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GENERAL ATOMICS ELECTROMAGNETIC SYSTEMS (GA-EMS) – NRC FEEDBACK REGARDING GA-EMS WHITE PAPER: ENERGY MULTIPLIER MODULE (EM^2) ACCELERATED FUEL QUALIFICATION STRATEGY (EPID L-2021-LRO-0034)

SPONSOR INFORMATION

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Brief Description of the White Paper: The purpose of this white paper, entitled Energy Multiplier Module Accelerated Fuel Qualification Strategy (hereafter referred to as EM^2-AFQ), is to describe an accelerated fuel qualification (AFQ) strategy for reducing the time and cost for qualifying new nuclear fuel and materials as part of licensing advanced reactors. The white paper: (1) identifies the regulations that General Atomics Electromagnetic Systems (GA-EMS) identified as applicable to fuel qualification; (2) provides an overview of the EM^2 design; (3) describes the design bases for the EM^2 fuel system; (4) provides a preliminary assessment of the EM^2 fuel system; and (5) describes an approach to qualify the EM^2 fuel system that leverages information obtained from advanced modeling and simulation and modern test techniques. The submittal letter associated with the white paper requested three areas be placed in priority for feedback: (1) the use of an approach that places stronger emphasis on modeling and simulation validated through separate effects testing; (2) the use of accelerated fuel irradiation test techniques; and (3) the use of interim burnup limits to allow for licensed operation prior to obtaining data at the desired lifetime burnup for the fuel.

REGULATORY ASSESSMENT

1.1 Regulatory Basis

The NRC staff is making no regulatory findings on this white paper. This paper has not been subject to NRC management and legal reviews and approvals, and its contents are subject to change and should not be interpreted as official agency positions.

GA-EMS provides a regulatory basis for fuel qualification in Section 2, “Regulatory Bases” of EM^2-AFQ. The NRC staff compared the applicable regulations identified by GA-EMS in Section 2.1, “NRC Regulations” of EM^2-AFQ with the regulatory basis specified in NUREG-2246, “Fuel Qualification for Advanced Reactors: Draft Report for Comment” (Reference 1) and made the following observations:

- EM^2-AFQ does not identify the testing and data requirements associated with Title 10 of the *Code of Federal Regulations* (10 CFR), Section 50.43(e), as part of the regulatory basis for fuel qualification. An application for a design certification, combined license, manufacturing license, operating license. or standard design approval must meet the requirements of 10 CFR 50.43(e). Under 10 CFR 50.34(a)(4), applications for a construction permit need to demonstrate that (Reference 2):

    - The design will be able to provide sufficient margins of safety during normal operations and transient conditions.

    - The applicant has identified the structures, systems, and components necessary for the prevention of accidents and the mitigation of the consequences of accidents.

    - The applicant has demonstrated an understanding of the uncertainty associated with the performance of structures, systems, and components necessary for the prevention of accidents and the mitigation of the consequences of accidents.

    Additionally, 10 CFR 50.34(a)(4) is also supported by 10 CFR 50.35(a)(3), which requires that safety features or components which require research and development have been described and that a research and development program will be designed and conducted to resolve any safety questions associated with such features or components.

- EM^2-AFQ does not identify the requirement for the design to withstand the effects of natural phenomena as provided in General Design Criterion (GDC) 2 and Advanced Reactor Design Criterion[1] (ARDC) 2, “Design basis for protection against natural phenomena,” of Appendix A, “General Design Criteria for Nuclear Power Plants,” to 10 CFR Part 50, and Appendix S to 10 CFR Part 50, “Earthquake engineering criteria for nuclear power plants.” The safety functions

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[1] Regulatory Guide 1.232, “Guidance for Developing Principal Design Criteria for Non-Light-Water Reactors,” (Reference 4) provides guidance on how the GDC in Appendix A to 10 CFR Part 50 may be adapted for non-LWR designs.

generally associated with nuclear fuel include control of reactivity, cooling of radioactive material, and confinement of radioactive material. Accordingly, the NRC staff expects that nuclear fuel qualification will demonstrate the ability of the design to withstand the effects of natural phenomena.

- EM^2-AFQ does not identify the requirement to achieve and maintain a safe, stable state under postulated accident conditions to provide assurance that the capability to cool the core is maintained as provided by GDC 27 and ARDC 26, “Combined reactivity control systems capability.” The NRC staff expects that fuel qualification would identify criteria for the fuel that would provide assurance that a coolable geometry is maintained under postulated accident conditions.

- EM^2-AFQ does not identify the requirement to evaluate against a postulated fission product release provided in 10 CFR 50.34(a)(1)(ii)(D), 10 CFR 52.47(a)(2)(iv), and 10 CFR 52.79(a)(1)(vi). As radionuclide inventory originates from the nuclear fuel, the NRC staff expects that fuel qualification would include characterizing the behavior of the fuel under accident conditions, consistent with its role in the protection against the release of radioactivity, so that its contribution to accident source term can be determined in a suitably conservative manner.

- EM^2-AFQ includes requirements for an emergency core cooling system, as given by GDC 35, “Emergency core cooling,” 10 CFR 50.46, and Appendix K to 10 CFR 50 in the regulatory basis. The NRC staff identified 10 CFR 50.46 and Appendix K to 10 CFR 50 as not applicable to non-light water reactors (Reference 3).

- EM^2-AFQ requires that the reactor core and associated coolant, control, and protection systems, be designed with the appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any conditions of normal operation, including the effects of anticipated operational occurrences (AOOs) as given by GDC 10 and ARDC 10, “Reactor design,” and appears to be consistent with NRC guidance.

- EM^2-AFQ identifies GDC 12, “Suppression of reactor power oscillations,” GDC 17, “Electric power systems,” GDC 20, “Protection system functions,” GDC 25, “Protection system requirements for reactivity control malfunctions,” GDC 26, “Reactivity control system redundancy and capability,” GDC 33, “Reactor coolant makeup,” and GDC 34, “Residual heat removal,” as being relevant to fuel qualification. The NRC staff recognizes the connection of these requirements to the fuel qualification through the identification of fuel design limits, but the NRC staff has not associated these specific requirements with the fuel qualification in the NRC guidance.

1.2 Application of NUREG-0800 to Advanced Reactors

Section 2.2.1, “Standard Review Plan,” of EM^2-AFQ, includes a comparison of the EM^2 fuel system against the acceptance criteria identified in Section 4.2, “Fuel System Design,” of NUREG-0800 (Reference 5). Section 2.2.1, “NUREG-0800, Section 4.2” of NUREG-2246 discusses the use of the standard review plan for advanced reactor designs and states:

[…] NUREG-0800, Section 4.2, evaluates fuel system designs for known fuel failure mechanisms from traditional LWR fuel (i.e., uranium dioxide (UO_2) 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. As such, the specific acceptance criteria provided in NUREG-0800, Section 4.2, may not apply or may not suffice to address advanced reactor technologies that use different fuel forms, or address situations in which the fuel plays different roles in the protection against the release of radionuclides. […]

The NRC staff did not identify information in EM^2-AFQ that would support a determination that the items identified in Section 2.2.1 of EM^2-AFQ, represent a sufficiently complete description of the degradation mechanisms and failure modes for the EM^2 fuel system. Such information would be sought during a detailed technical review to support findings associated with the physical modeling capabilities of the evaluation model(s) (i.e., the NRC staff expects that evaluation models contain adequate physics modeling capabilities to address known fuel degradation mechanisms and failure modes).

1.3 Adaption of Non-LWR Design Criteria to EM^2

EM^2-AFQ discusses the application and some modification of design criteria to the EM^2 design in Section 2.3, "GA Position on Adaption of Non-LWR Criteria to EM^2," as follows:

- EM^2-AFQ states that GDC 35, "Emergency core cooling," is not applied to the EM^2 design because maintaining helium coolant inventory is not necessary to maintain acceptable core cooling under accident conditions and that heat removal during postulated accidents is accomplished by a passive heat removal system (see EM^2-DC 34 below). This statement appears to be consistent with the guidance provided in RG 1.232, "Guidance for Developing Principal Design Criteria for Non-Light Water Reactors," (Reference 4) regarding modular high temperature gas-cooled reactor (MHTGR) Design Criterion (DC) 35.

- EM^2-AFQ proposes design criterion EM^2-DC 10, "Reactor design," for use in the EM^2 design that is based on GDC/ARDC 10 but replaces the term "coolant system" with "heat removal system." The NRC staff has no objections to the proposed modification.

- EM^2-AFQ proposes design criterion EM^2-DC 34, "Passive residual heat removal," for use in EM^2. The NRC staff compared EM^2-DC 34 to MHTGR-DC 34 of RG 1.232 and noted the following differences:

    - EM^2-DC 34 maintains use of the term "specified acceptable fuel design limits" (SAFDLs) from GDC 34 where MHTGR-DC 34 replaced this term with "specified acceptable system radionuclide release design limit," (SARRDL). The NRC staff does not object to this modification but notes that the EM^2 design appears to have structures beyond the fuel that may contribute to dose during conditions of normal operation, including the effects of AOOs (similar to MHTGRs for which the SARRDL concept was proposed). The NRC staff would consider the contribution to dose from these structures during a detailed technical review of the EM^2.

- o EM^2-DC 34 does not address the considerations for suitable redundancy in components and features and suitable interconnections, leak detection, and isolation capabilities to ensure that the systems' safety functions can be accomplished, assuming a single failure.

TECHNICAL ASSESSMENT

The NRC staff's observations are developed by comparing EM^2-AFQ against the fuel qualification assessment framework outlined in NUREG-2246, and are provided below in Section, 2.1, "Comparison Against NUREG-2246." Some design features described in EM^2-AFQ, involve new or novel approaches that may require additional consideration in a licensing review. These features are highlighted in Section 2.2, "Novel features of the EM^2 Fuel System." Additionally, GA-EMS requested feedback is provided in Section 2.3, "GA-EMS Requested Feedback".

2.1 Comparison Against NUREG-2246

The NRC staff released NUREG-2246, "Fuel Qualification for Advanced Reactors: Draft Report for Comment," (Reference 1) which provides a framework to support the regulatory findings associated with advanced reactor nuclear fuel qualification. NUREG-2246 is currently published as a draft for comment, and is based upon the NRC staff's experience of performing fuel design reviews. Additionally, NUREG-2246 considers the use of AFQ techniques and lead test specimen programs that may shorten the timeline for qualifying fuel for use in a nuclear reactor at the desired parameters (e.g., burnup). The following sections (Section 2.1.1 through Section 2.1.4), compare the information in EM^2-AFQ, against the framework provided in NUREG-2246.

2.1.1 G1 – Fuel Manufacturing Specification

Section 3.2, "EM^2 Fuel System," of EM^2-AFQ provides summary information describing pellet and cladding dimensions for the EM^2 fuel system and fabrication processes. The NRC staff observed few details in EM^2-AFQ, regarding tolerances for the key dimensions, identification of key constituents with allowance for impurities, and information necessary to capture the desired end-state (e.g., microstructure) for the materials used in the fuel system. As described in NUREG-2246:

> *[…] Staff recognizes that manufacturing processes for a nuclear fuel product may evolve over the product life cycle; therefore, a complete manufacturing specification is not expected as part of the licensing documentation. However, the licensing documentation should include sufficient information to ensure the control of key parameters affecting fuel performance during the manufacturing process. […]*

2.1.2 G2 – Safety Criteria

2.1.2.1 G2.1 – Design limits during normal operation and anticipated operational occurrences

G2.1.1 - Fuel performance envelop is defined. Table 4, “EM^2 core characteristics,” of EM^2-AFQ, provides some information describing the conditions under which the EM^2 fuel system needs to perform (e.g., nominal primary system parameters and maximum exposure). Additionally, Section 6.3, “Accident Conditions,” provides representative accident conditions for the EM^2 of uncontrolled control rod (CR) withdrawal, loss-of-flow accident (LOFA), and loss-of-coolant accident (LOCA). The information contained within EM^2-AFQ, aids the NRC’s understanding of the types of conditions that the fuel is expected to encounter. However, the NRC staff would need additional information, during a detailed technical review, regarding the conditions that the EM^2 fuel design is expected to encounter during normal operation, AOOs, and design-basis accidents.

G2.1.2 - Evaluation model. Section 4, “Fuel Design Basis and Criteria,” of EM^2-AFQ, discusses some of the fuel damage and fuel failure criteria from NUREG-0800 that GA-EMS identified as being applicable to the EM^2 fuel system[2] in Section 2.2.1. As discussed above in Section 1.2, “Application of NUREG-0800 to Advanced Reactors,” the NRC staff did not identify information in EM^2-AFQ to justify that the items listed in Section 2.2 of EM^2-AFQ, represent a sufficiently complete description of the degradation and failure mechanisms for the EM^2 fuel system. Additionally, Section 2.2 of EM^2-AFQ clarifies that the final criteria for the applicable damage and failure mechanisms are still being established.

Section 5, “Analysis Method and Material Properties,” of EM^2-AFQ, discusses the use of FRAPCON-4.0GA and FRAPTRAN-2.0GA. Section 8.2.3 of EM^2-AFQ, “Phase 2 Targeted Experiments: MiniFuel Irradiation tests,” discusses some preliminary analyses performed with BISON. The NRC staff’s assessments of these methods are provided below in Section 2.1.3, “Evaluation Models.” In Section 2.1.3, the NRC staff clarifies the type of information that it would need to determine that the analysis methods are capable of demonstrating margin to design limits under normal operation and the effects of AOOs.

2.1.2.2 G2.2 – Margin to radionuclide release limits under accident conditions can be demonstrated

The NRC staff did not identify information in EM^2-AFQ, that could address G2.2, “Margin to radionuclide release limits under accident conditions can be demonstrated,” from NUREG-2246, Figure 3-3, “Decomposition of G2, ‘Safety Criteria.’” However, Section 3, “Description of EM^2 System,” of EM^2-AFQ includes a brief description of a fission product capture system which is discussed below in Section 2.2, “Novel Features of EM^2 fuel system.” It is unclear to the NRC staff whether the AFQ strategy discussed in EM^2-AFQ would be applied to inform accident source term for the EM^2 design.

[2] Fuel damage and failure mechanisms of fretting wear, corrosion, hydraulic loading, excessive fuel enthalpy, pellet/clad interaction, clad burst, and mechanical fracturing are identified in Section 2.2 of EM^2-AFQ as being applicable or partially applicable to the EM^2 fuel system but are not discussed in Section 4.

2.1.2.3 G2.3 – Ability to achieve and maintain safe shutdown can be assured

NUREG-2246 identifies the components of achieving a safe shutdown as maintaining coolable geometry and ensuring that reactivity control elements can be inserted. These items are addressed in the subsections below.

Fuel coolability. Section 2.2.1.3, "Fuel coolability," of EM^2-AFQ compares the EM^2 fuel system against the criteria in NUREG-0800, Section 4.2 for fuel coolability and identifies several of the criteria as not applicable. As discussed in Section 1.2, "Application of NUREG-0800 to advanced reactors," the specific acceptance criteria provided in NUREG-0800 may not apply or may not suffice to address advanced reactor technologies. During a detailed technical review, the NRC staff would need to verify the appropriate identification of the phenomena that could lead to a loss of coolable geometry and that evaluation models are available to assess margin to a loss of coolable geometry.

Section 7, "Legacy Approach to Fuel Qualification," of EM^2-AFQ, discusses the design-basis and beyond-design-basis accident testing typically done to establish margin to fuel failure. Section 8.3, "Overall EM^2 Qualification Plan," of EM^2-AFQ, clarifies that transient tests are performed on irradiated fuel for reactivity-initiated accidents and LOCA conditions to measure fuel rod deformation, fission gas release, and fuel failure. The safety tests described in EM^2-AFQ, appear to be consistent with the type of tests that should be considered in a test envelope as described in Section 3.4.2, "ED G2-Test Envelope," of NUREG-2246. Additionally, Figure 32 of EM^2-AFQ shows that component irradiation and transient testing are addressed during Phase 2 of the AFQ strategy. Based on the inclusion of transient safety tests, the completion of component irradiation and transient tests, and the emphasis on modeling, the NRC staff determined that the fuel qualification strategy in EM^2-AFQ, appears to provide a reasonable approach for identifying phenomena that could lead to a loss of coolable geometry and informing the development of evaluation models to assess margin to a loss of coolable geometry. However, the irradiated specimens used for transient testing, appear to be obtained using accelerated fuel irradiation techniques. As discussed below in Section 2.3, "GA-EMS Requested Feedback," the NRC staff has not observed sufficient information to justify the use of test data obtained from accelerated irradiation testing for assessing evaluation models.

Control element insertion. The NRC staff did not identify information in EM^2-AFQ that could address G2.3.2, "Control element insertion can be demonstrated," from NUREG-2246. However, the NRC staff recognizes that the evaluation of material properties, performed as part of Phase 2 in the AFQ strategy, may inform evaluation models used to assess the fuel response under loads resulting from internal and external events.

2.1.3 Evaluation Models

2.1.3.1 FRAPCON-4.0GA and FRAPTRAN-2.0GA

Section 5.1, "Thermal-Mechanical Analysis Methods," of EM^2-AFQ, states that FRAPCON-4.0GA and FRAPTRAN-2.0GA are developed from FRAPCON-4.0 and FRAPTRAN-2.0 and include the addition of materials used in the EM^2 fuel system. The capabilities and assessment of these codes are addressed in Sections, "EM G1 – Evaluation model capabilities," and "EM G2 – Evaluation model assessment," below.

EM G1 - Evaluation model capabilities

EM G1.1 – Geometric modeling. The geometric modeling schemes in FRAPCON-4.0GA and FRAPTRAN-2.0GA, appear capable of modeling the geometry of a fuel rod used in the EM^2 fuel system (which uses a central hole in the fuel pellet) based on the code descriptions provided in PNNL-19418 (Reference 6) and PNNL-19400 (Reference 7) as well as the information in Section 5.1 of EM^2-AFQ describing that FRAPCON-4.0GA and FRAPTRAN-2.0GA are developed from FRAPCON-4.0 and FRAPTRAN-2.0.

EM G1.2 – Material modeling. FRAPCON-4.0GA and FRAPTRAN-2.0GA appear to have some capability to model the materials used for the fuel rods in the EM^2 fuel system based on the incorporation of peer reviewed material property models as described in Section 5.2, "Material Properties," of EM^2-AFQ. However, EM^2-AFQ does not address the validation of these models as an integrated system and some material property models discussed in Section 5.2 of EM^2-AFQ, appear to require further development.

The need for further material property model development is highlighted in Table 9, "Gap assessment in uranium carbide fuel properties and models," and Table 10, "Gap assessment in silicon carbide composite cladding properties and models," of EM^2-AFQ which identify material properties and models of high uncertainty and high importance. The approach to identify these development needs, appears to be reasonable. However, the NRC staff did not identify information in EM^2-AFQ, describing the process used to identify and rank the properties. The NRC staff would seek such information during a detailed technical review.

While a detailed technical review of a requested licensing action (e.g., a combined operating license application) is expected to focus on the integrated code assessment (as opposed to individual material property models), justification for the material property models is expected. The approach for evaluating material properties, as discussed in Section 8.2 and shown in Figure 32 of EM^2-AFQ, appears to be capable of providing justification for the material property models.

EM G1.3 – Physics modeling. Section 5.1, "Thermal-Mechanical Analysis Methods," of EM^2-AFQ, discusses potential deficiencies in the physical models, currently present in FRAPCON-4.0, for the analysis of fuel outside of its validation basis. Additionally, the NRC staff did not identify information in EM^2-AFQ that could address EM G1.3, "The evaluation model contains the necessary physics," from NUREG-2246, Figure 3-12, "Decomposition of EM G1, 'Evaluation of Model Capabilities,'" for FRAPCON-4.0GA and FRAPTRAN-2.0GA. Specifically, the physics modeling capabilities are necessary to capture fuel degradation mechanisms and failure modes applicable to the EM^2 fuel system. However, Section 8.2.3, "Phase 2 Targeted Experiments: MiniFuel Irradiation Tests," and Section 8.2.4, "Models and Tests for Fuel Form (pellet) Design and Analysis: Fission Accelerated Steady-State Testing (FAST)," of EM^2-AFQ, discuss testing techniques which the NRC staff have recognized in Section 3.3.1.3, "EM G1.3 – Physics Modeling," of NUREG-2246 as potentially acceptable means of identifying fuel degradation and failure mechanisms.

EM G2 - Evaluation model assessment

The NRC staff did not identify information in EM^2-AFQ that shows that the model has been adequately assessed against experimental data and addresses EM G2, "Evaluation Model Assessment," of NUREG-2246. Specifically, information that could support determinations that:

(1) experimental data is available to assess FRAPCON-4.0GA and FRAPTRAN-2.0GA applicability to the EM^2 fuel system; and (2) that FRAPCON-4.0GA and FRAPTRAN-2.0GA have demonstrated the ability to predict fuel failure and degradation over a test envelope applicable to the EM^2 design. However, Section 8.2.5, “Phase 3: Integral Fuel Testing,” of EM^2-AFQ, clarifies that integral fuel tests are incorporated into the EM^2 AFQ strategy. The NRC staff’s assessment of integral fuel testing is provided below in Section 2.1.4, “Experimental Data.”

2.1.3.2 BISON

The NRC staff did not identify information in EM^2-AFQ addressing the modeling capabilities or assessment of BISON. If BISON were used to support a detailed technical review for the EM^2, the NRC staff would need to determine if BISON has adequate modeling capabilities (geometric, material, and physics models) and has been adequately assessed against experimental data applicable to the EM^2 fuel system.

2.1.4 Experimental Data

Section 8.2.5, “Phase 3: Integral Fuel Testing,” of EM^2-AFQ discusses the use of integral fuel testing to qualify fuel. The incorporation of integral test data into the AFQ strategy described in EM^2-AFQ, is consistent with considerations for experimental data highlighted in Section 2.3, “Accelerated Fuel Qualification,” of NUREG-2246. During a detailed technical review, the NRC staff would be reviewing if the integral test data: (1) are independent of the data used to develop/train evaluation models; (2) was collected over a test envelope that covers the fuel performance envelope; (3) was accurately measured; and (4) was obtained from tests that are representative of prototypical conditions.

Table 8, “AFQ Phases,” and Section 8.3, “Overall EM^2 Qualification Plan,” of EM^2-AFQ mention some of the integral testing that would be performed as part of the AFQ strategy, but the NRC staff identified few specifics regarding transient testing within EM^2-AFQ. The NRC staff’s considerations for a test envelope are described in Section 3.4.2, “ED G2-Test Envelope,” of NUREG-2246, which states:

> *Data should be collected over a test envelope that spans the performance envelope (see section 3.2.1.1). The performance envelope should address normal operation, AOOs, and postulated accident conditions. The development of the test envelope should consider (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 margins, (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 the source term under accident conditions. Typical design-basis accident scenarios of interest include overpower events (e.g., reactivity-initiated accidents) and undercooling events (e.g., loss-of-coolant accidents).*

2.2 Novel Features of EM^2 Fuel System

The EM^2 fuel system appears to include safety features that need to be demonstrated through either analysis, appropriate test programs, experience, or combination thereof in accordance with 10 CFR 50.43(e). Some aspects of the EM^2 fuel system beyond fuel rods themselves are discussed below.

Section 3.2, "EM^2 Fuel System," of EM^2-AFQ, states that the EM^2 core utilizes the convert-and-burn concept in order to achieve high fuel utilization. The NRC staff expects that the convert-and-burn process may impact fuel properties and performance, and the NRC staff did not identify information that supports the applicability of the evaluation models to a convert-and-burn reactor design. The NRC staff would need this justification during a detailed technical review of the EM^2 fuel system.

Section 3.3, "EM^2 Safety Features," of EM^2-AFQ, discusses a fission product capture system that removes fission gas from the fuel and locates it to a high temperature absorber outside of the reactor vessel. The NRC staff notes that this system impacts the role of the fuel in the protection against the release of radioactivity and appears to have source term implications. This system also appears to impact the fuel qualification process by modifying the fuel performance envelope (i.e., modifying the environment under which the fuel will perform). However, the NRC staff does not see this system as an obstacle to fuel qualification but recognizes that such systems may be necessary to address performance envelope needs for the fuel and would expect such conditions (e.g., fuel venting) to be addressed during a detailed technical review.

2.3 GA-EMS Requested Feedback

2.3.1 Stronger Emphasis on Modeling and Simulation

GA-EMS requested concurrence, or further guidance on implementation of a science-based approach that includes the use of fuel performance models and separate effects testing to validate predictive capabilities. The development and use of validated physics-based models (as opposed to empirical models) has the potential to increase understanding of relevant physical phenomena that impact fuel performance such that relaxation in some areas may be justified. This is acknowledged in Section 2.3, "Accelerated Fuel Qualification," of NUREG-2246, where the NRC staff states:

> *[…] validated physics-based models may support some extrapolation of evaluation models beyond the limits of available integral test data, as noted under EM G.2.2.4, "Restricted Domain," in Section 3.3.2.2.4. Ultimately, the AFQ process relies on integral irradiation test data 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 appear to be consistent with the considerations in the experimental data assessment framework discussed in Section 3.4.*

The AFQ strategy discussed in EM^2-AFQ appears to be consistent with the AFQ framework considered by NUREG-2246. Specifically, EM^2-AFQ retains the need for engineering-scale integral testing in the fuel qualification strategy. Additionally, the NRC staff recognized, in Section 3.3.1.3, "EM G1.3 – Physics Modeling," of NUREG-2246 that the use of separate effects testing (that are performed as part of the AFQ strategy) may be a means to justify the adequacy of physics modeling in a fuel performance evaluation model. However, the NRC staff did not identify information in EM^2-AFQ that clearly describes the evaluation model assessment process, including acceptance criteria.

Section 3.2.2, "EM G2-Evaluation Model Assessment," of NUREG-2246 provides criteria associated with the assessment of evaluation models that inform the range and number of tests needed to adequately assess an evaluation model. These criteria address: (1) the quantification of error in an evaluation model through a comparison against experimental data, (2) the span of validation data, (3) the justification of sparse data regions, and (4) restrictions on the use of an evaluation model within and outside its test envelope. Additionally, Section 3.4, "Assessment Framework for Experimental Data," of NUREG-2246 includes criteria related to the assessment of experimental data.

The challenges associated with obtaining irradiated fuel samples are recognized several times in NUREG-2246. One potential challenge of using irradiated fuel samples is collecting sufficient data to establish confidence intervals for evaluation model uncertainty. In scenarios where sufficient data is not collected, a more bounding or conservative approach can also be taken (e.g., showing that the model is inherently conservative or applying a bias or penalty to the model prediction). The NRC staff cannot provide generic criteria to address cases where objective statistical analysis is not possible due to data limitations. Data limitations and the impact on the criteria for adequate margin should be addressed on a case-by-case basis.

2.3.2 Accelerated Fuel Irradiation Test Techniques

GA-EMS requested input on the NRC staff's view of incorporating accelerated fuel irradiations as part of the science-based modeling. The NRC staff has considered the use of FAST and MiniFuel in the development of NUREG-2246, and recognizes that these testing techniques are capable of providing insight into the physics modeling needs for evaluation models. In a detailed technical review, the NRC staff would review the experimental data, used to assess evaluation models, to determine that the tests are representative of prototypical conditions. As discussed in Section 3.4.4, "ED G4 Test Conditions," of NUREG-2246, the NRC staff would review to verify that the test specimens are fabricated consistently with fuel manufacturing specifications and that test distortions (e.g., differences in test dimensions or conditions) are adequately justified.

Accelerated fuel irradiations may provide enhanced understanding of fuel behavior, but the NRC staff has not identified information to clarify how differences in manufacturing or test conditions impact the data obtained from these irradiations. Accordingly, accelerated irradiation techniques can be a valuable tool for increasing understanding of fuel behavior under irradiation, but the NRC staff has not observed sufficient information to justify the use of test data obtained from accelerated irradiation testing for assessing evaluation models (i.e., fuel performance codes).

2.3.3 Interim Burnup Limits

GA-EMS is seeking NRC staff agreement that a conditional operating license is possible for the EM^2 long core life reactors prior to obtaining full burnup fuel test data under prototype conditions. The regulations in 10 CFR 50.43(e)(1) require applications for a design certification, combined license, manufacturing license, operating license or standard design approval that: (1) propose nuclear reactor designs which differ significantly from light water reactor designs that were licensed before 1997, or (2) use simplified, inherent, passive, or other innovative means to accomplish their safety functions to:

(i) demonstrate the performance of each safety feature of the design through either analysis, appropriate test programs, experience, or a combination thereof;

(ii) demonstrate that interdependent effects among the safety features are acceptable as demonstrated by analysis, appropriate test programs, experience, or combination thereof; and

(iii) provide sufficient data on the safety features of the design to assess the analytical tools used for safety analysis over a sufficient range of normal operating conditions, transient conditions, and specified accident sequences, including equilibrium core conditions.

Alternatively, 10 CFR 50.43(e)(2) allows the use of a prototype plant to comply with the testing requirements. Use of a prototype plant may involve the application of additional NRC imposed requirements on siting, safety features, or operational conditions to protect the public and the plant staff from the possible consequences of accidents during the testing period. To date, the NRC has not licensed a nuclear power plant as a prototype; however, it has been envisioned that this could be a pathway for licensing advanced reactors (see Appendix B to Enclosure 1 of the Regulatory Roadmap (Reference 8)).

Nuclear fuel contributes to the reactivity balance and is a source of heat and fission products. Therefore, it is generally recognized as impacting the safety functions of reactivity control, heat removal, and confinement of radioactive material. Accordingly, nuclear fuel would generally be considered a safety feature subject to the requirements of 10 CFR 50.43(e), and would require demonstration prior to licensing. The GA-EMS proposal is to conduct fuel surveillance, inspection, and testing in the first of a kind unit after licensing and prior to obtaining the data needed to support the entire lifetime of a proposed fuel design. This proposal could be accommodated by the prototype option allowed by 10 CFR 50.43(e)(2), provided that there is sufficient basis for the NRC staff to make a finding regarding fuel performance. However, the need to use the prototype option available under 10 CFR 50.43(e)(2), would depend upon whether sufficient information is available to support findings under 10 CFR 50.43(e)(1). The basis for the NRC staff's finding under 10 CFR 50.43(e)(2), can include additional NRC imposed requirements for siting, safety features, or operational conditions to protect the public and the plant staff from the possible consequences of accidents during the testing period.

The NRC imposed requirements under 10 CFR 50.43(e)(2), may appear as license conditions. EM^2-AFQ does not provide sufficient information for the NRC staff to comment on any specific license conditions that may be imposed to provide adequate protection of the public health and safety. However, the NRC staff notes that any imposed conditions would consider risk insights and any uncertainties associated with fuel performance that are to be addressed by testing in the prototype reactor. Furthermore, the adequacy of these license conditions would be subject to a mandatory hearing and the NRC staff expects license conditions to be an area of significant focus during a detailed technical review.

To support information needs associated with 10 CFR 50.43(e)(1), the NRC staff provides guidance regarding the use of test fuel above its qualified limit in Section 3.4.2, "ED G2-Test envelope," of NUREG-2246, which states:

> *[…] an extended use of lead test specimens (e.g., relaxation of the number and/or location of the test specimens) may be allowable if justified by a safety analysis that includes margin to account for the uncertainty in the performance of fuel above its burnup limit. The use of fuel above its qualified limit should be supported by sufficient monitoring to detect potential failures. Methods are available, such as gas tagging (McCormick & Schenter, 1974) (Pollack, Lewis, &*

Kelly, 2013), that can be used to identify the precise source of potential fuel failures. Additionally, if lead test specimens are subjected to conditions beyond existing data ranges, a licensing review may be necessary to ensure the appropriate level of safety before the extended limits are applied to the fuel design. […]

The use of interim burnup limits is expected to have a significant impact on the overall safety review of the facility. Accordingly, the NRC staff encourages any applicant considering such a licensing strategy to have significant pre-application engagement on the topics of fuel qualification (Reference 9) to ensure that there is a common understanding of associated technical, regulatory, and policy issues and to reduce regulatory uncertainty.

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4. Regulatory Guide 1.232, Revision 0, "Guidance for Developing Principal Design Criteria for Non-Light Water Reactors," (ADAMS Accession No. ML17325A611).

5. NUREG-0800, "Standard Review Plan: Section 4.2, Fuel System Design," March 2007 (ADAMS Accession No. ML070740002).

6. PNNL-19418, Volume 1, Revision 2, "FRAPCON 4.0: A Computer Code for the Calculation of Steady-State, Thermal-Mechanical Behavior of Oxide Fuel Rods for High Burnup," September 2015.

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9. Draft Pre-application Engagement to Optimize Advanced Reactors Application Reviews, May 2021, (ADAMS Accession No. ML21145A106).

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