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Presentation: Accelerating Nuclear Fuels and Materials Qualification by Multi-Level Irradiation Experiment Campaign

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Changing the World's Energy Future

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Accelerating Nuclear Fuels and Materials Qualification by Multi-Level Irradiation Experiment Campaign

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FAILURE IS NOT AN OPTION.

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Objectives and Motivations

- 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, post-irradiation testing, and advanced modeling [2].

Objectives and Motivations (cont'd)

- The challenges in accelerating nuclear FMQ for new and advanced reactor (AR) designs differ based on
  - fuels and materials (F&M) composition, coolant type (e.g., corrosion environment), operating conditions (e.g., radiation level, temperature), and structural materials [3].

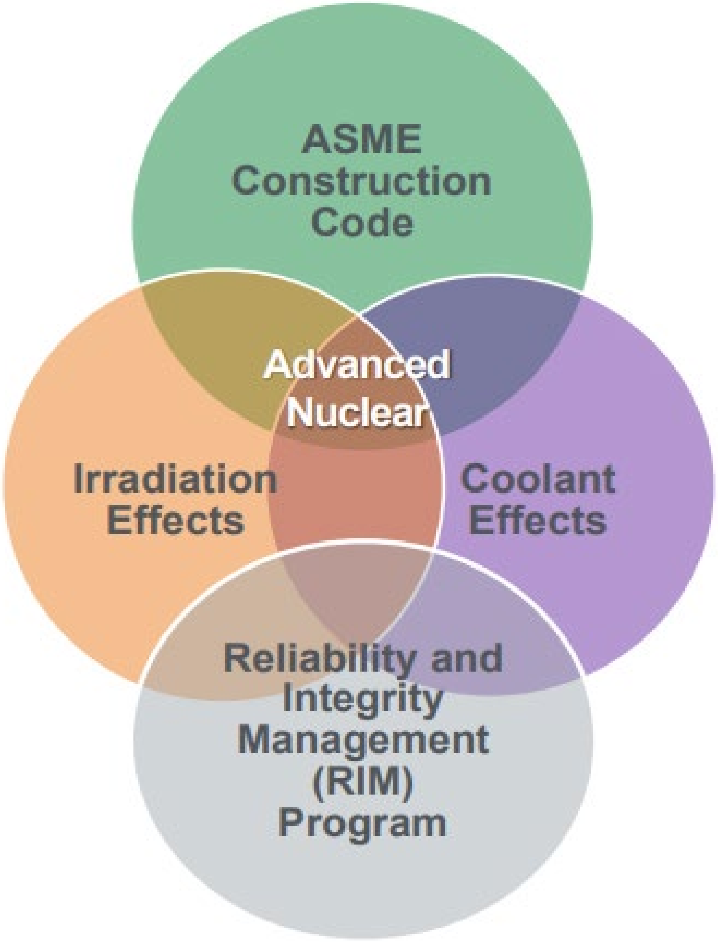

Fig. 1: Dependencies of FMQ for ARs [3].

Objectives and Motivations (cont'd)

- Nuclear FMQ is a concern for each nuclear fuel cycle (NFC).
- The main challenges in accelerating the qualification of nuclear F&M 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**.

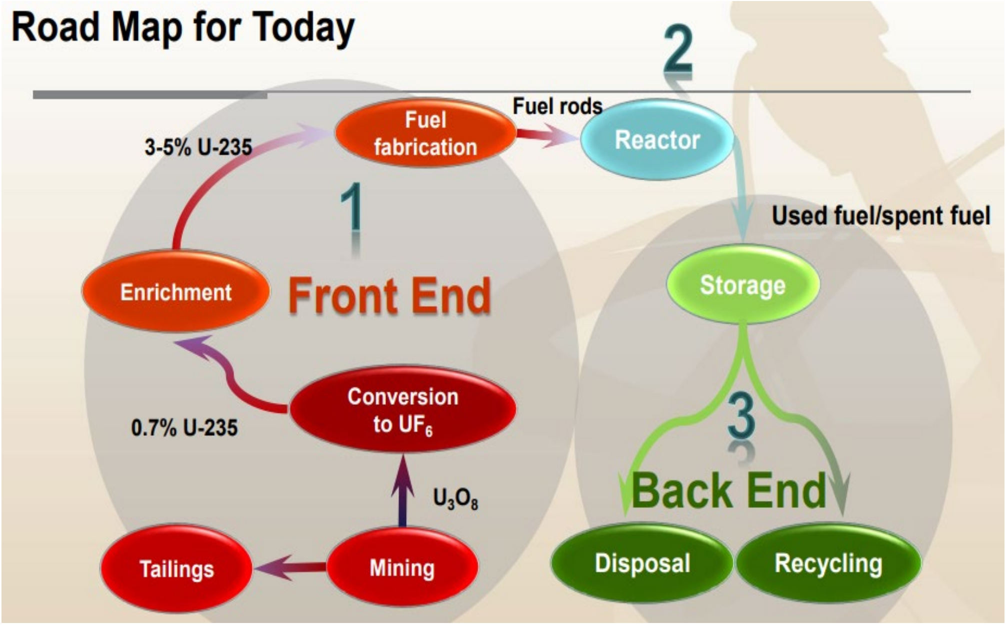

Fig. 2: Process workflow for NFC [4].

Understanding the Needs

- Regulatory Requirements and Licensing Guidelines:
  - Nuclear F&M used in a nuclear reactor system (NRS) must be qualified to ensure their safety and reliability [5].
- Required Testing and Analysis:
  - This process typically involves a series of testing and modeling, imitating prototypic reactor conditions, including:
    - Irradiation testing
    - Thermal testing
    - Mechanical testing
    - Chemical testing
    - Nondestructive testing (NDT).

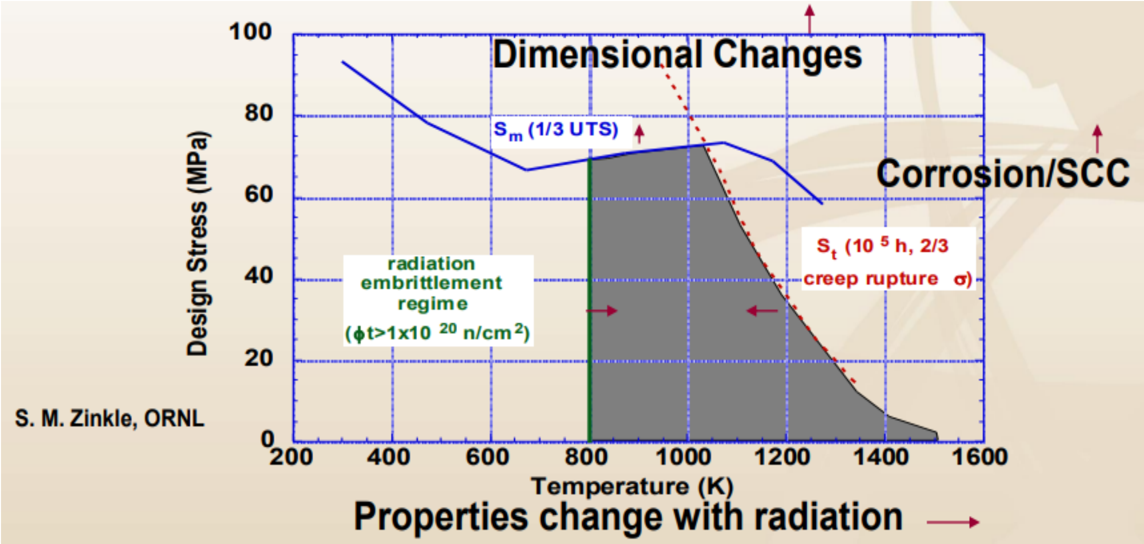

Fig. 3: The reactor materials-design envelope [6].

Understanding the Needs (cont'd)

- Required Irradiation Test Facilities [7]
  in laboratory and test reactor facilities, such as:
  - Advanced Test Reactor (ATR)
  - Transient Reactor Test (TREAT)
  - High Flux Isotope Reactor (HFIR).

- Appropriate Testing Apparatus -
  The development of:
  - flexible experimental platforms
  - good test matrices, and
  - high-throughput tests

  are needed to use the available facilities to get the required qualification data [2].

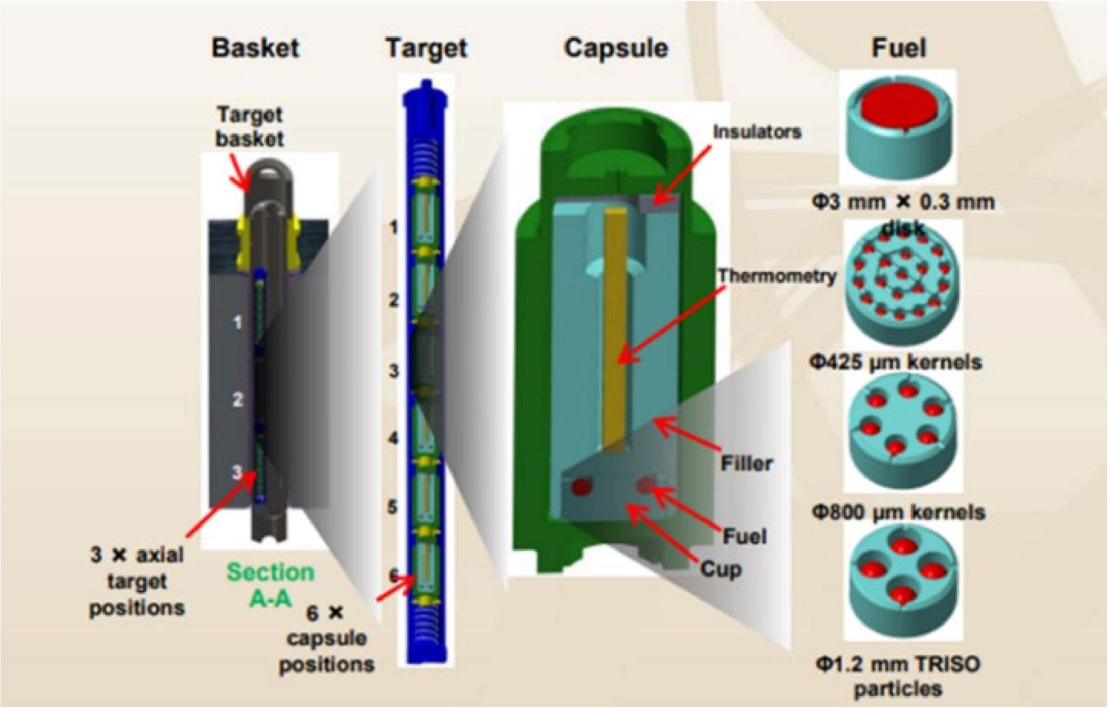

Fig. 4: The mini fuel test vehicle of HFIR [8].

Understanding the Needs (cont'd)

- Required Simulation and Modeling Tools [9]:
  - The complexity in 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 [9].
  - These simulation tools require coupled and integrated modeling, which challenges analysis.

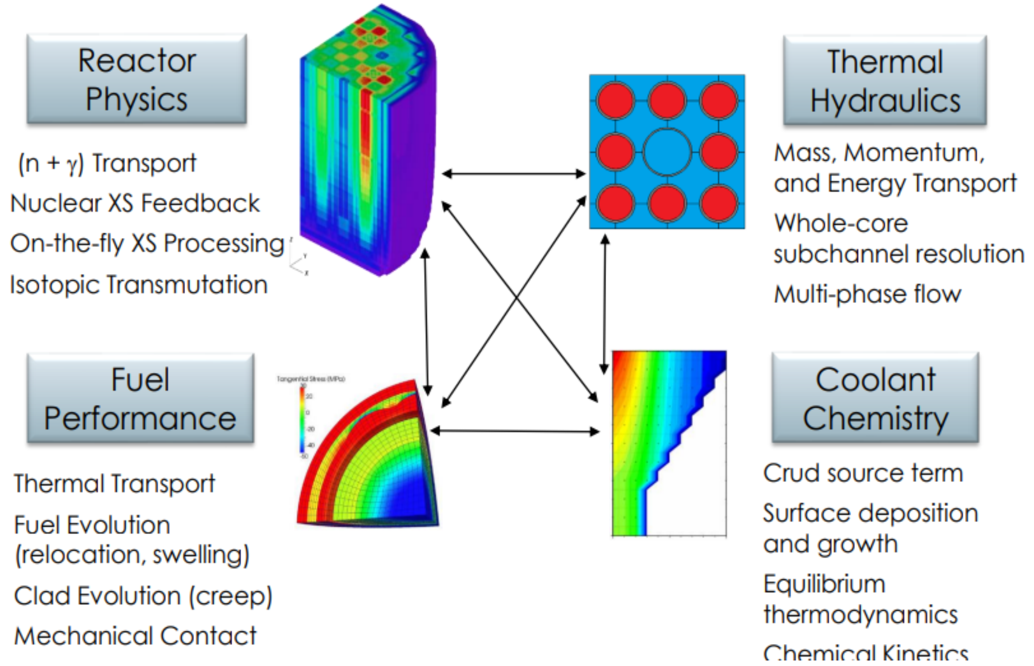

Fig. 5: Complexity in nuclear F&M modeling [9].

Recommended Solution Path Forward

- A Multi-Level Experiment Campaign:
  - These processes can be repeated to confirm the success of the irradiation test campaign [10].
  - The proposed multi-level irradiation experiment campaign includes an ion beam facility, IVEM, HFIR, ATR, and TREAT based on technology readiness level (TRL).
  - Identifying the knowledge gaps is the prerequisite, then developing a road map of experiments to gain that information [2].

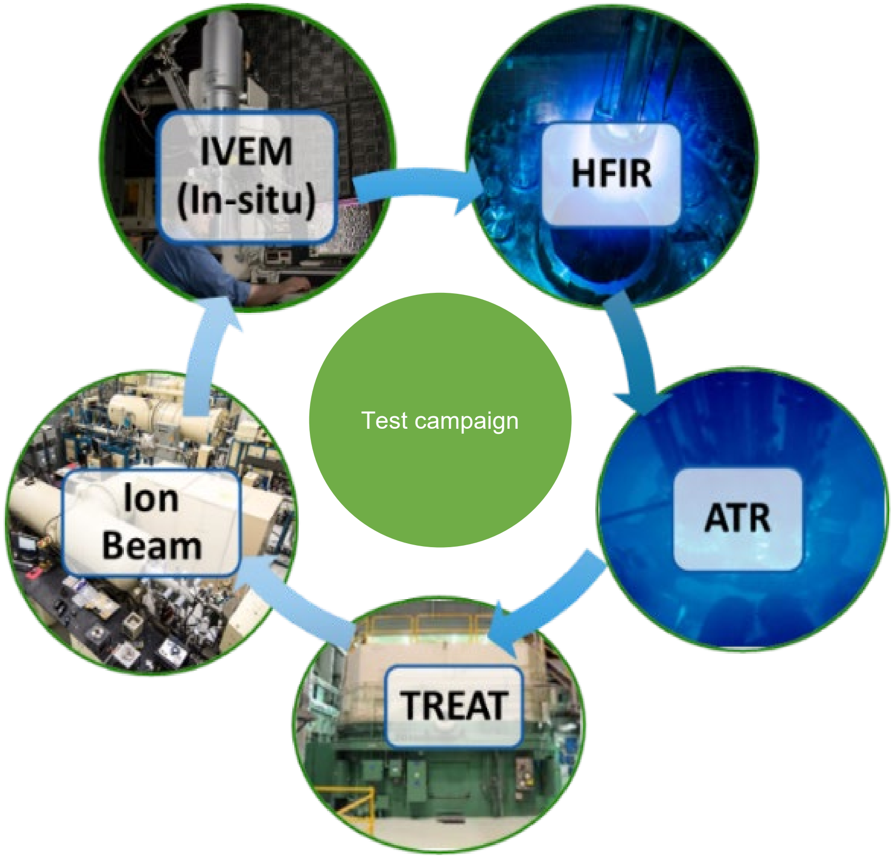

Fig. 6: A multi-level irradiation experimental campaign [8].

Recommended Solution Path Forward (cont'd)

- A Multi-Scale Simulation Approach
  - Several simulation tools were developed to study nuclear F&M modeling and analysis that varies timescale and length scale [1].
  - These simulation tools were developed considering the constitutive properties and boundary conditions for various time and length scales.
  - Identifying the knowledge gaps is the prerequisite, then developing a road map of experiments to gain that information [2].
  - Therefore, to accelerate nuclear FMQ, multi-scale simulations and modeling approaches are recommended.

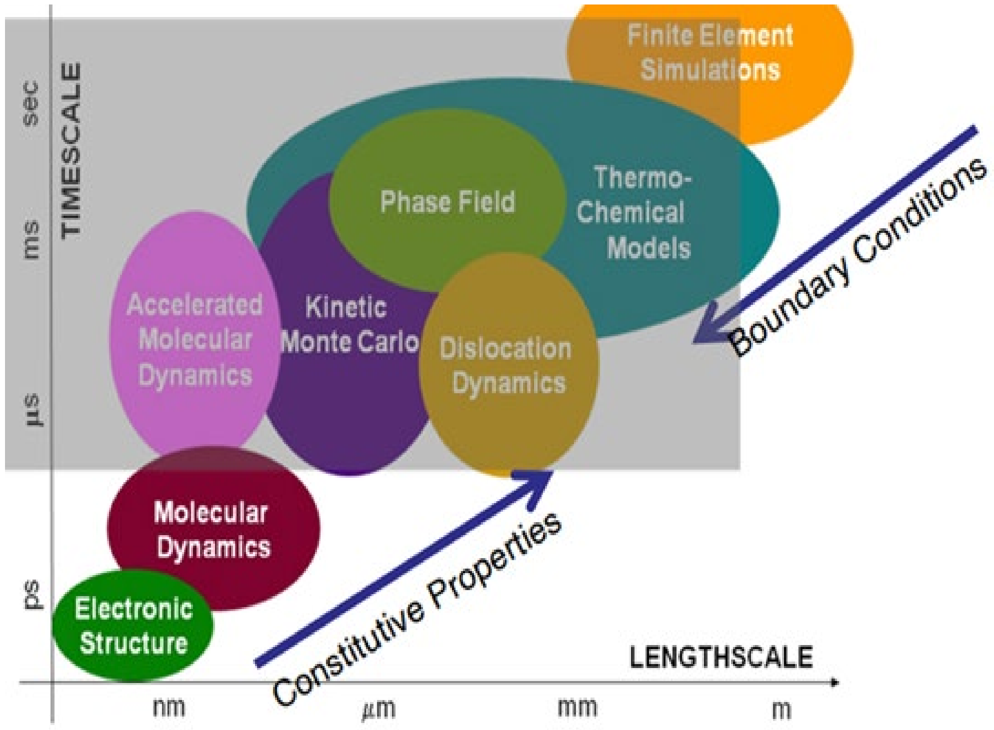

Fig. 7: Multi-scale simulation approach [11].

Recommended Solution Path Forward (cont'd)

- A Science-Based and Engineering-Driven Design
  - 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.

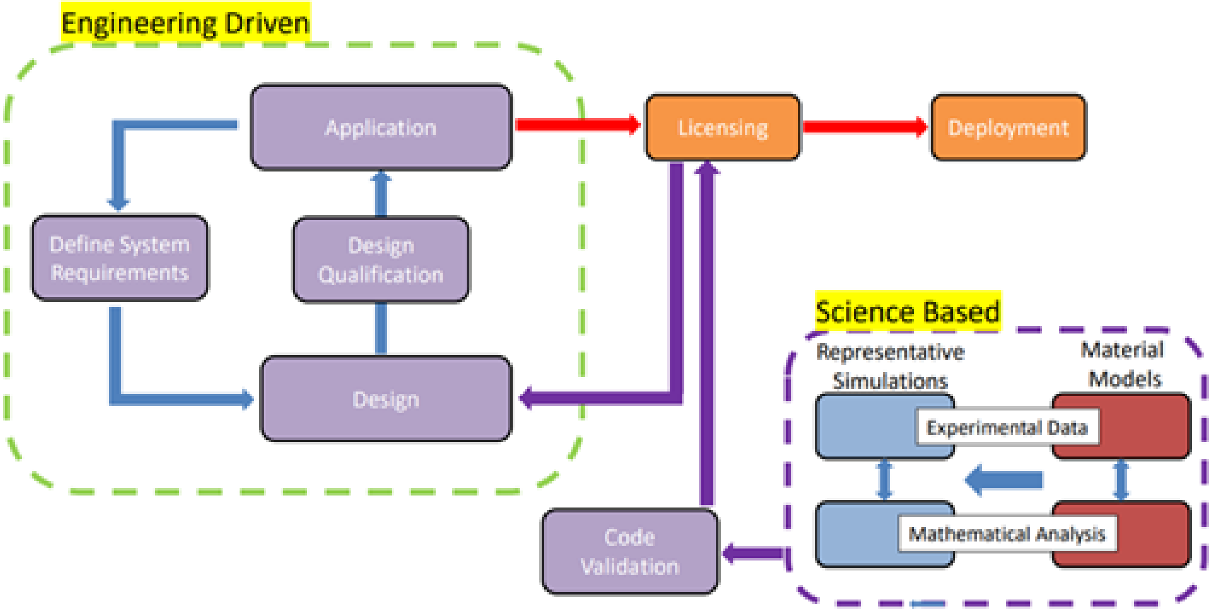

Fig. 8: Science-based engineering-driven design [12].

Recommended Solution Path Forward (cont'd)

- A Physics-Informed and Data-Driven Approach
  - Advanced data-driven tools such as:
    - AI and machine learning (ML) tools,
    - libraries combined with physics-informed modeling,
    - experimental validation, and
    - uncertainty quantification

  are recommended to accelerate nuclear FMQ.

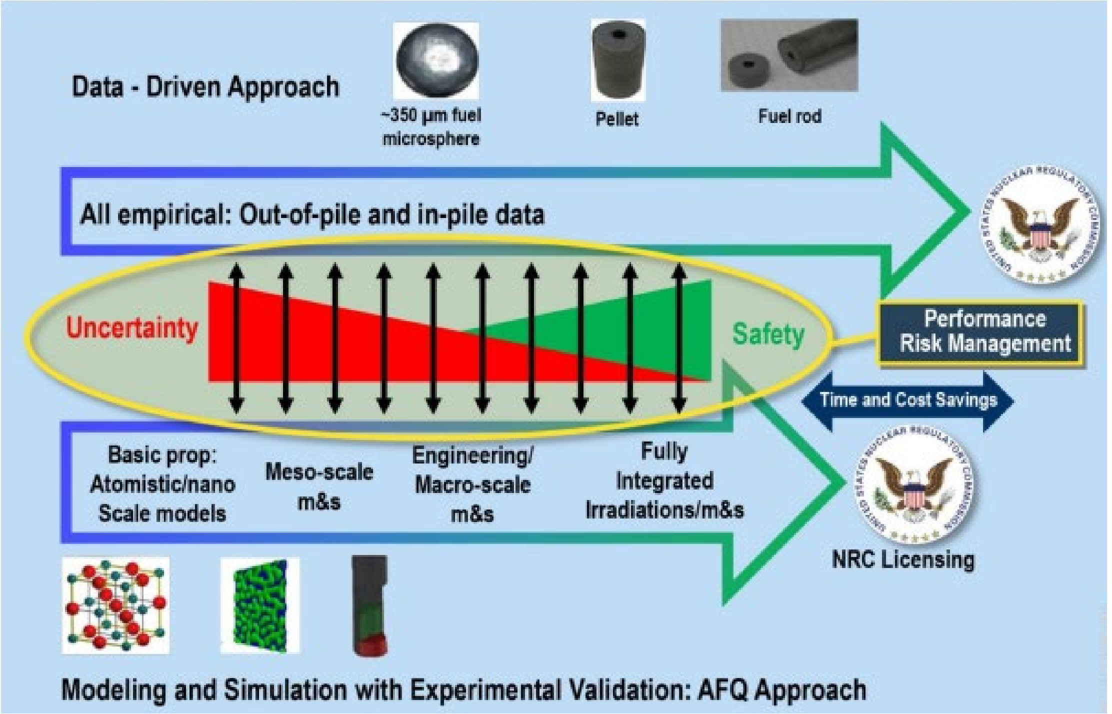

Fig. 9: Physics-informed data-driven FMQ approach [1].

Summary: Findings and Conclusions

- 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 would be experienced in a nuclear reactor, which allows researchers to assess the properties and performance of the F&M, including changes in their microstructure, mechanical properties, and chemical stability.
  - The results and findings from the irradiation experiments are then used to:
    - improve nuclear F&M models and tools to accelerate FMQ, and
    - ensure safety and regulatory acceptance for use in nuclear reactors.
- A multi-level irradiation experimental and a multi-scale simulation approach for science-based engineering-driven design with a physics-informed data-driven solution approach would accelerate nuclear FMQ.

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Thank you for your attention!