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INTRODUCTION

Certain proposed advanced reactor technologies call for novel nuclear fuel/material designs for use in new operating environments that may significantly differ from those seen in the current reactor fleet. Pushing through a new design is not easy. According to Crawford et al. [1], the current licensing and testing approach typically requires about 20–25 years to move a new fuel from conceptual design to commercialization. Comprehensive test matrices and extensive experimental data are needed to demonstrate fuel and material performance and to satisfy regulatory requirements. Key challenges also exist in selecting and justifying testing conditions for imitating the maximum credible licensing basis events (LBEs). A long timeline can introduce a high degree of uncertainty into the licensing process, putting advanced reactor projects at high risk.

It is critical that nuclear fuel qualification for advanced reactors be accelerated. Two approaches are commonly used to reduce the testing timeline—both based on the current practice of test matrix development. The first is to shorten the duration of a single test by establishing advanced test capabilities in order to more quickly obtain relevant data. Among such capabilities are the Fission Accelerated Steady State Test [2] and High Flux Isotope Reactor MiniFuel irradiation methods [3]. The second approach is to replace some of the tests with high-fidelity, physics-based modeling and simulation, as was recently proposed in the Accelerated Fuel Qualification methodology [4].

New opportunities for accelerating fuel and material qualification are currently emerging under the risk-informed regulatory framework for advanced reactors that is being developed under U.S. Nuclear Regulatory Commission (NRC) regulations; namely, Title 10 of the Code of Federal Regulations (10 CFR), Part 53, "Risk-Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors" [5].

The present paper discusses the potential for incorporating a risk-informed, performance-based (RIPB) process into nuclear fuel and material development. Such a process promises to both accelerate development and improve economic competitiveness.

RIPB IN GENERAL

Risk-informed approaches, which are intended to improve economic efficiency without sacrificing safety, are utilized to assess the risks involved with different decision alternatives and to prioritize limited resources in order to reduce dominant risk drivers.

For decades, the NRC has used risk-informed approaches to improve regulatory efficiency [6]. Furthermore, numerous success stories exist in regard to applying risk-informed approaches at commercial nuclear power plants in order to improve their economic efficiency by supporting licensing-basis changes such as extended surveillance test intervals and streamlined maintenance requirements for low-safety-significance equipment [7].

Note that risk-informed processes distinctly differ from risk-based processes, in which risk is used as the sole (or at least the dominant) metric upon which decisions are based. Per NRC regulations on risk-informed processes, "risk inform" is here defined as the use of risk in combination with many other important principles to jointly guide decision-making activities. Thus, development of an RIPB approach for nuclear fuel and material development is intended to complement—not replace or revolutionize—the existing process.

Performance-based approaches focus on "what" must be accomplished to satisfy the regulatory requirements, as opposed to prescribing "how" it is to be accomplished. Performance requirements can be set up at various different levels; for example, (1) the margins to design limits at the fuel and material level (Table I), and (2) quantifiable performance metrics for LBE frequencies and radiological consequences (Fig. 1).

TABLE I. Examples of Fuel and Material Design Limits

Category	Design Limit
Thermal	Temperature limit
Mechanical	Stress limit
Mechanical	Strain limit
Mechanical	Fatigue cycle limit

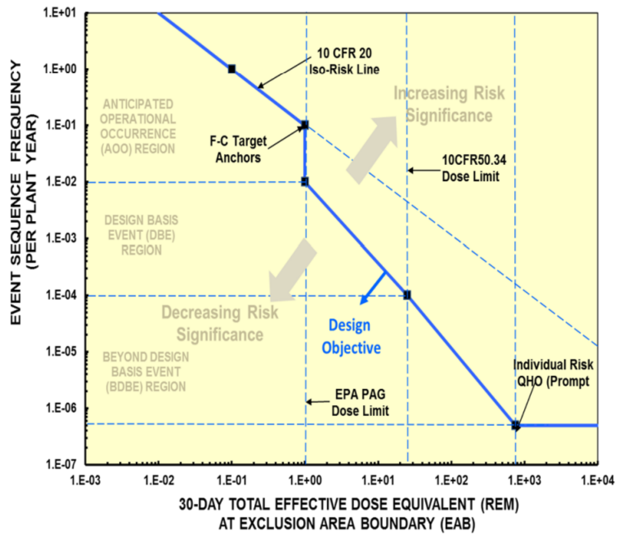

Fig. 1. Frequency-consequence target (taken from Nuclear Energy Institute 18-04) [8].

RIPB APPLICATIONS FOR FUEL AND MATERIALS

Nuclear fuel and material qualification is a critical aspect of license applications. It is not, however, a field in and of itself, and must fit into the big picture of plant design. RIPB is usually referenced as a general overarching concept for use in regulations, plant design, operation improvements, and beyond. This section discusses how to tie RIPB to nuclear fuel and material development. Specially, three potential RIPB applications are proposed:

(1) RIPB fuel and material test matrix development
(2) RIPB fuel and material test matrix reduction
(3) RIPB fuel and material design optimization.

RIPB Fuel and Material Test Matrix Development

Justification of the LBE selection is a key challenge that introduces regulatory uncertainty. One recent example is the NRC's denial of Oklo's Aurora reactor license application, largely due to their failure to justify their postulated maximum credible accidents. An existing risk-informed process (Fig. 2) that was developed under the Licensing Modernization Project (LMP) is dedicated to LBE selection and may help resolve this challenge.

LMP was cost shared by the Department of Energy, and its outputs were endorsed by the NRC in Regulatory Guide 1.233 [9]. LMP has already been piloted by several advanced reactor developers in regard to determining LBEs. It fully utilizes insights from systematic risk assessment, in combination with structured prescriptive rules, to select LBEs, evaluate their risk frequencies and consequences, and compare the risks to regulatory requirements.

As shown in Fig. 2, the selected LBEs can serve as input to many RIPB decisions. Fuel and material test matrix development could be another decision-making domain that may benefit from using the LMP-selected LBEs as a justifiable technical basis for developing safety test matrices.

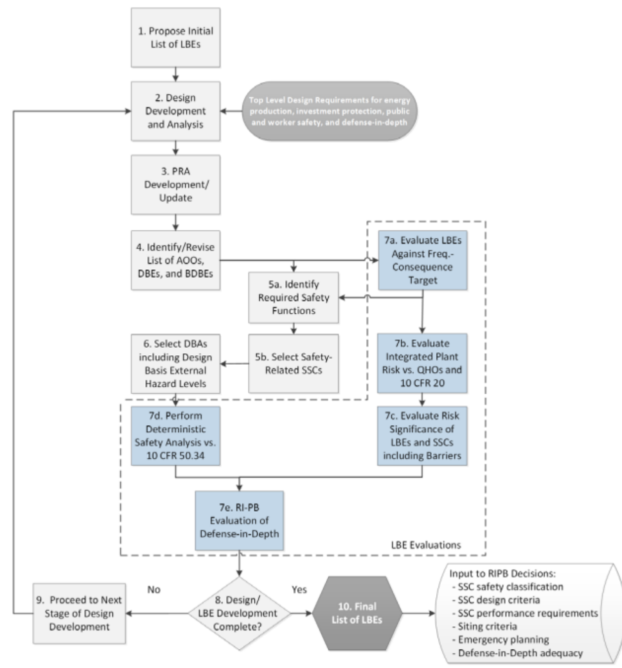

Fig. 2. LBE selection and evaluation process (taken from Nuclear Energy Institute 18-04) [8].

RIPB Fuel and Material Test Matrix Reduction

Taking fuel as an example, a typical test matrix will consider multiple variables such as fuel burnup, operation history, fuel/cladding average and maximum temperatures, cladding degradation and embrittlement, fuel-cladding eutectic reactions, and neutron irradiation damage (measured in displacements per atom [dpa]). Utilization of risk insights represents a promising method for identifying risk-significant test conditions, narrowing down test matrices, and reducing the required numbers of fuel tests.

The proposed risk-informed approach can utilize fuel performance data from a limited number of bounding tests and evaluate the risk significance of specific test input parameters such as irradiation. For example, if the difference between the demonstrated margins of samples irradiated under high and low doses (dpa) negligibly impacts the plant risk, this may help justify the decision not to require that high-dose samples be used to conduct tests. In certain scenarios, it may successfully justify the use of non-irradiated samples for testing, thus effectively reducing the required volume of irradiated materials and simultaneously shortening testing timelines.

RIPB Fuel and Material Design Optimization

Though considerations can vary, fuel and material design can be formulated (in highly simplified fashion) as an optimization problem:

(1)

where:

represents the fuel/material design parameters
is the cost of a given design
is the margin to design limits of design
is the risk of design
is the minimum margin allowed by the regulatory requirements
is the maximum risk allowed by the regulatory requirements.

In comparison to the LBEs selected based on deterministic safety analysis, the RIPB-selected LBEs may lead to a more realistic test matrix, larger margins to design limits, and higher regulatory risk thresholds. This could help relax design optimization limitations and allow for more flexibility in enhancing designs and reducing development costs.

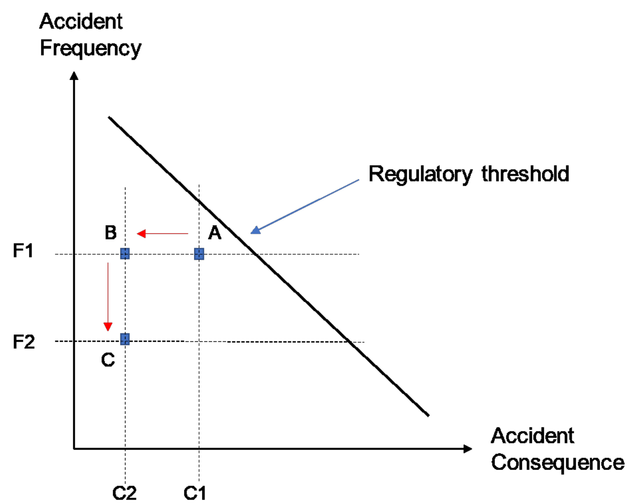

Fig. 3. Potential increase in risk margin when using an RIPB approach.

Fig. 3 is a conceptual presentation of the risk curve given in Fig. 1. Point A stands for the occurrence frequency (or yearly likelihood) () and radiological consequence () that result from an LBE selected using a conservative approach, such as using 1600℃ for safety testing. Point B stands for the LBE frequency () and consequence () determined by using a risk-informed approach, which could enable the utilization of a much lower temperature (e.g., 1400℃). Under a lower temperature, the fuel integrity will be less challenged and fission products better retained, reducing the severity of any radiological consequences. The gained margin in consequence () and potentially slower accident progression will afford a longer coping time for accident mitigation and will reduce the LBE frequency (), eventually moving to point C.

BENEFITS OF RIPB APPLICATIONS FOR FUEL AND MATERIALS

Fig. 4 presents our preliminary thoughts on the potential benefits of developing RIPB applications for fuel and materials. Reduction of the qualification timeline is the most promising benefit, followed by certain "byproduct" benefits pertaining to cost and regulatory risk reductions.

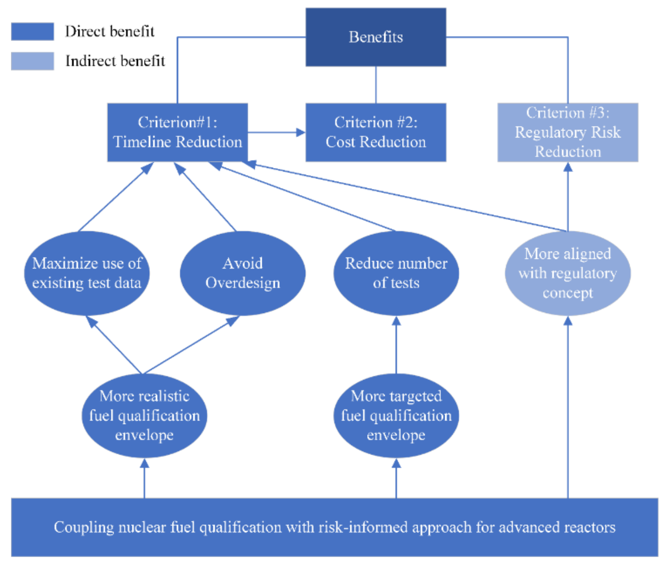

Fig. 4. Projected benefits of incorporating an RIPB process into fuel and material development.

The aforementioned primary benefit (i.e., qualification timeline reduction) is evaluated under Criterion 1, while the byproduct benefits are measured under Criteria 2 and 3. Criterion 2 is the cost reduction impact. Conservative fuel/material qualification envelopes and test matrices lead to over-designed fuel and materials, and could significantly impact the economic competitiveness of advanced reactor projects. The RIPB applications can be used to generate a less conservative, more realistic envelope and to facilitate the adoption of more economic designs. Monetary savings can also be achieved by reducing the required number of tests, per Criterion 1. Criterion 3 is the regulatory risk reduction. The risk-informed approach closely aligns with the NRC's new risk-informed regulatory concept for advanced reactors, as presented under 10 CFR 53 [5]. The proposed RIPB applications enable alignment of fuel testing with regulatory expectations, and foster engagement with the regulator early on in the process. In this manner, they directly support and increase the likelihood of obtaining timely regulatory approval.

SUMMARY

The NRC's new risk-informed regulatory approach for advanced reactors (under 10 CFR 53) promotes utilization of RIPB processes, which are usually referenced as general overarching methodologies. The present paper focused on how—and whether it would be worthwhile—to incorporate an RIPB process into nuclear fuel and material development for advanced reactors.

This paper proposed three potential RIPB applications for nuclear fuel and material development: RIPB test matrix development, RIPB test matrix reduction, and RIPB design optimization. It then discussed the projected benefits of incorporating RIPB in terms of reduced development timelines, costs, and regulatory risk.

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