

Accelerating Nuclear Fuels and Materials Qualification-Learning from MeV Summer School 2022

September 2022

Palash Kumar Bhowmik





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Accelerating Nuclear Fuels and Materials **Qualification-Learning from MeV Summer School 2022**

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Presentation outline

- Part-1: Overview of MeV Summer School
- Part-2: Advancement of Reactor Technologies
- Part-3: Advancement of Reactor Fuel and Materials
 Research and Development (R&D)
 - Modeling
 - Experimentation
 - Validation (qualification and licensing)

Content Note

The content of this presentation is taken from the lecture notes of MeV Summer School 2022. The sources are cited as per lecture notes.

This presentation focused on the general overview of the lecture content that related to nuclear fuels and material qualification.

MeV School 2022





The Modeling, Experimentation, and Validation (MeV) Summer School is an intensive two-week program (July 18-29, 2022) for early career researchers and scientists. This year's school will be hosted by Oak Ridge National Laboratory (ORNL) and will focus on Accelerating nuclear fuels and materials qualification by combining high through-put materials irradiation and testing, advanced PIE, and Multiphysics modeling.

Taken from: MeV (2022),



NUCLEAR FUNDAMENTALS



IRRADIATION TESTING AND EXAMINATION



ENHANCING CURRENT REACTOR TECHNOLOGIES



NUCLEAR FUEL CYCLE



ADVANCED REACTOR FUEL AND MATERIALS



ADVANCED NUCLEAR ENERGY TECHNOLOGIES



FUSION ENERGY TECHNOLOGIES AND CHALLENGES



COMPUTATIONAL METHODS FOR NUCLEAR CHALLENGES









Enhancing Reactor Technologies and Systems



ENHANCING CURRENT REACTOR **TECHNOLOGIES**

LWRS

Plant Modernization

Flexible Plant Operation & Generation

Risk Informed System Analysis

Materials Research

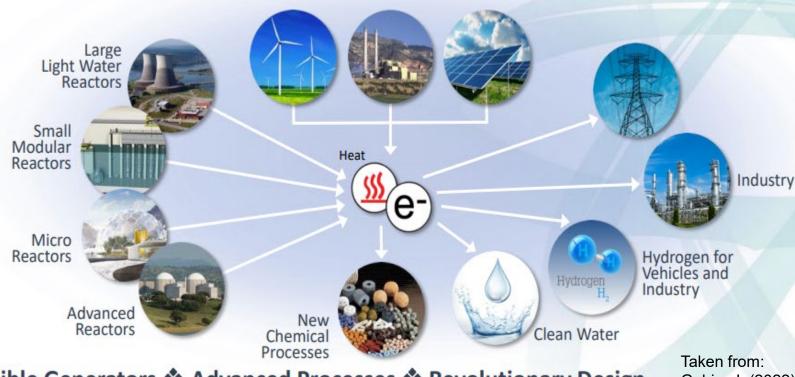
Physical Security

Today Electricity-only focus



Potential Future Energy System

Enhanced energy system leverages contributions from low emission energy generation for electricity, industry, and transportation



Flexible Generators ❖ Advanced Processes ❖ Revolutionary Design

Gehin, J. (2022)

Advanced Reactors: Testing at INL

\$

ADVANCED NUCLEAR ENERGY TECHNOLOGIES

National Reactor Testing Station 52 Reactors at INL over 25 years

National Reactor Innovation Center





MARVEL 2022-23



NRIC Test Beds 2023



DOD Pele Reactor 2023-24



Southern/Terapower MCRE 2025



UAMPS/NuScale SMR 2029

Taken from: Gehin, J. (2022)

Advanced Reactors: Demonstration and Deployment



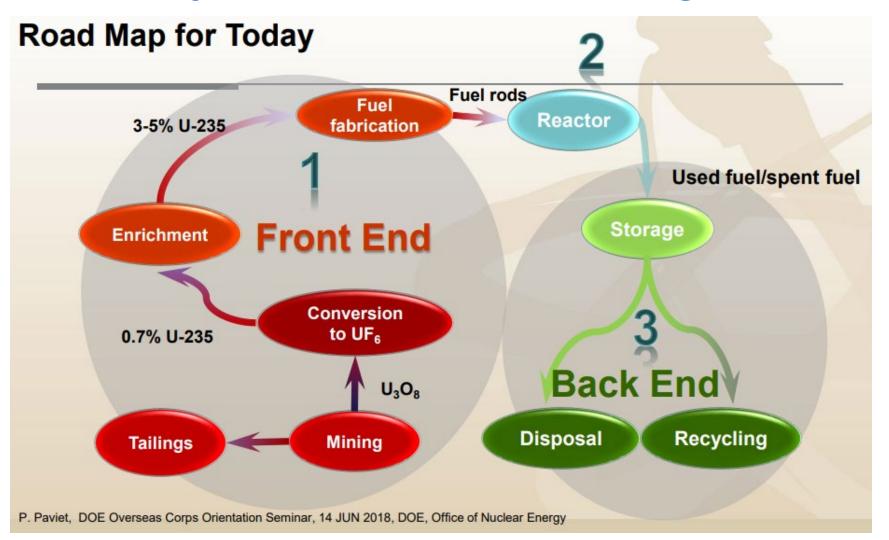
ENERGY TECHNOLOGIES



Taken from: Gehin, J. (2022)



Nuclear Fuel Cycle: Overview and Challenges



NUCLEAR FUEL CYCLE

Taken from: Paviet, P. (2022)

Advanced Reactors Fuel and Materials

ADVANCED REACTOR FUEL AND MATERIALS

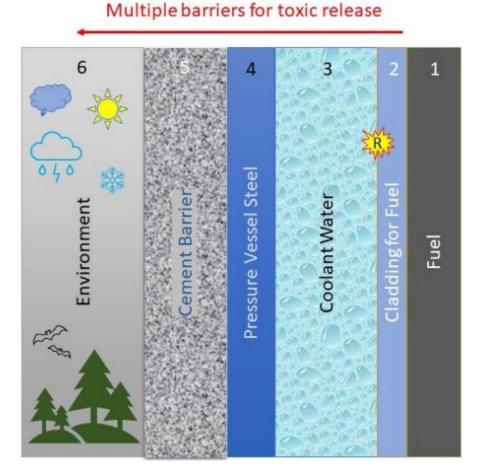




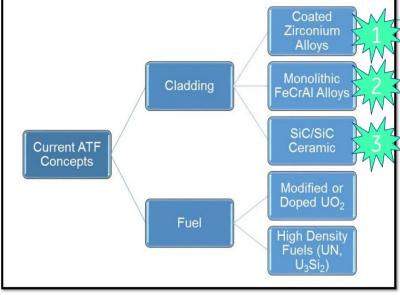








Advanced Fuel & Materials: Example



Taken from: Rebak, R. B. (2022)



Nuclear and Radiation Challenges: Fundamentals



NUCLEAR FUNDAMENTALS

Five main radiation damage "scourges":

- 1. Radiation hardening and embrittlement $(<0.4 T_M, >0.1 dpa)$
- 2. Phase instabilities from radiation-induced precipitation (0.3-0.6 T_M , >10 dpa)
- 3. Irradiation creep and growth ($<0.45 T_M$, >10 dpa)
- 4. Volumetric swelling from void formation $(0.3-0.6 T_M, >10 dpa)$
- 5. High temperature He embrittlement (>0.5 T_M , >10-100 appm He)

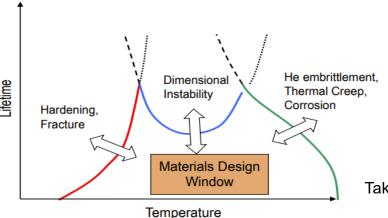
Bubbles, voids, precipitates, solute segregation SFT. Dislocation loops Grain boundary helium cavities Amorphization **Network dislocations** (intermetallics & ceramics) 10 nm Stage I Stage III Stage V 0.1 0.2 0.5 0.6 Irradiation Temperature (T/T_M) Taken from: Zinkle, S. (2022)

S.J. Zinkle, Phys. Plasmas 12 (2005) 058101; Zinkle & Busby, Mater. Today 12 (2009) 12

Nuclear and Radiation Challenges: Applications

- NUCLEAR FUNDAMENTALS

- Low T (< 0.4 Tm, < 0.1 dpa)
- Intermediate T (0.3 < Tm < 0.6, > 10 dpa)
- High T (> 0.4 Tm, > 10 dpa)

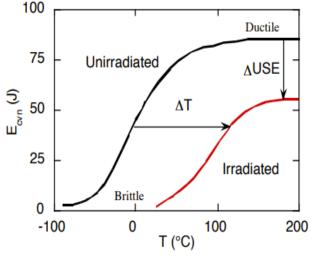


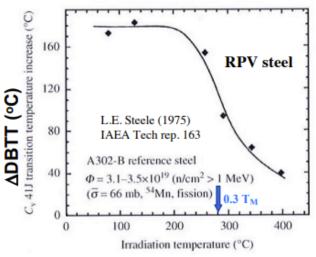
Wirth et al., 2013 SOFE proceedings

Taken from: Wirth, B. (2022)

RPV DBTT- Ductile to brittle transition temperature

Reactor pressure vessel (RPV) can be embrittled by exposure to neutrons, manifested by transition temperature increases (ΔT) and upper shelf energy decreases (ΔUSE) .





Fuel rod bowing

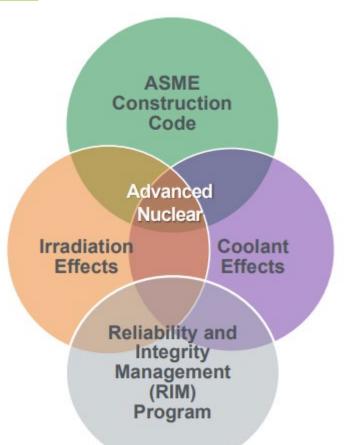


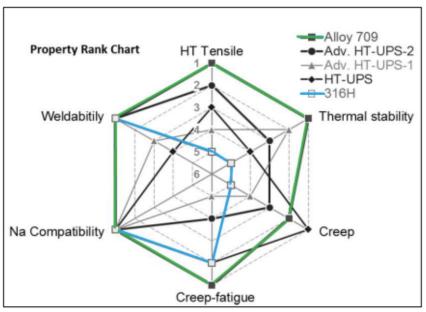
Taken from: Zinkle, S. (2022)

Nuclear and Radiation Challenges: New Reactors



NUCLEAR FUNDAMENTALS





Property rank chart for austenitic alloys

Power density
(W/cc)

10

AGR (US)

German

Japan

Fast fluence
(×10²⁵ n/m²)

Packing

fraction (%)

Taken from: Sham, S. (2022)

Taken from: Sham, S. (2022)

New and advanced reactors design differs based on fuel, coolant, operating conditions and structural materials!!

Taken from: Demkowicz, D. (2022)

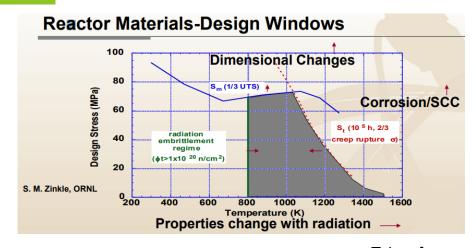
Conventional TRISO fuel performance envelopes

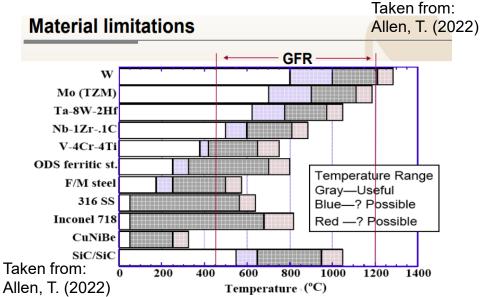
ADVANCED REACTOR

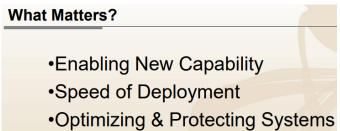
FUEL AND

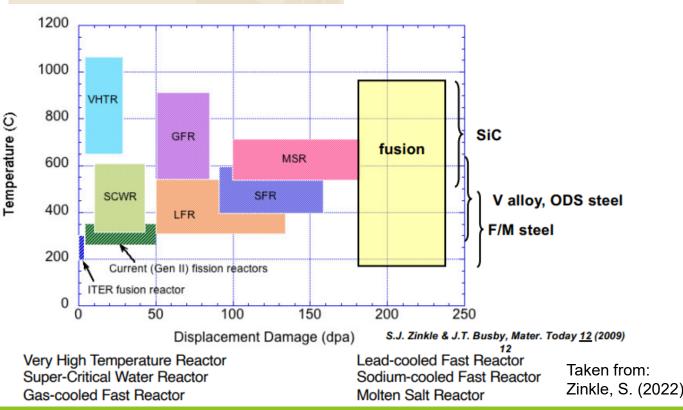
MATERIALS

Fuel and Materials: R&D Challenges





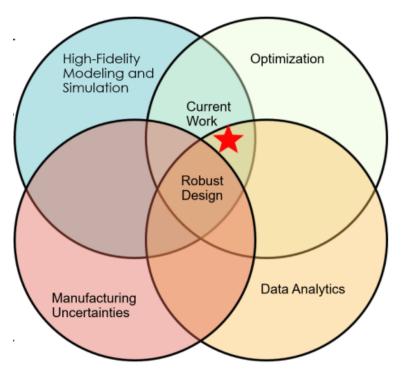




Part-3:

Modeling: Computational Methods for Nuclear Challenge





Ref. Gurecky, et al., "Parallel Simulated Annealing with Embedded Machine Learning and Multifidelity Models for Reactor Core Design, PHYSOR 2022

Simulations TIMESCALE sec Boundary Conditions Thermo-**Phase Field** Chemical ms Models Kinetic Monte Carlo Constitutive Properties Molecular **Dynamics** Electronic Structure LENGTHSCALE nm mm m

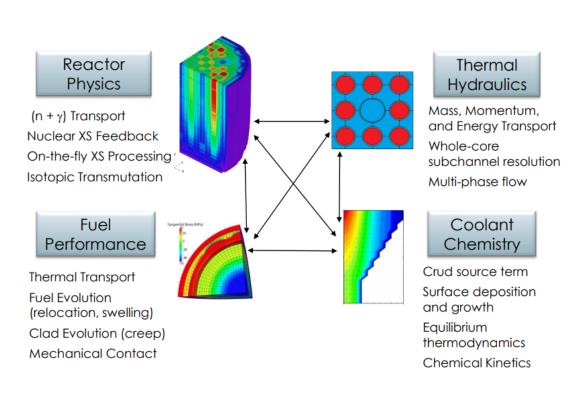
Finite Element

Taken from: Kropaczek, D. (2022)

Taken from: Wirth, B. (2022)

Modeling: Computational Complexity





Complexity of nuclear fuel performance Operating **Variables** Conditions Densification Fission gas Thermal Clad Creep **Fuel Swelling** Grain size conductivity Fuel Creep Clad Clad Swelling Elastic dislocations constants Grain growth Clad oxidation Fuel point Clad pressure defects Defect prod. & transport Clad Yield Microcracks H transport stress FG prod. & Sintered por Fracture transport Hydride stress precipitation Clad point FG release defects FG diffusivity Fuel Clad Zr-hydride defect cracking plasticity diffusivity Clad H conc **Fuel Unit** Material Clad Unit mechanisms State variables properties mechanisms From M. Tonks et al., Annal. Nucl. Energy 105, 11–24 (2017).

Taken from:

Andersson, D. (2022)

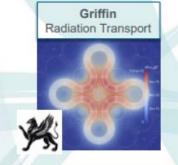
Taken from:

Kropaczek, D. (2022)

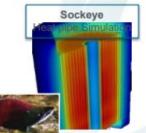


COMPUTATIONAL METHODS FOR

NUCLEAR CHALLENGES







MOOSE

Bison

Nuclear Fuel Performance

Marmot

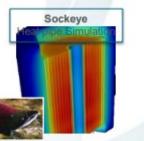
Mesoscale Materials

SAM

Multiscale Multiphysics

Taken from:

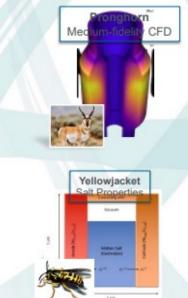
Gehin, J. (2022)



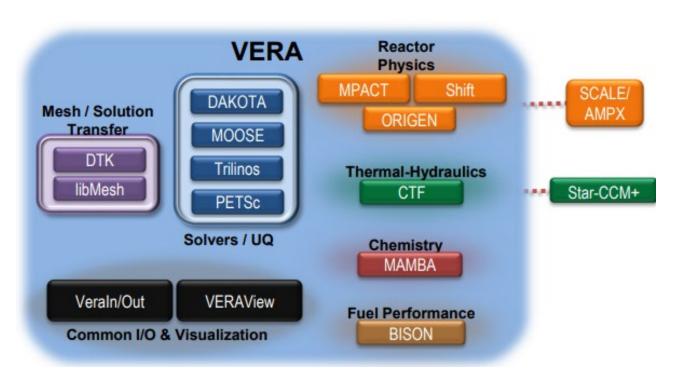
Grizzly

Structural Mechanics for

Component



Modeling: Computational Tools



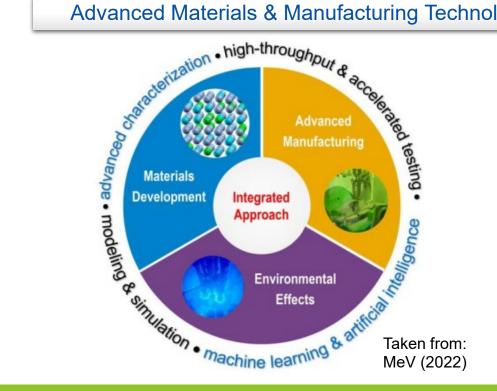
Taken from: Kropaczek, D. (2022)

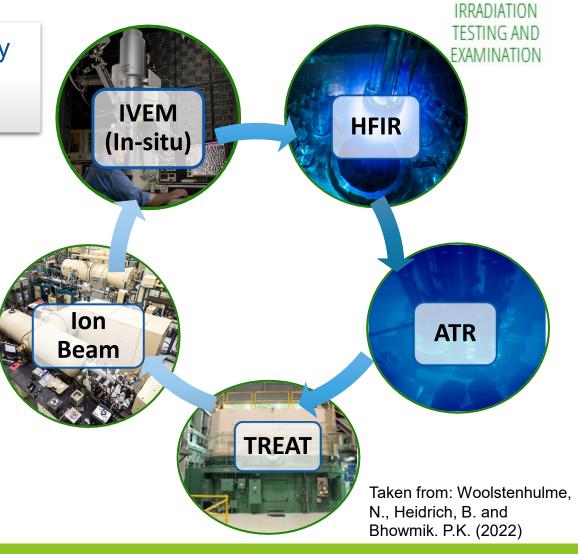


Experiment: Irradiation Testing and Examination

Accelerating nuclear fuels and materials qualification by combining high through-put materials irradiation and testing, advanced PIE, and Multiphysics modeling

Advanced Materials & Manufacturing Technologies



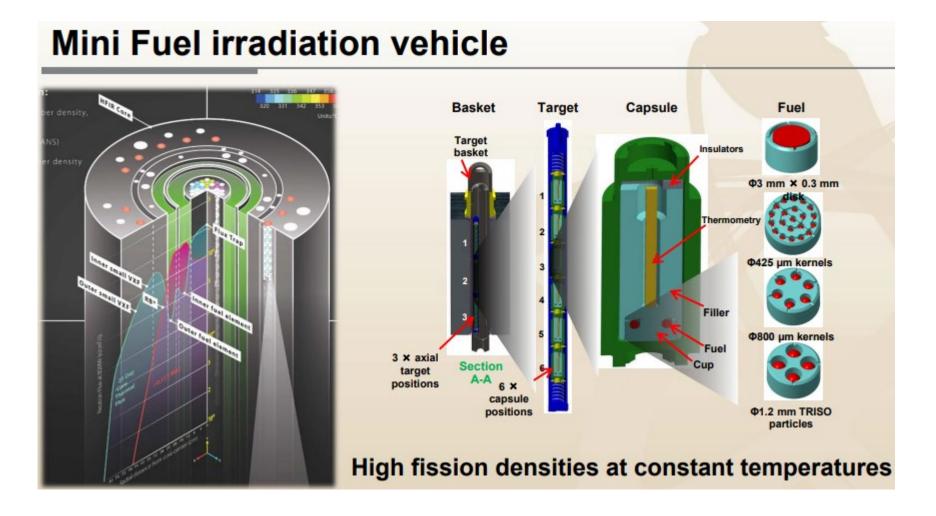


Experiment: Irradiation Test Apparatus at HFIR



TESTING AND

EXAMINATION



Taken from: Bhowmik. P.K. (2022)

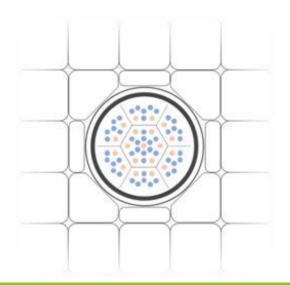
Experiment: Irradiation Test Capabilities at TREAT

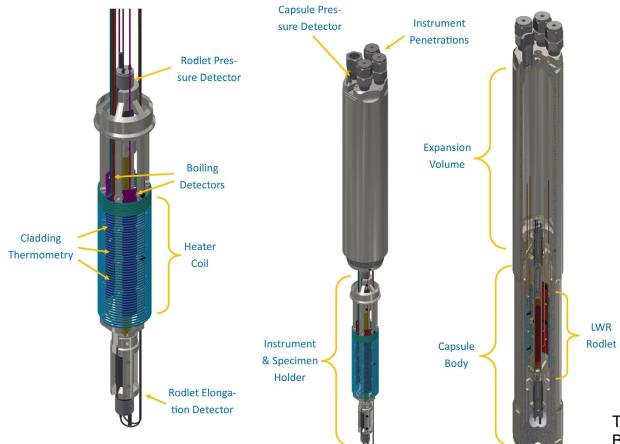
IRRADIATION

TESTING AND

EXAMINATION

- Microreactor system scale benchmark experiments (NIMBLE)
- Inert gas test capsule (SETH)
- Sodium capsule (THOR)
- Sodium loop (Mk-IIIR)
- Gas Fast Reactor Loop
- Molten Salt





Taken from: Bhowmik. P.K. (2022)

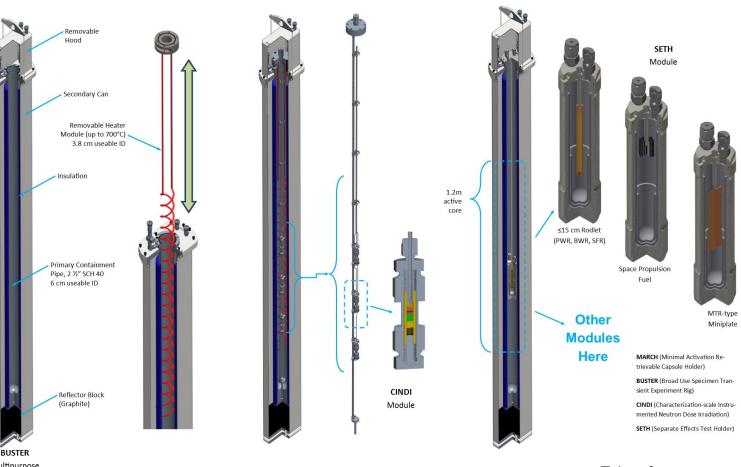


IRRADIATION

TESTING AND

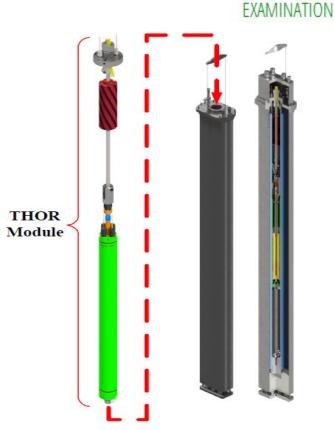
Experiment: Irradiation Test Capabilities at TREAT (cont'd)

The MARCH System



TREAT is the nexus, MARCH is the gateway

Taken from: Bhowmik. P.K. (2022)



Temperature Heatsink Overpower Response (THOR)

Containment

Structure

Validation: Reactor Fuel and Materials Licensing Approaches

The NRC Regulates

Radioactive materials for medical, industrial and academic use

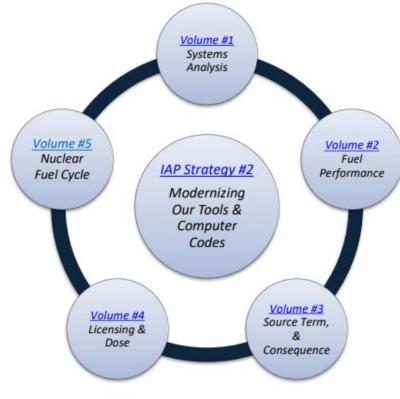


Transportation, storage and disposal of nuclear material and waste, and decommissioning of nuclear facilities

Commercial power reactors, research and test reactors and new reactor designs



Physical security, source security and cyber security



NRC advancing by













Taken from: Furstenau, R. (2022),

Validation: Reactor Fuel and Materials Licensing Challenges

Advanced Manufacturing Technologies (AMT)





Licensing Modernization Project





Components of an AMT Qualification Program

Approved Quality Assurance Program

Fabrication Process
Qualification

Supplemental Testing Production Process
Control and
Verification

Monitoring

Performance

Advanced and New Fuels

Taken from: Furstenau, R. (2022),

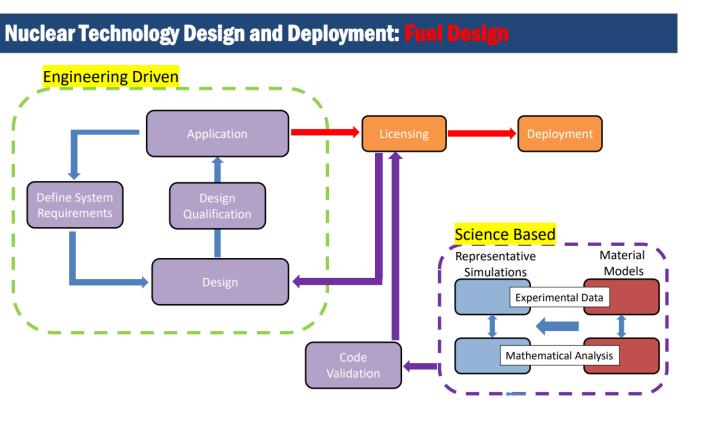
Unirradiated Materials Testing Test Reactor Irradiations and Testing Lead Test Assembly Irradiations and Testing Transient Irradiations and Testing

Updates to Analyses of Record

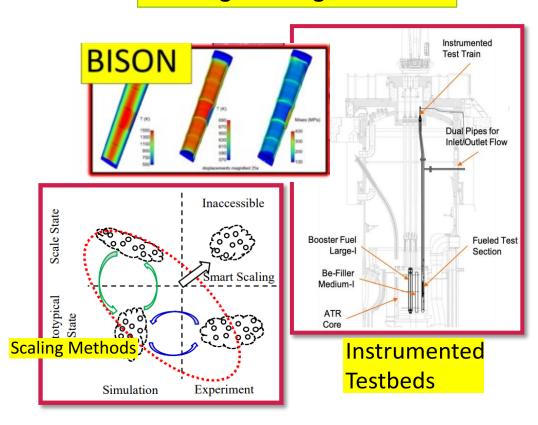
Source Term and Other Non-Fuel Performance Testing

Part-3:

Validation: Fuels and Materials Licensing Pathways

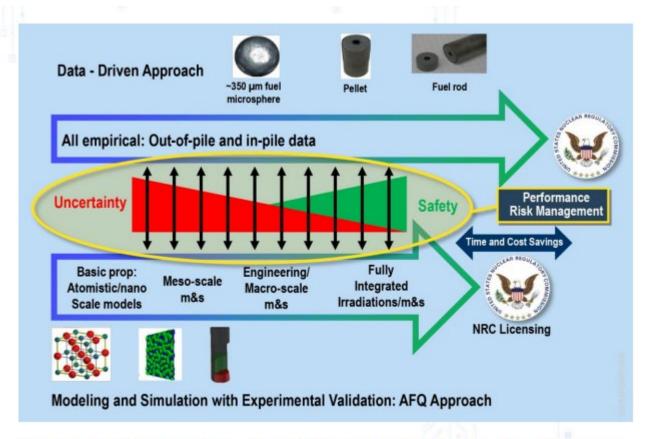


Engineering Driven



Taken from: Wachs, D. (2022)

Validation: Accelerated Fuel Qualification and Licensing



Accelerated Fuel Qualification White Paper, by the Accelerated Fuel Qualification Working Group White Paper Task Force (slide courtesy R. Faibich, GA).

Taken from: Andersson, D. (2022)



Accelerating nuclear fuels and materials qualification by

- Combining high through-put materials irradiation and testing,
 - Advanced PIE, and
 - Multiphysics modeling

References

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- Rebak, R. B. (2022), "ATF Cladding," Lecture notes, MeV Summer School, General Electric Research.
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- Wachs, D. (2022), "Bridging Modeling and Experimentation: Methodologies for Accelerating the Development and Qualification of Advanced Nuclear Fuel Technology," Lecture notes, MeV Summer School, Idaho National Laboratory.
- Woolstenhulme, N. (2022), "Accelerated Irradiation Design," Lecture notes, MeV Summer School, Idaho National Laboratory.
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Thank you for your attention!

The speaker acknowledges contributions from the MeV School 2022 for the content presented here.