 3.4.2 of this report) may be justified based on physical arguments (e.g., the evaluation model provides a simplified or bounding treatment of physical phenomena). This goal is satisfied by specifying the application domain of the evaluation model as supported by the test envelope and/or additional physical arguments. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.4 Assessment Framework for Experimental Data (ED)

An assessment of experimental data is the biggest area of review for fuel qualification. The assessment framework developed here supports all goals requriing evaluatons against assessment data. Due to the several types of experiments that are expected as part of a fuel qualification program (e.g., steady-state irradiation of integral test specimens, transient ramp testing, design basis accident testing), transient test facility limitations, and the risks associated with irradiated fuel testing (environmental, safety, and economical) it is recognized that the level of evidenct expected to support a goal can vary betweent the types of data collected. This variance in the levels of evidence is discussed as applicable in the development of this assessment framework. The top goal for assessment data is decomposed in Figure 3-15 and discussed in the following subsections.

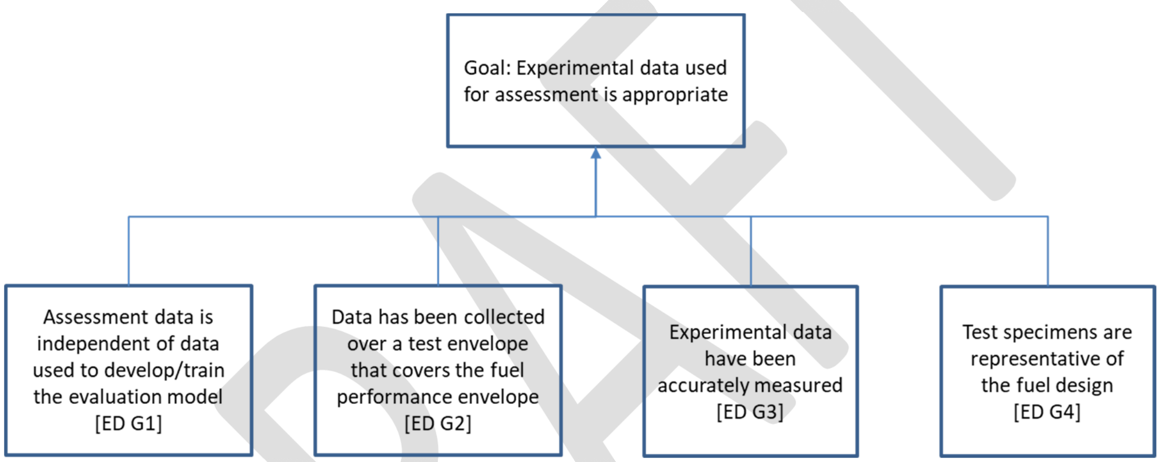

Figure 3-15. Decomposition of the main goal for data assessment

3.4.1 ED G1 Independence of Validation Data

Assessment data are the experimentally measured values that are used to quantify the evaluation model's error. Ideally, assessment data should be independent from any data used in the development (i.e, training) of the evaluation model. Although it may seem that use of the training data would be appropriate, the evaluation model has already been "tuned" to that data. Thus, quantifying the error of the training data would provide an estimate of "how well the model can predict data that were used in the generation of the model." This is different from "how well the model can predict data that were not used to generate the model." Because substantially more data points appear in the application domain (an infinite number) than were used to generate the model and because these points are the ones of most interest in future uses of the model, the focus should be on generating an estimate of the error over those points which were not used to generate the model. Thus, experimental data that have not been used to train the model should be held in reserve and used only to validate the model because the model's behavior using these data are indicative of the type of predictions that will be made in its future uses.

In some instances, the validation data and the training data are one and the same. There are methods in machine learning that can be applied to determine whether the selection of the training data affects the resulting uncertainty, such as random subsamples and k-folds. In each of these methods, the data are randomly separated into subsets of training and validation data. The training data are used to develop the coefficients of the model, and the validation data are used to determine the overall uncertainty of the model. Then, the process is repeated with a different randomly-selected data set assigned to training and the remaining data assigned to validation. Processes like these can provide reasonable estimates of the impact of using the same training data as validation data.

The discussion regarding data independence has so far considered scenarios where sufficient number of data points exist to train and validate a model using statistical approaches (i.e., model regression and calculating confidence intervals). It is also recognized that the collection of data involving irradiated fuel samples has environmental, safety, and economic risks that must be considered such that a limited number of data points may be available. Experience from transient overpower testing has shown that it may be acceptable to develop criteria using fewer data points [18].

This goal is satisfied by demonstrating that the data used in the evaluation model assessment is sufficiently independent. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.4.2 ED G2 Test Envelope

Data should be collected over a test envelope that spans the performance envelope (see Section 3.2.1.1 of this report). The performance envelope should address normal operation, AOOs, and postulated accident conditions. The types of tests that should be considered in the development of the test envelope include (1) steady-state integral testing of the fuel system in a prototypical environment, (2) high power and undercooling tests to address AOO conditions and to assess design margin, (3) power ramp testing to assess fuel performance during anticipated power changes, and (4) design basis accident tests to establish margin to fuel breach and contribution to source term under accident conditions. Design basis accident scenarios of typical interest include overpower events (e.g., reactivity insertion accidents) and undercooling events (e.g., loss-of-coolant accidents).

Many of the data necessary to qualify fuel for use involves the use of irradiated test specimens. However, a situation is often encountered where test specimens are not available at the desired burnups. To address such situations, it may be possible to propose the use of lead test specimens in order to extend the burnup limits of a fuel type. A lead test specimen program should include provisions to ensure safe operation of the fuel design during operation. Provisions such as ensuring that a limited number of lead test specimens are located in non-limiting regions of the reactor core to maximize safety margin and ensuring that sufficient monitoring is in place to detect potential failures should be considered if a lead test specimen program is being proposed. Additionally, the use of lead test specimens to extend burnup when existing data is not available should address the need for licensing commitments to ensure that the appropriate level of safety review is completed prior to extending burnup limits for the fuel design.

This goal is satisfied by demonstrating that the test envelope addresses the necessary performance envelope for the fuel design. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.4.3 ED G3 Data Measurement

An understanding of measurement accuracy is essential to establish overall confidence in the data used to develop and assess evaluation models. This goal is decomposed in Figure 3-16 and discussed in the subsections below.

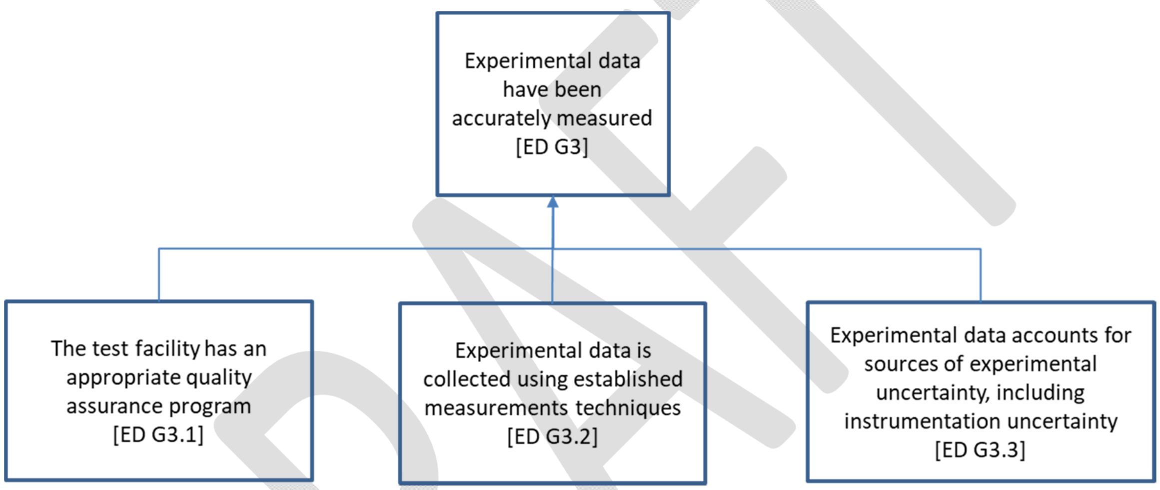

Figure 3-16. Decomposition of ED G3 – Data measurement

3.4.3.1 ED G3.1 Test Facility Quality Assurance

Experimental data should be collected under an appropriate quality assurance program. Standards are available to address quality assurance for test facilities such as the American Society of Mechanical Engineers (ASME) NQA-1. Additionally, provisions may be applied to existing data in order to make it compliant with quality assurance requirements [24]. This goal is satisfied by demonstrating that data collection was performed under an appropriate quality assurance program or providing an alternative justification for use of existing data. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.4.3.2 ED G3.2 Measurement Techniques

Data should be collected using established or otherwise proven measurement techniques. Use of novel and first-of-a-kind measurement techniques should provide adequate justification for its use. This goal is satisfied by specifying the measurement techniques and providing justification for the use of any novel or first-of-a-kind techniques. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.4.3.3 ED G3.3 Experimental Uncertainties

An error analysis of the experiment should be performed to assess sources of bias and uncertainty. Measurement uncertainty should be quantified when possible, and a discussion on the overall impact on assessment data should be provided. This goal is satisfied by providing an experimental error analysis. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.4.4 ED G4 Test Specimens

The test specimens used in the experiment should be representative of the proposed fuel design (i.e., the fuel design submitted for safety review). This goal is decomposed in Figure 3-17 and discussed in the subsections that follow.

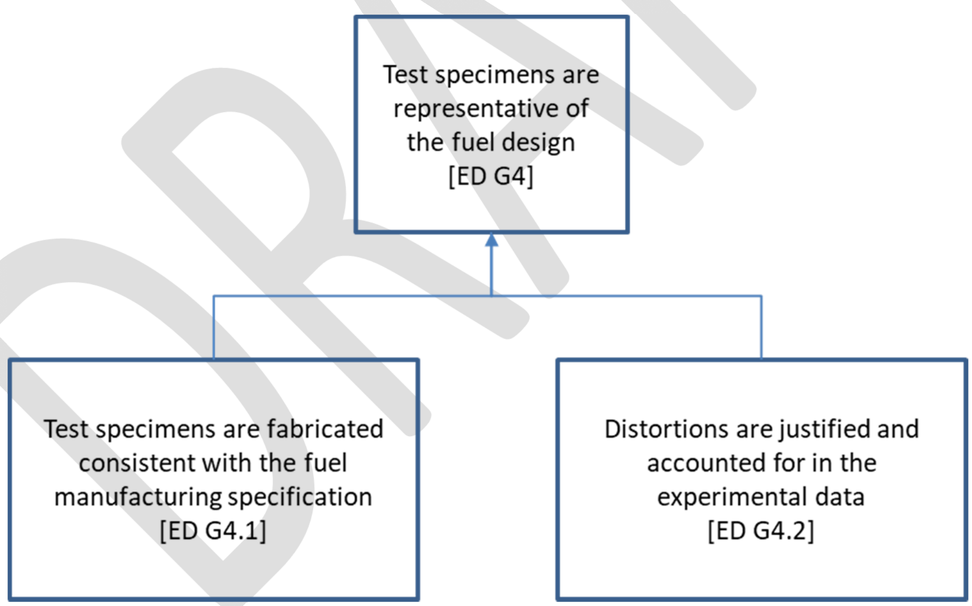

Figure 3-17. Decomposition of ED G4 – Test specimens

3.4.4.1 ED G4.1 Manufacturing of Test Specimens

Test specimens should be fabricated consistent with the manufacturing specification. This goal is associated closely with G1 Fuel Manufacturing Specification discussed in Section 3.1, which highlighted that fuel performance during normal operation and accident conditions can be highly sensitive to the fuel fabrication process. Alternatively, it may be possible to provide justification that differences in fuel fabrication between the fuel design and test specimens are acceptable. Such justifications are expected to be addressed on a case-by-case basis. This goal is satisfied by demonstrating that test specimens are fabricated consistent with the fuel manufacturing specification. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

3.4.4.2 ED G4.2 Evaluation of Test Distortions

An evaluation of test distortions should be conducted. Test distortions are in reference to differences between test specimen and proposed fuel design. These differences may be associated with fabrication techniques, dimension, composition, and environment. An example of a test distortion that is expected is the geometry distortion typically associated with transient testing in a test reactor as test reactors are typically too small to accommodate the full size fuel design. This goal is satisfied by an analysis of the test distortions and justification for any identified distortions. This goal is recognized as an objective criterion that can be directly supported by evidence and is not decomposed any further.

4. SUMMARY AND CONCLUSION

A systematic evaluation of the requirements for qualifying nuclear fuel has been performed and a list of criteria has been identified to support a determination that nuclear fuel is qualified for use. The evaluation and justification are provided in Section 3 of this report. The table in Appendix A provides a concise list of all the criteria.

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APPENDIX A LIST OF ALL GOALS

List of Goals in Fuel Qualification Assessment Framework

GOAL				Fuel is qualified for use
G1				Fuel is manufactured in accordance with a specification
	G1.1			Key dimensions and tolerance of fuel components are specified
	G1.2			Key constituents are specified with allowance for impurities
	G1.3			Microstructure attributes for materials within fuel component are specified for otherwise justified
G2				Margin to safety limits can be demonstrated with high confidence
	G2.1			Margin to design limits under conditions of normal operation and AOOs
		G2.1.1		Fuel performance envelope is defined
		G2.1.2		Evaluation model (go to EM Assessment Framework)
	G2.2			Margin to radionuclide release limits for accident conditions
		G2.1.1		Fuel performance envelope is defined
		G2.2.1		Radionuclide retention requirements are specified
		G2.2.2		Criteria for barrier degradation and failure
			(a)	Conservative criteria
			(b)	Experimental data is appropriate (go to ED Assessment Framework)
		G2.2.3		Radionuclide retention and release from fuel matrix
			(a)	Conservative model
			(b)	Experimental data is appropriate (go to ED Assessment Framework)
	G2.3			Maintain coolable geometry
		G2.3.1		Criteria specified for ensuring coolable geometry
			(a)	Criteria to ensure coolable geometry are specified
			(b)	Criteria are shown to provide conservative prediction of coolable geometry loss
			(c)	Criteria are supported by experimental data (go to ED Assessment Framework)
		G2.3.2		Control element insertion can be demonstrated with high confidence
			(a)	Criteria provided to ensure control element insertion path is not obstructed
			(b)	Evaluation model (go to EM Assessment Framework)

List of Goals in Evaluation Model Assessment Framework

GOAL	Evaluation model is acceptable for use		
EM G1	Evaluation model contains the appropriate modelling capabilities		
	EM G1.1	Geometry	
	EM G1.2	Materials	
	EM G1.3	Physics	
EM G2	Evaluation model has been adequately assessment against experimental data		
	EM G2.1	The data used for assessment is appropriate (go to ED Assessment Framework)	
	EM G2.2	The evaluation model has demonstrated the ability to predict fuel failure and degradation mechanism over the test envelope	
		EM G2.2.1	Evaluation model error is quantified through assessment against experimental data
		EM G2.2.2	Evaluation model error is determined through the fuel performance envelope
		EM G2.2.3	Sparse data regions are justified
		EM G2.2.4	Evaluation model is restricted to use within its test envelope

List of Goals in Experimental Data Assessment Framework

GOAL	Experimental data used for assessment is appropriate	
ED G1	Assessment data is independent of data used to develop/train the evaluation model	
ED G2	Data has been collected over a test envelope that covers the fuel performance envelope	
ED G3	Experimental data have been accurately measured	
	ED G3.1	The test facility has an appropriate quality assurance program
	ED G3.2	Experimental data is collected using established measurement techniques
	ED G3.3	Experimental data accounts for sources of experimental uncertainty
ED G4	Test specimens are representative of the fuel design	
	ED G4.1	Test specimens are fabricated consistent with the fuel manufacturing specification
	ED G4.2	Distortions are justified and accounted for in the experimental data