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Changing the World's Energy Future

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INTRODUCTION

Advanced reactor technologies feature fuels, coolants, and materials that promise safer operating conditions under normal and accident scenarios. However, nuclear fuels and materials qualifications (FMQ) require several decades for approval (e.g., new reactor fuel qualifications from conceptualization requires about 20 years) [1]. Therefore, accelerating nuclear FMQ is essential, and it can be achieved by combining high throughput materials irradiation and post-irradiation testing and advanced modeling [2].

The challenges in accelerating nuclear FMQ for new and advanced reactor (AR) designs differ based on fuels and materials (F&M) compositions, coolant type (e.g., corrosion environment), operating conditions (e.g., radiation level, temperature), and structural materials, as shown in Figure 1 [3]. In addition, there are limitations due to test facilities, modeling tools, licensing guidelines, and management programs. These challenges of accelerating the FMQ need to address adequately to find a general solution path forward, which is the focus of this study.

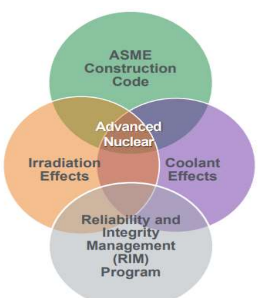

Fig. 1: Dependencies of FMQ for ARs [3].

Nuclear FMQ is a concern for each nuclear fuel cycle (NFC), including front and back ends, as shown in Figure 2.

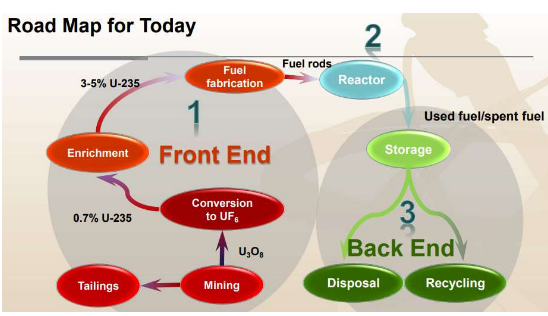

Fig. 2: Process workflow for NFC [4].

The front end (i.e., fuel development) consists of mining, conversion, enrichment, and fabrication, whereas the back end covers used/spent fuel storage, recycling, and disposal.

This study focused on assessing the main challenges in accelerating the qualification of nuclear F&M for AR technologies, which include:

- Understanding the needs—regulatory requirements, licensing guidelines, testing, and modeling.
- Differences in operational and testing conditions—radiation levels, operating temperatures, and pressures, environment.
- Limitations in experimental facilities enabling the prototypic environment, validated modeling tools, and associated management.
- Constraints due to materials manufacturing process.

These challenges must be overcome with a solution path forward to achieve a faster FMQ process that supports enhancing the safety and reliability of nuclear installations and advancement in new and AR technology deployment.

UNDERSTANDING THE NEED

Understanding the need for nuclear FMQ is pivotal for developing and demonstrating new AR systems or extending the license and relicensing of the operational reactors by improving the structures, systems, and components (SSC).

Regulatory Requirements and Licensing Guidelines

The United States (U.S.) Nuclear Regulatory Commission (NRC) requires that nuclear F&M used in a nuclear reactor system (NRS) must be qualified to ensure their safety and reliability [5]. Nuclear F&M concern is involved at various levels in all NRC regulations—nuclear reactors, nuclear materials, radioactive waste, and nuclear security.

The reactor vendors and users must follow the regulatory requirements and licensing guidelines during the reactor lifecycle—design, development, transportation, deployment, operation, and decommissioning.

Required Testing and Analysis

The nuclear FMQ process involves rigorous testing and analysis to demonstrate that the F&M can withstand the harsh environments of a nuclear reactor and maintain its structural integrity and performance. This process typically involves a series of testing and modeling, imitating prototypic reactor conditions, including:

- Irradiation testing in a research or test reactor.
- Thermal testing at required temperatures and pressures, simulating the conditions inside a reactor during normal and accident conditions.
- Mechanical testing, such as strength and ductility checks, ensures that F&M can withstand the stresses and strains of reactor operation.
- Chemical testing (i.e., chemical composition check), including corrosion effects, to ensure allowable degradation over time.
- Nondestructive testing (NDT), such as X-ray or ultrasound, to inspect the F&M without damaging it.

Once the qualification process is complete, the NRC will review the results to ensure that the F&M meets its safety and performance standards before approving its use in the NRS.

The reactor materials-design envelope considers the properties changes (with temperature and design stress limits), dimensional changes, and corrosion effect (e.g., sulfide stress cracking and stress corrosion cracking [SCC]) changes due to radiation effects, such as radiation embrittlement and creep rupture, as shown in Figure 3 [6].

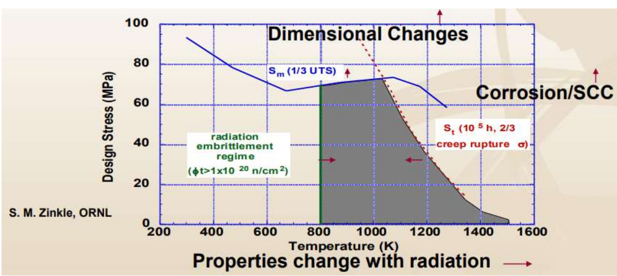

Fig. 3: The reactor materials-design envelope [6].

Required Irradiation Test Facilities

The irradiation experiments for nuclear F&M in the U.S. are mainly performed at high temperatures, in radiation and corrosive environments in laboratory and test reactor facilities, such as the Advanced Test Reactor (ATR) and Transient Reactor Test (TREAT) facility at Idaho National Laboratory (INL) and the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) [7]. Likewise, research reactors, university campus reactors, and other radiation sources—such as ion beams and intermediate voltage electron microscopy (IVEM) facility at Argonne National Laboratory (ANL) are also utilized for irradiation testing [7]. For F&M qualification purposes, using research reactors is very unlikely. The development of flexible experiment platforms, good test matrices, and high-throughput tests are needed to use the available facilities to get the required qualification data [2].

Nuclear F&M testing for NRC licensing utilizes HFIR, ATR, and TREAT test facilities. Developing suitable test vehicles, capsules, and/or test loops is required to perform the F&M test simulating specific radiation environments and heat rates. For example, the mini fuel test vehicle of HFIR consists of a basket, target, capsule, and fuel sample coupons, as shown in Figure 4.

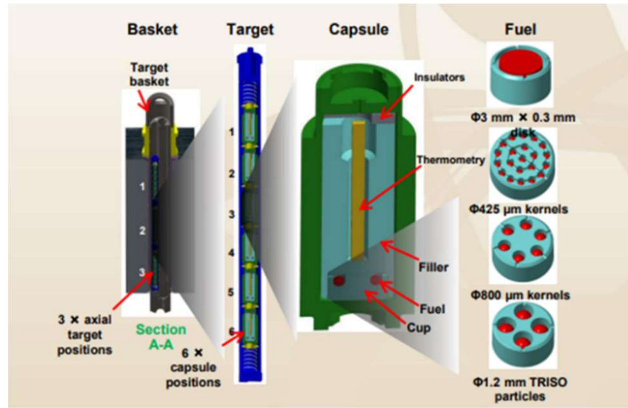

Fig. 4: The mini fuel test vehicle of HFIR [8].

Candidate Materials and Manufacturing Process

Understanding the constraints of the candidate materials and manufacturing process is essential for nuclear FMQ. Several candidate F&M are being researched and developed. Structural materials are mostly stainless steel, alloys, graphite, and concrete used for SSC, containment, and shielding. The candidate fuel materials are uranium nitride (UN), uranium silicide (U_3Si_2), silicon carbide (SiC), and metal and ceramic fuels. This candidate F&M inhabits various features that support AR design—such as thermal conductivity, neutron cross-section, strength, temperature, and corrosion resistance. Advanced manufacturing (AM) techniques are ongoing to improve the performance and safety of nuclear facilities. However, the candidate material must qualify with adequate irradiation testing and analysis.

Required Simulation and Modeling Tools

The complexity in the nuclear F&M simulation and modeling is due to the interdependency of the physics models—such as reactor physics, thermal hydraulics, fuel performance, and coolant chemistry, as shown in Figure 5 [9]. These simulation tools require coupled and integrated modeling, which challenges analysis.

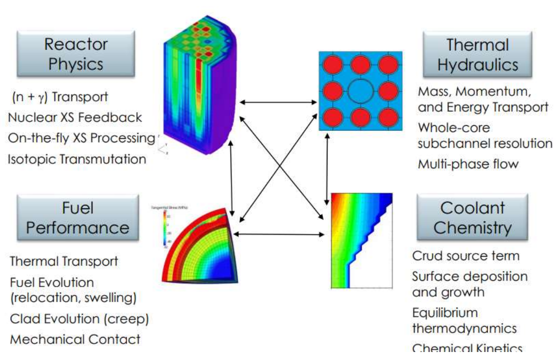

Fig. 5: Complexity in nuclear F&M modeling [9].

RECOMMENDED SOLUTION PATH FORWARD

Understanding the challenges and limitations is the first essential step in accelerating the FMQ toward the solution discussed in the previous section. This section covers the recommended approaches toward the solution path forward.

A Multi-Level Experiment Campaign

Several test facilities can be utilized for radiation testing of nuclear F&M. However, each facility features uniqueness in its simulated radiation environment and testing. Therefore, a multi-level experimental campaign that involves several experimental facilities in a systematic approach is recommended, as shown in Figure 6. The proposed multi-level irradiation experiment campaign includes an ion beam facility, IVEM, HFIR, ATR, and TREAT based on the technology readiness level (TRL). Identifying the knowledge gaps is the prerequisite, then developing a road map of experiments to gain that information [2]. Irradiation experiments using an ion beam would be the first step as it is simpler than another facility to operate and require less operational safety procedure and cost. Then, the candidate material can be tested in IVEM. Next is using the HFIR high flux facility, followed by prototypic high radiation and high-temperature conditions at ATR. Finally, the safety and accident condition testing will need to be completed using the TREAT facility. These processes can be repeated to confirm the success of the irradiation test campaign [10].

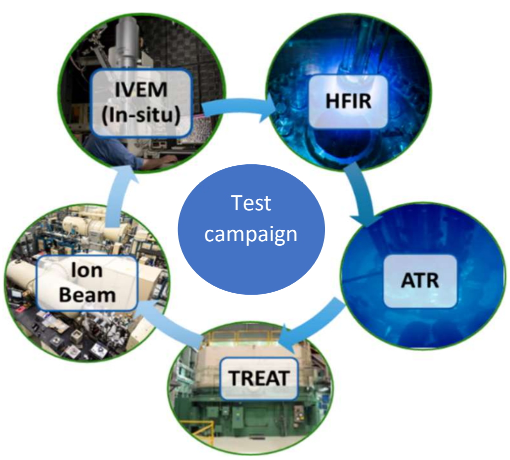

Fig. 6: A multi-level irradiation experimental campaign [8].

A Multi-Scale Simulation Approach

Several simulation tools were developed to study nuclear F&M modeling and analysis that varies timescale and length scale, as shown in Figure 7 [1]. These simulation tools were developed considering the constitutive properties and boundary conditions for various time and length scales.

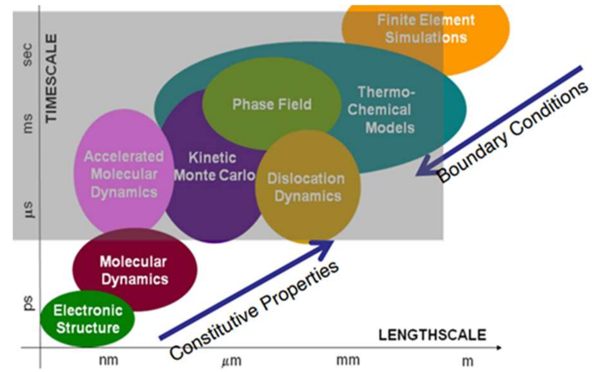

Fig. 7: Multi-scale simulation approach [11].

The common modeling approaches are molecular dynamics simulations, dislocation dynamics, and phase-field modeling for micro- and meso-scale modeling, whereas the thermochemical and finite element models are for continuum-scale simulations. Therefore, to accelerate nuclear FMQ, multi-scale simulations and modeling approaches are recommended.

A Science-Based and Engineering-Driven Design

The design approaches of nuclear F&M can be grouped into science-based and engineering-driven, as shown in Figure 8 [12]. The engineering-driven design approaches consider system requirements to design qualifications. However, the science-based design approaches consider physics and mathematical models with adequate experimental data for design and code validation. Both design approaches have pros and cons; therefore, a blended approach is recommended to accelerate nuclear FMQ.

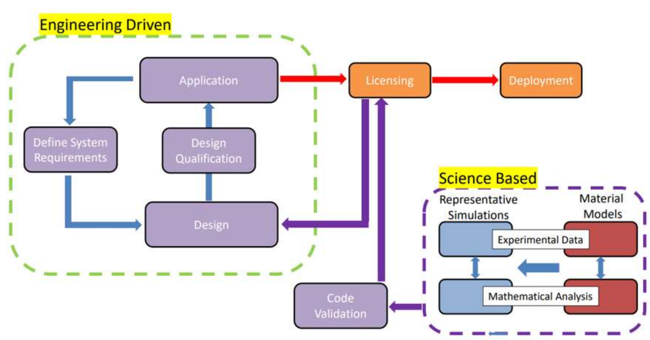

Fig. 8: Science-based engineering-driven design [12].

A Physics-Informed and Data-Driven Approach

Advanced computational resources, such as artificial intelligence (AI) and data-driven tools, could support nuclear F&M assessment and qualification, as shown in Figure 9, per the nuclear fuel qualification working group [1].

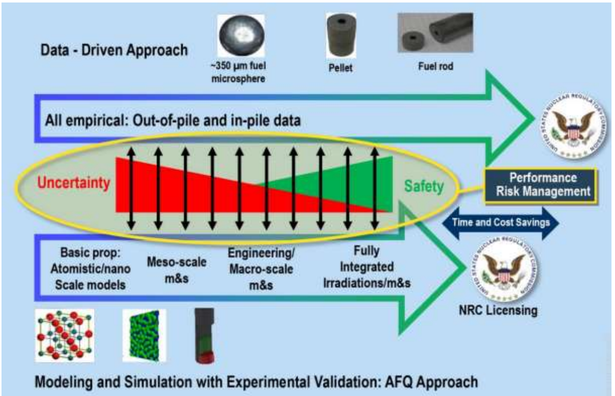

Fig. 9: Physics-informed data-driven FAQ approach [1].

Advanced data-driven tools like AI and machine learning (ML) tools and libraries combined with physics-informed modeling, experimental validation, and uncertainty quantification are recommended to accelerate nuclear FMQ.

FINDINGS AND DISCUSSIONS

Irradiation experiments with supportive simulation and modeling are prerequisites for nuclear FMQ. Irradiation experiments involve exposing samples of F&M to a simulated or actual radiation environment similar to what they would experience in a nuclear reactor. This allows researchers to assess the properties and performance of the F&M, including changes in their microstructure, mechanical properties, and chemical stability. The challenges and prospective solutions for accelerating FMQ are as follows:

- Understanding the regulatory requirements and licensing guidelines (e.g., manufacturing and fabrication parameters related to safety criteria).
- Utilizing nuclear science user facilities (NSUF) for irradiation testing in a prototypic radiation environment. A multi-level experiment campaign is suggested.
- Complexity in simulation and modeling tools due to time and length scales. A multi-scale simulation and modeling approach is recommended.
- Distinction in design approaches—engineering-driven or science-based. A science-based and engineering-driven blended approach is suggested.
- Adopting advanced data-driven analytical tools in combination with physics-informed models is recommended.
- Suggested high-throughput testing and experimental validation with qualified irradiation and post-irradiation test data, including uncertainty quantification.

The results and findings from the irradiation experiments are then used to improve the nuclear F&M models and tools to accelerate FMQ and ensure safety and regulatory acceptance for use in nuclear reactors.

CONCLUSION

This study discusses nuclear F&M qualification, which includes testing and verifying the safety, performance, and compatibility of fuels, coolants, and materials used in nuclear reactors. The findings and suggested approaches support accelerating the qualification process, which currently takes several decades of continuous efforts, by using multi-level high-throughput materials irradiation and testing, post-irradiation examinations, multi-scale simulation and modeling efforts, a hybrid design approach, and advanced physics-informed data-driven analytics.

ACKNOWLEDGMENT

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