INL/MIS-22-69220-Revision-0

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

September 2022

Palash Kumar Bhowmik

Changing the World's Energy Future

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/MIS-22-69220-Revision-0

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

Palash Kumar Bhowmik

September 2022

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

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

Palash K. Bhowmik, PhD
Irradiation Experiment Thermal Hydraulics Analysis, Post-doctoral Research Associate
PalashKumar.Bhowmik@inl.gov

Idaho National Laboratory

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

mevschool.net | July 18-29, 2022 | mevschool@inl.gov

MeV Modeling, Experimentation & Validation SUMMER SCHOOL

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

Argonne NATIONAL LABORATORY | INL Idaho National Laboratory | OAK RIDGE National Laboratory | Idaho State UNIVERSITY

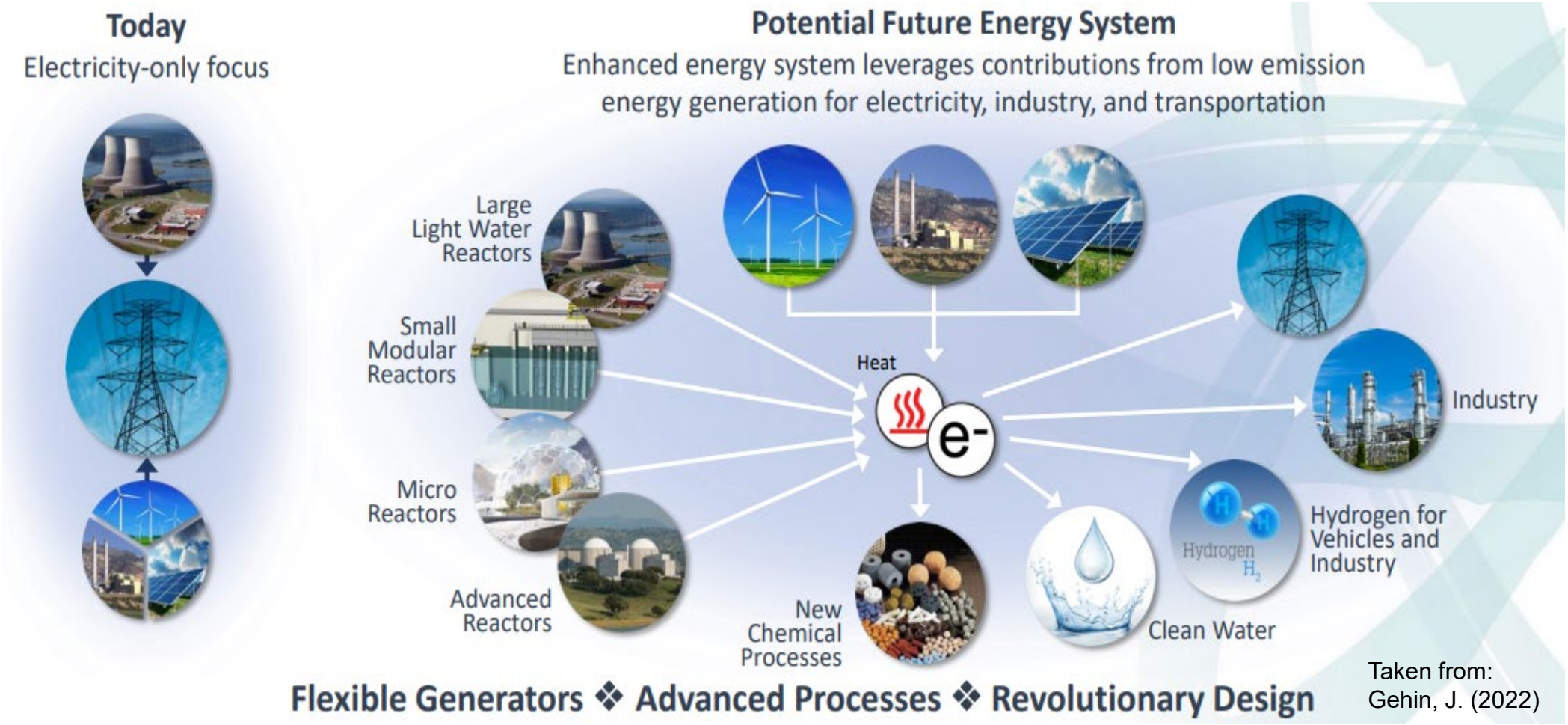
Part-2:

Enhancing Reactor Technologies and Systems

ENHANCING CURRENT REACTOR TECHNOLOGIES

LWRS

- Plant Modernization
- Flexible Plant Operation & Generation
- Risk Informed System Analysis
- Materials Research
- Physical Security



Taken from: Gehin, J. (2022)

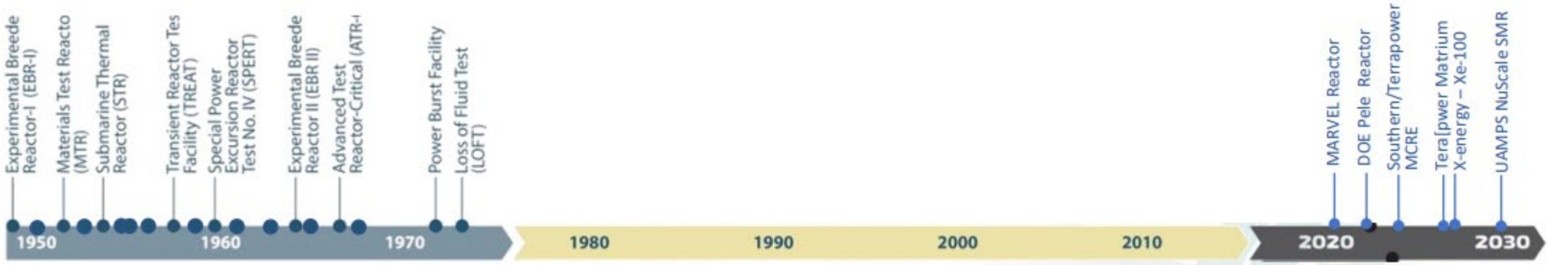
Part-2:

Advanced Reactors: Testing at INL

ADVANCED NUCLEAR ENERGY TECHNOLOGIES

National Reactor Testing Station
52 Reactors at INL over 25 years

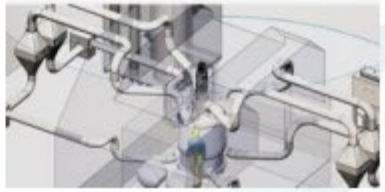
National Reactor Innovation Center



MARVEL
2022-23

NRIC Test Beds
2023

DOD Pele Reactor
2023-24



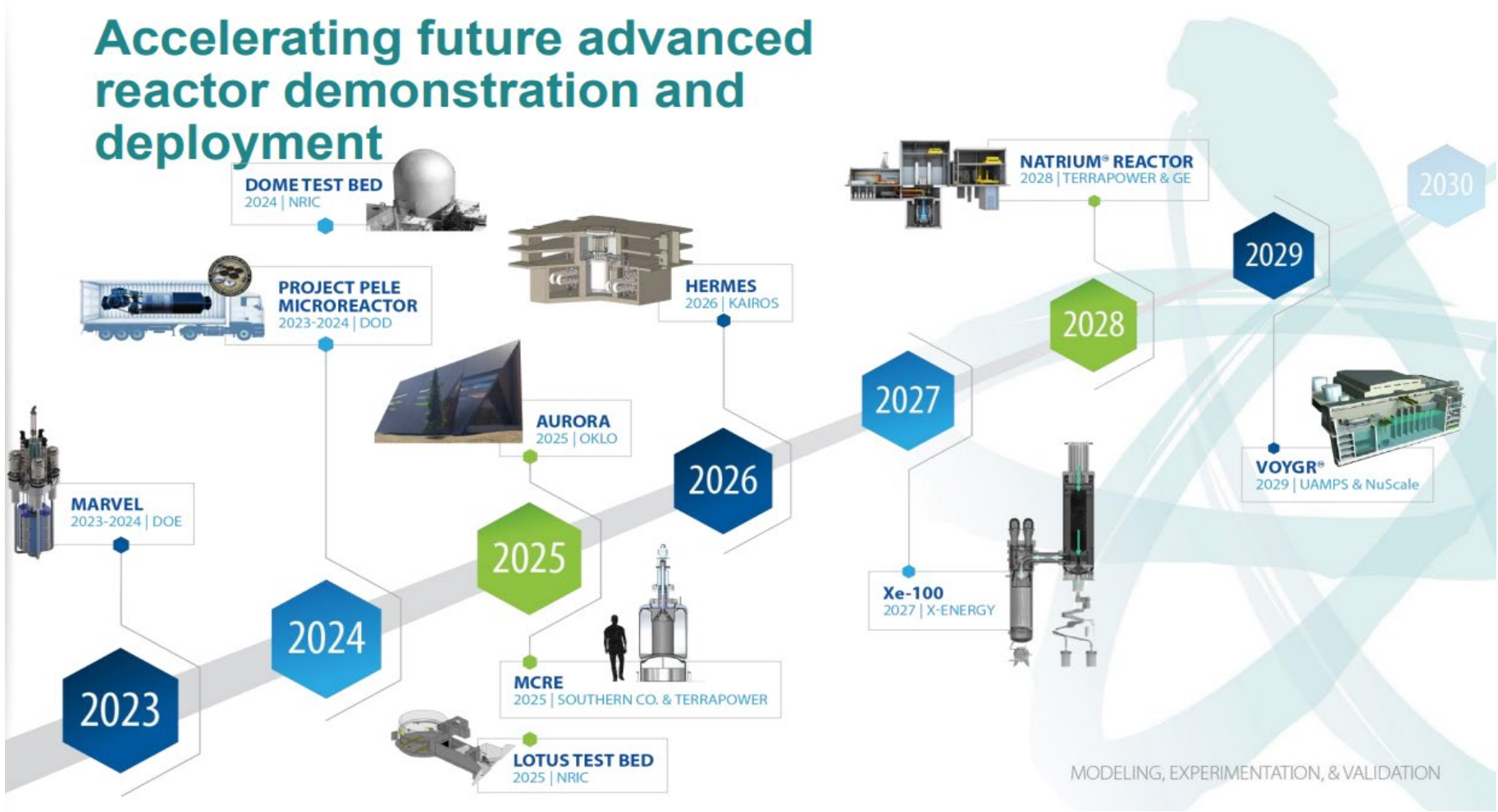
Southern/Terapower MCRE
2025

UAMPS/NuScale SMR
2029

Taken from:
Gehin, J. (2022)

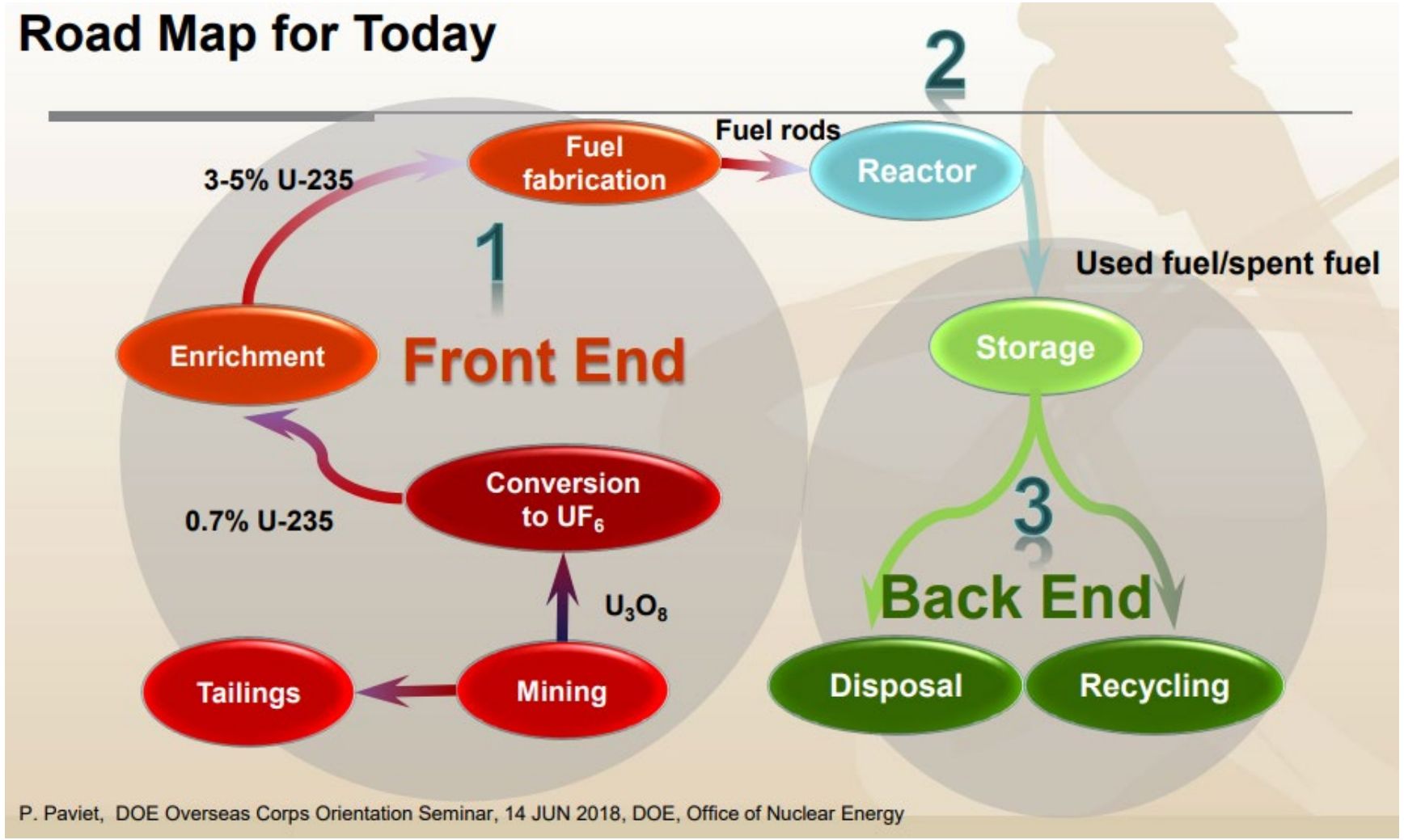
Advanced Reactors: Demonstration and Deployment

ADVANCED NUCLEAR ENERGY TECHNOLOGIES



Taken from:
Gehin, J. (2022)

Nuclear Fuel Cycle: Overview and Challenges



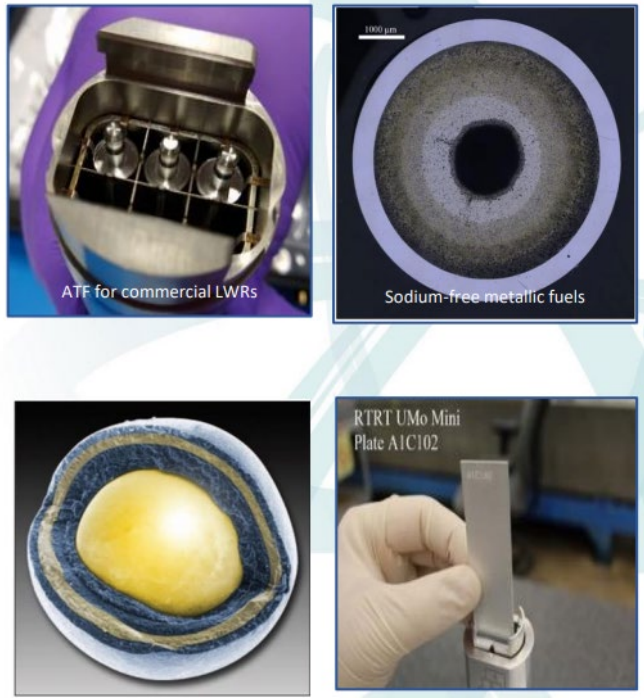
Taken from:
Paviet, P. (2022)

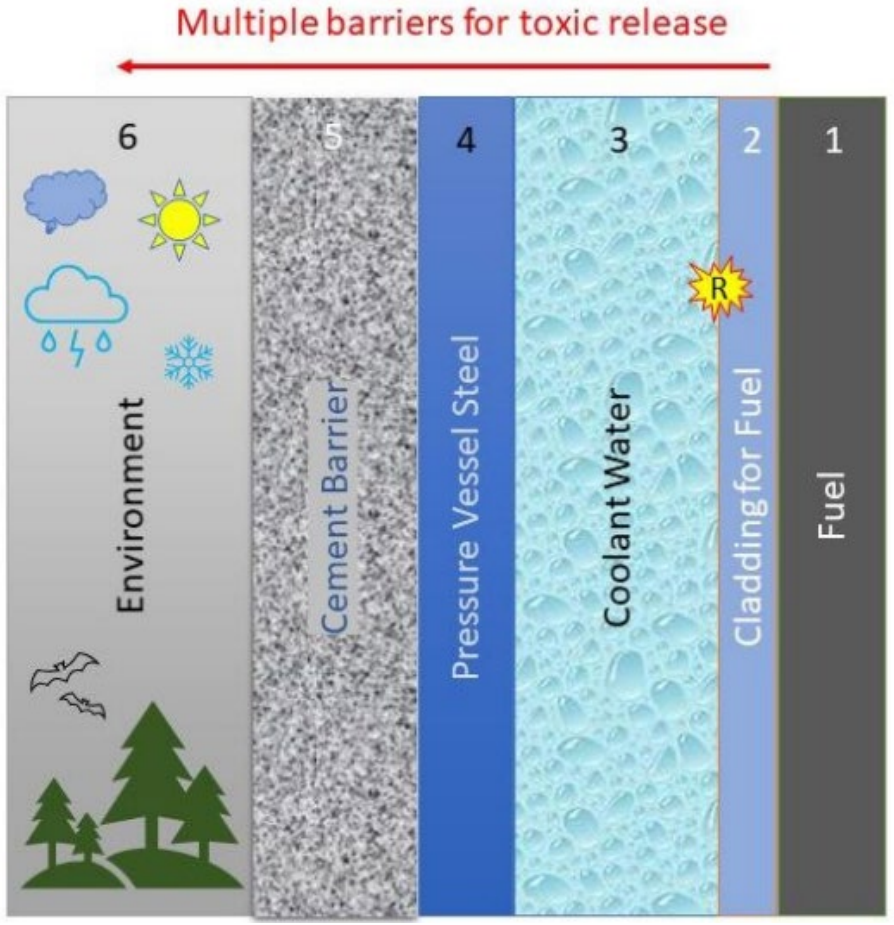
Part-3:

Advanced Reactors Fuel and Materials

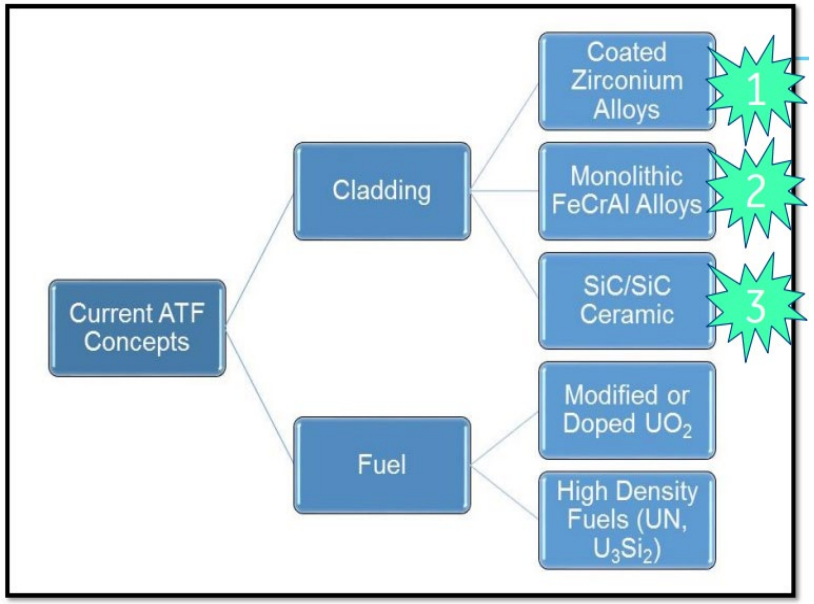
ADVANCED REACTOR FUEL AND MATERIALS

Fuel & Materials





Advanced Fuel & Materials: Example

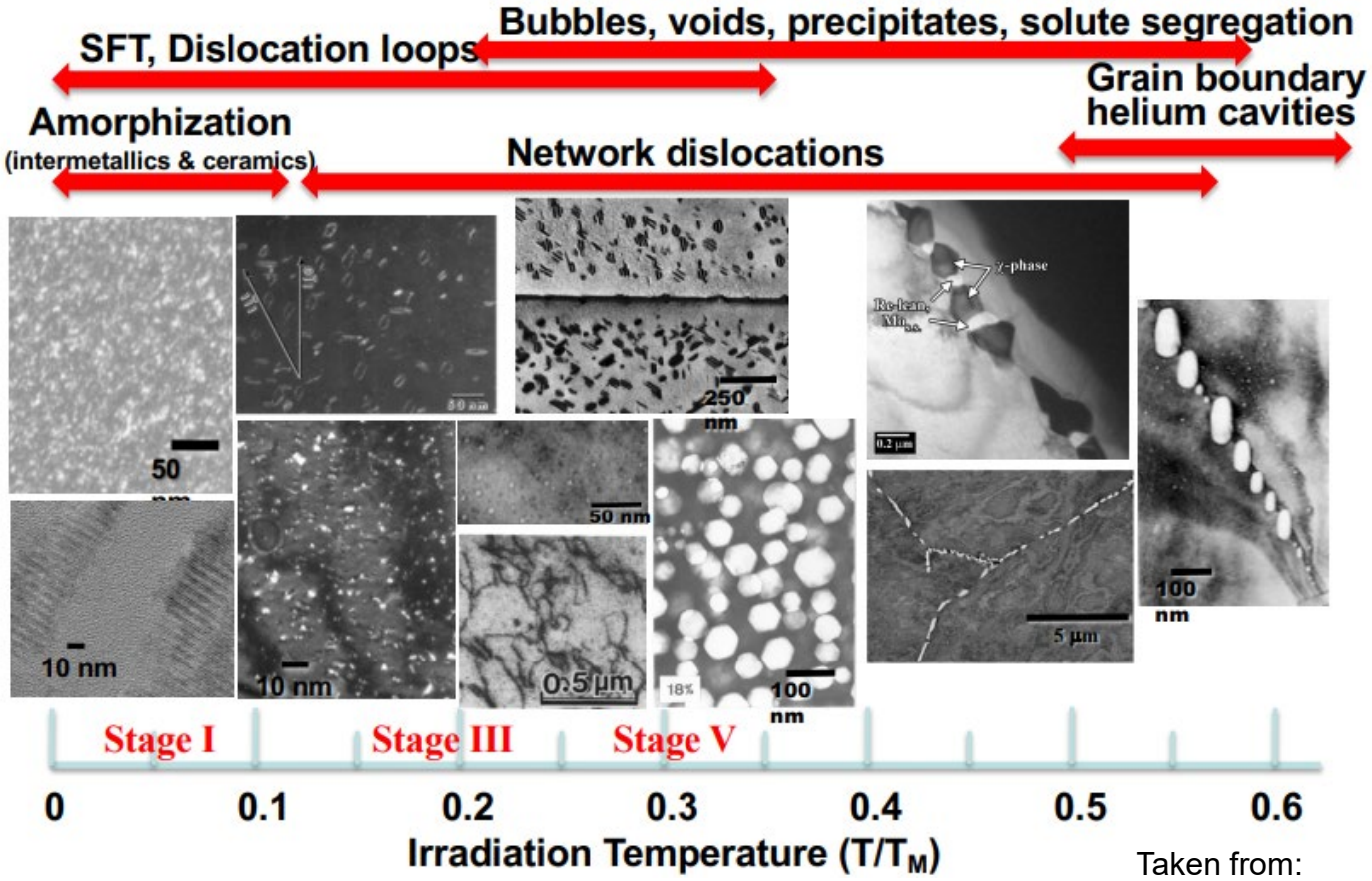


Taken from: Rebak, R. B. (2022)

Nuclear and Radiation Challenges: 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)



Taken from:
Zinkle, S. (2022)

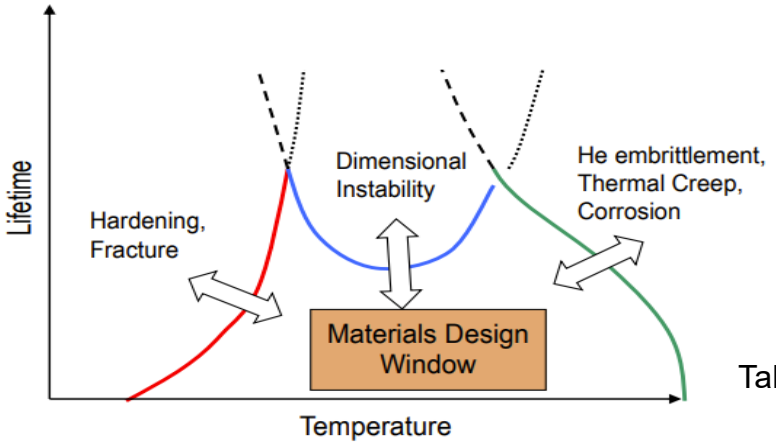
S.J. Zinkle, Phys. Plasmas 12 (2005) 058101;
Zinkle & Busby, Mater. Today 12 (2009) 12

Part-3:

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)

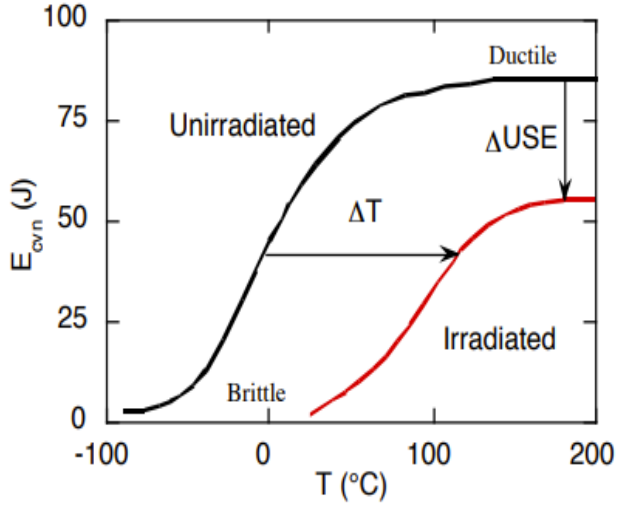


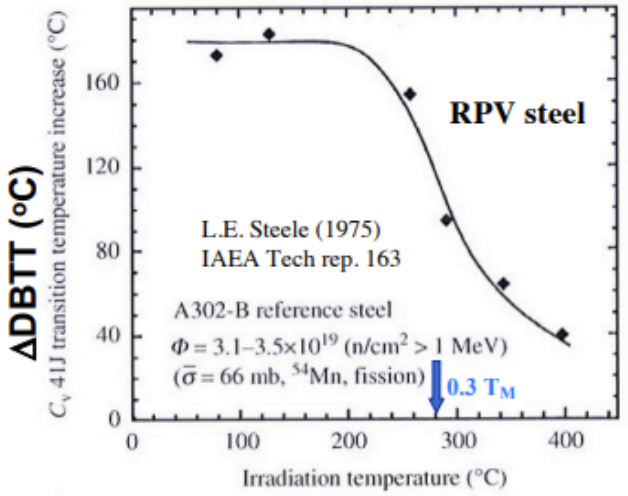
Taken from: Wirth, B. (2022)

RPV DBTT- Ductile to brittle transition temperature

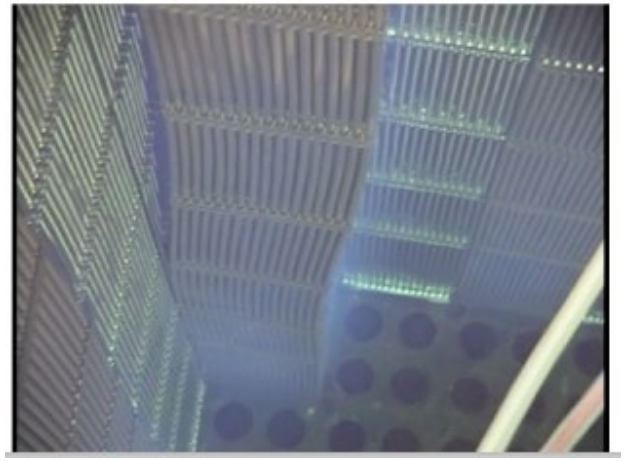
Wirth et al., 2013 SOFE proceedings

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

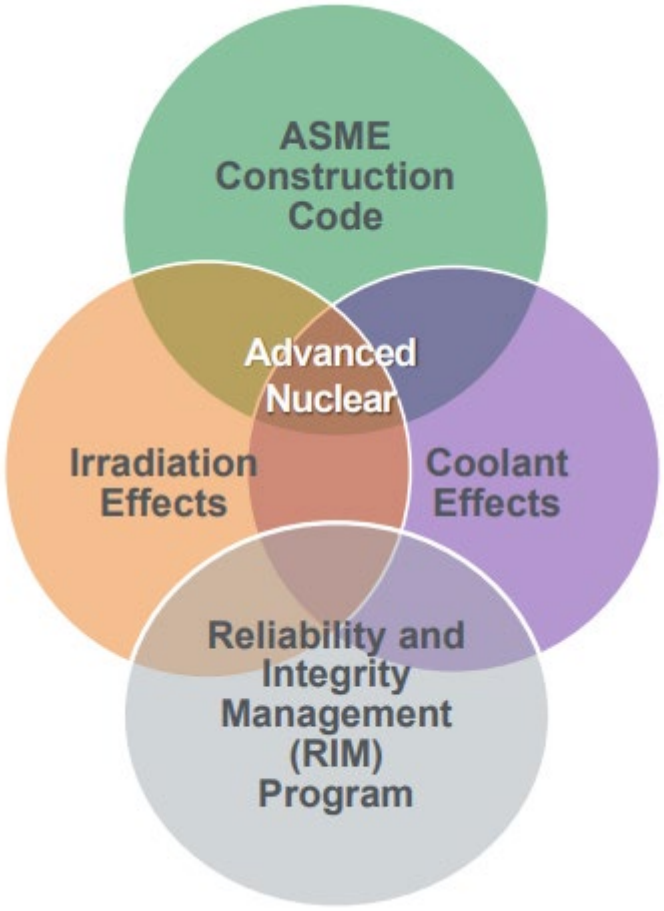


Taken from: Zinkle, S. (2022)

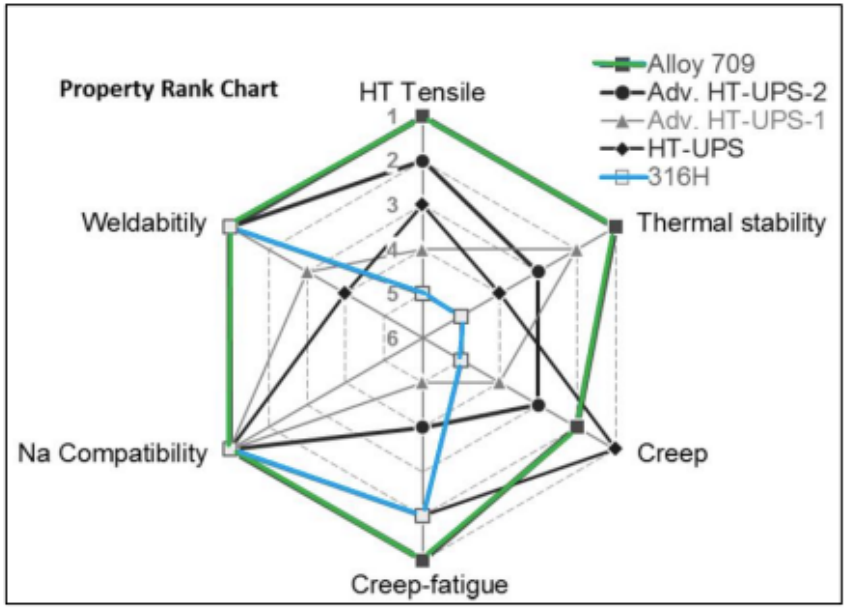
Part-3:

Nuclear and Radiation Challenges: New Reactors

NUCLEAR FUNDAMENTALS

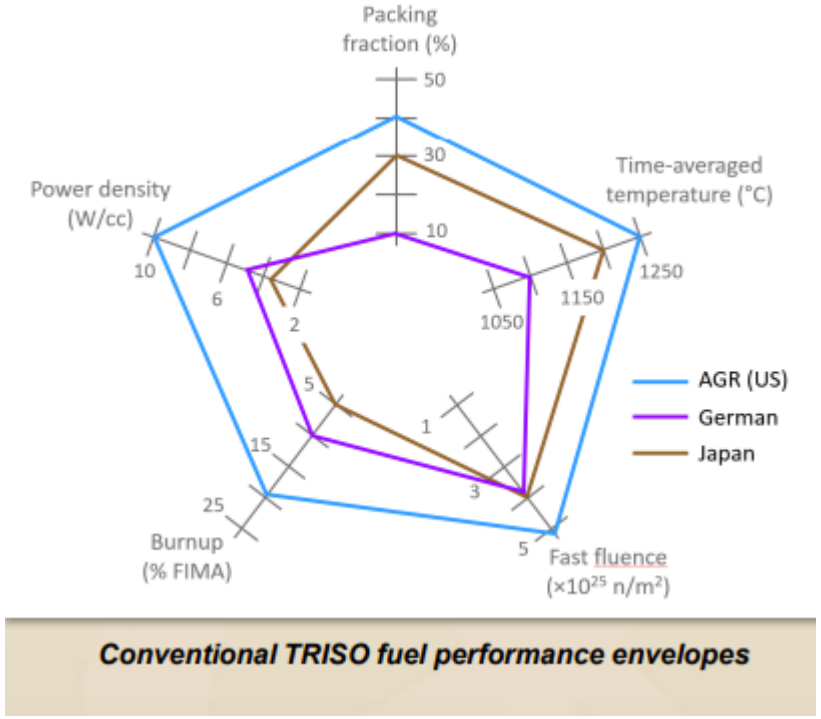


Taken from: Sham, S. (2022)



Property rank chart for austenitic alloys

Taken from: Sham, S. (2022)



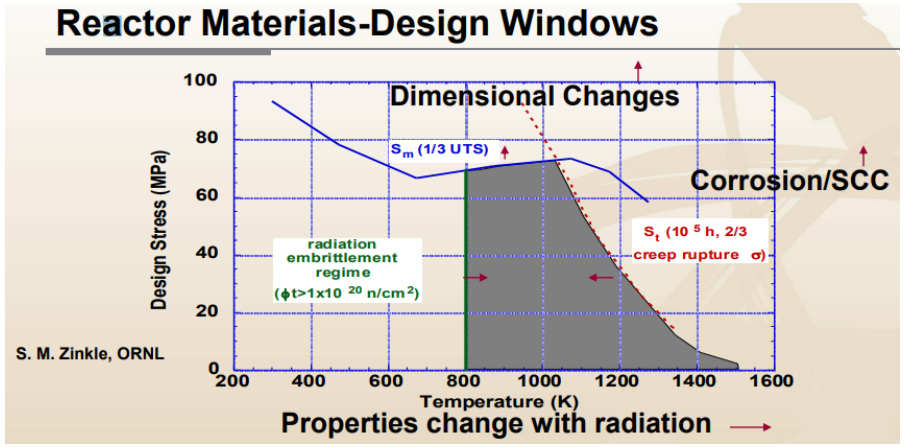
Conventional TRISO fuel performance envelopes

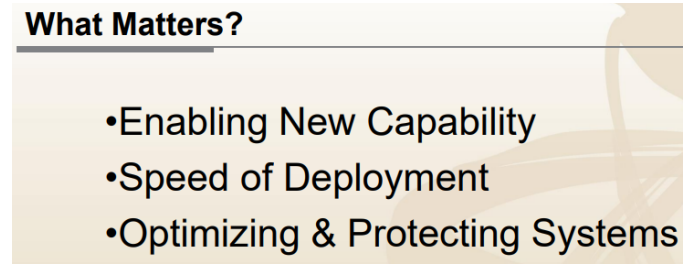
Taken from: Demkowicz, D. (2022)

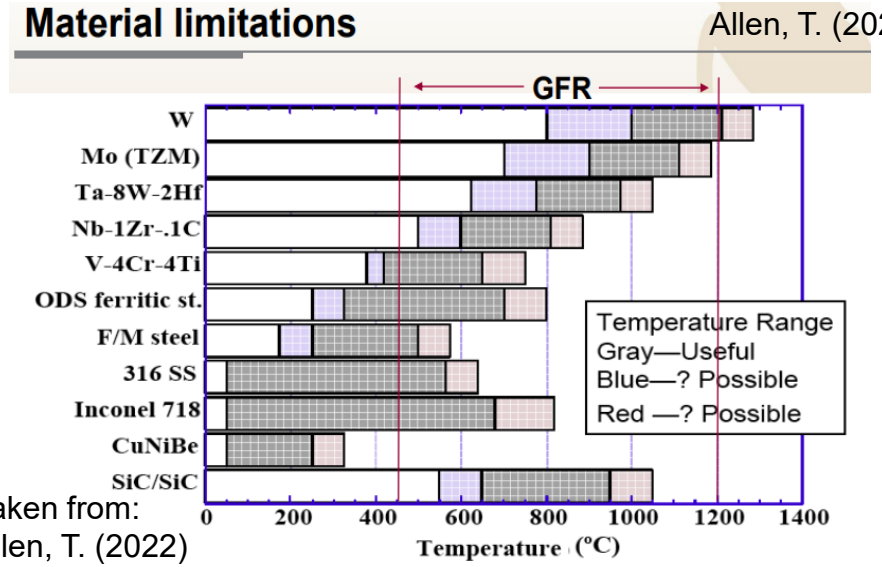
New and advanced reactors design differs based on fuel, coolant, operating conditions and structural materials !!

Fuel and Materials: R&D Challenges

ADVANCED REACTOR FUEL AND MATERIALS

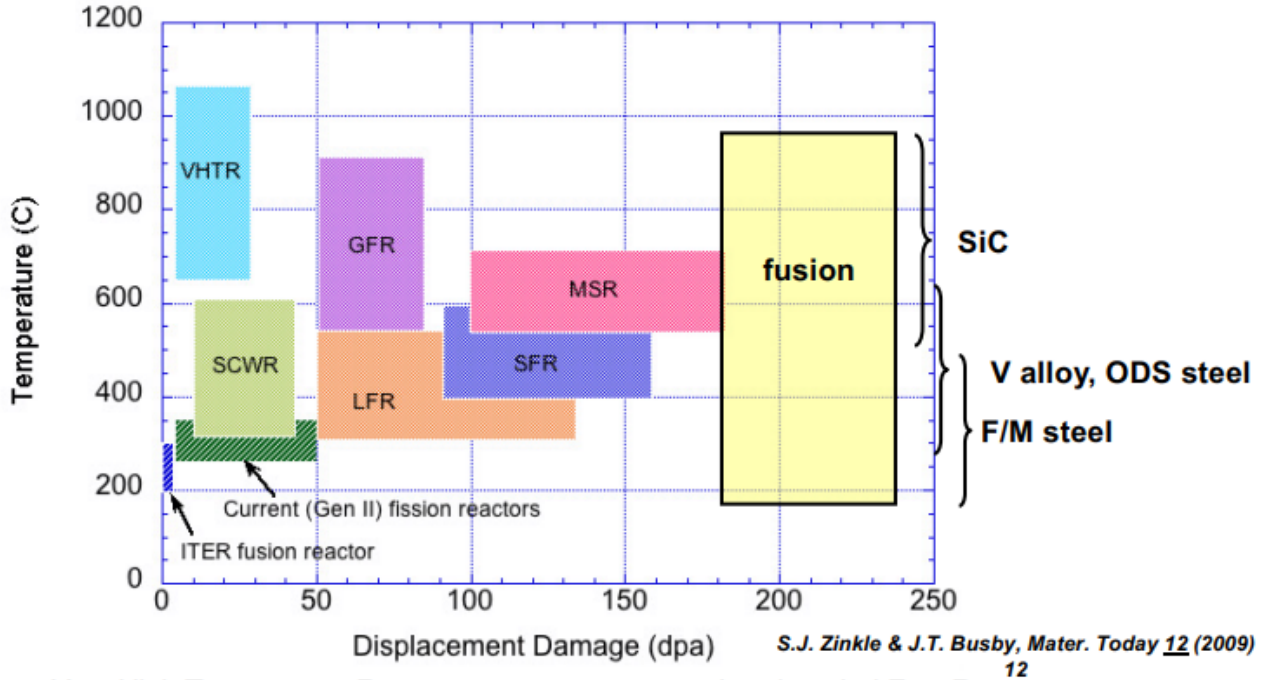






Taken from:
Allen, T. (2022)

Taken from:
Allen, T. (2022)



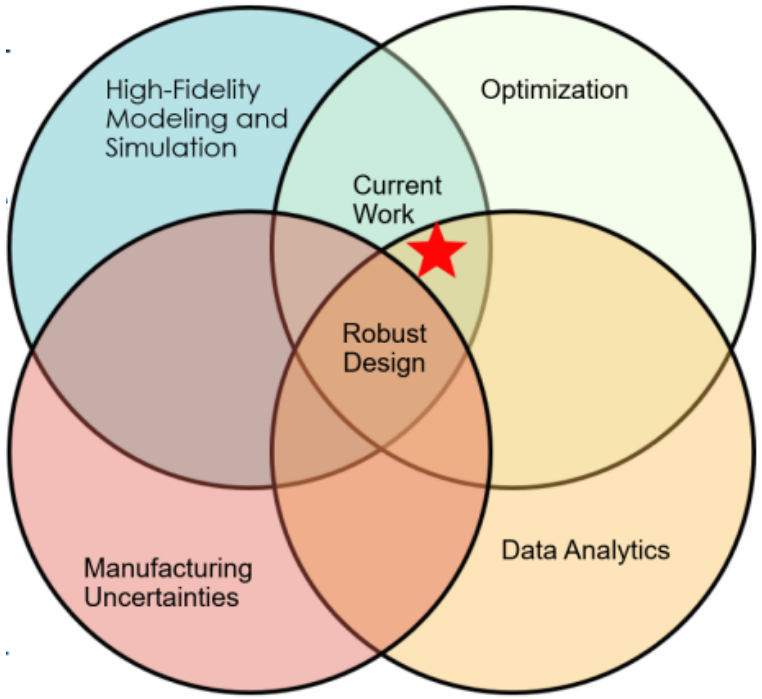
Very High Temperature Reactor
Super-Critical Water Reactor
Gas-cooled Fast Reactor

Lead-cooled Fast Reactor
Sodium-cooled Fast Reactor
Molten Salt Reactor

Taken from:
Zinkle, S. (2022)

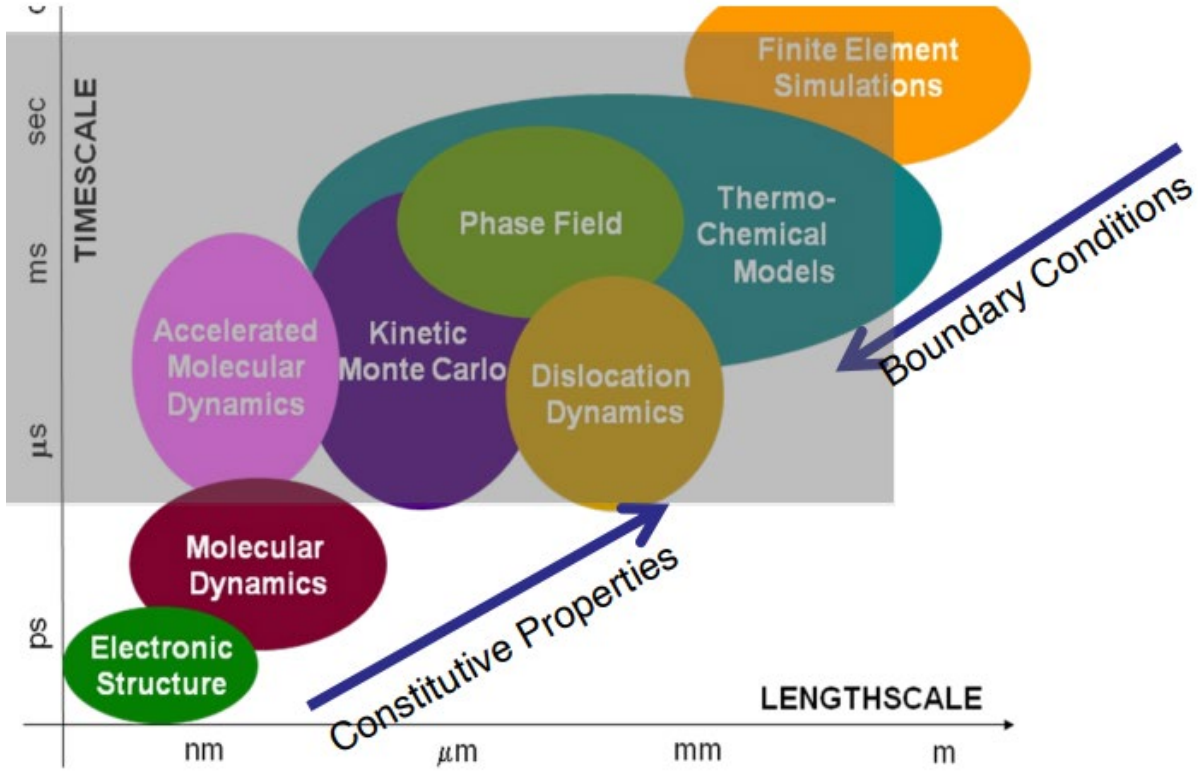
Modeling: Computational Methods for Nuclear Challenge

COMPUTATIONAL METHODS FOR NUCLEAR CHALLENGES



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

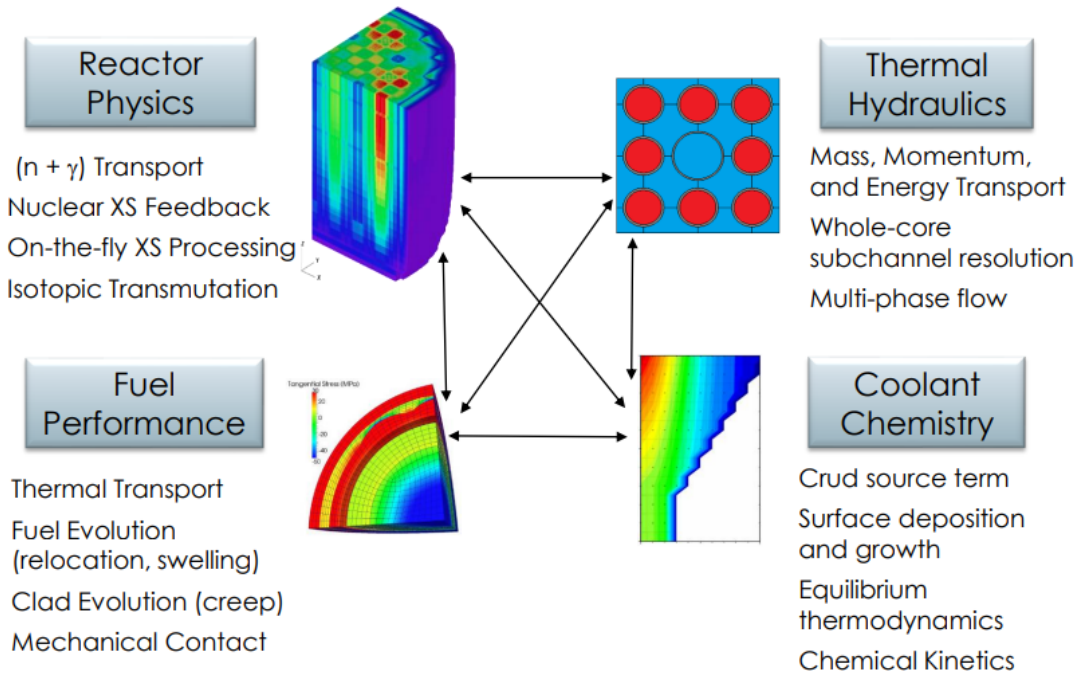
Taken from:
Kropaczek, D. (2022)



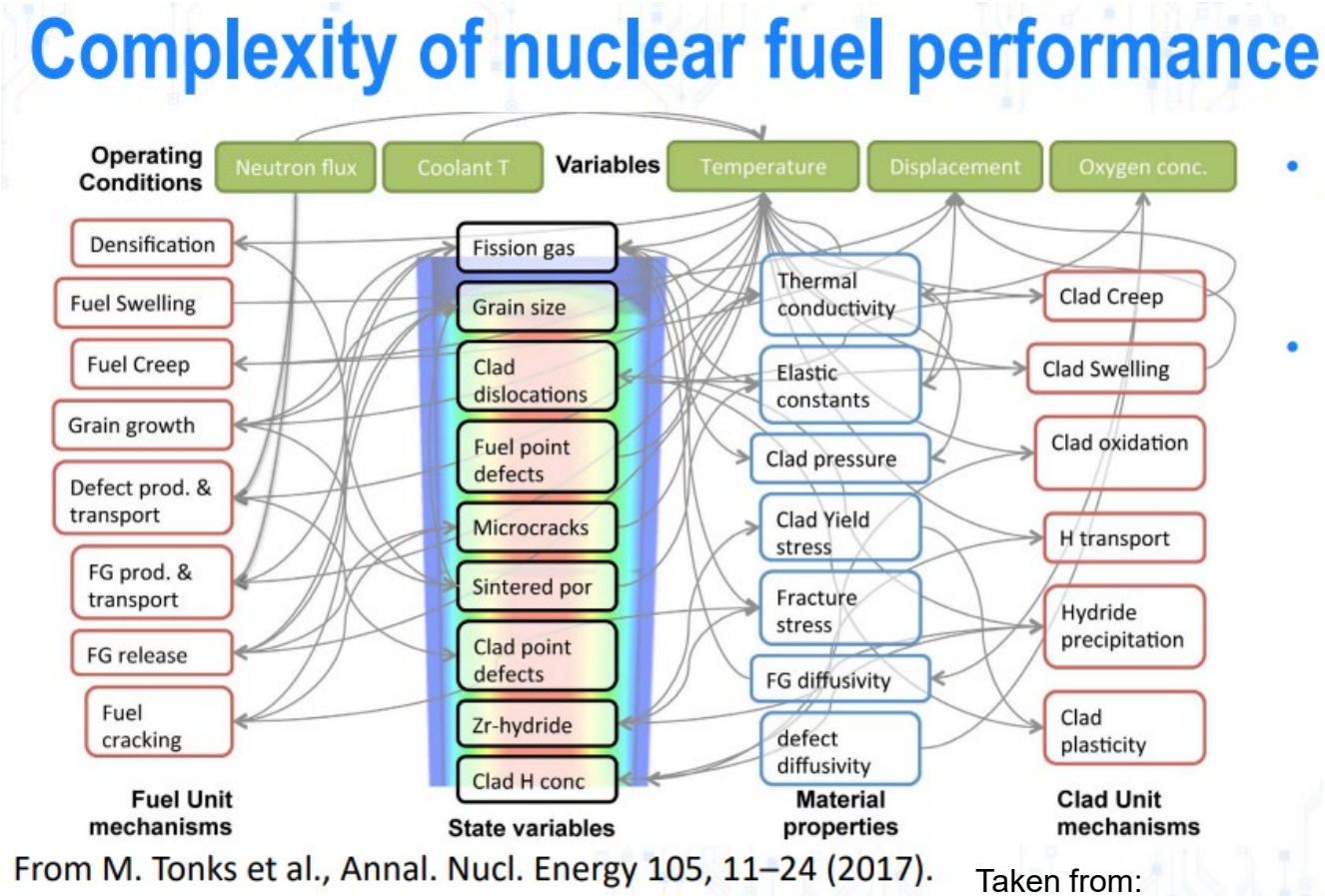
Taken from:
Wirth, B. (2022)

Modeling: Computational Complexity

COMPUTATIONAL METHODS FOR NUCLEAR CHALLENGES



Taken from:
Kropaczek, D. (2022)

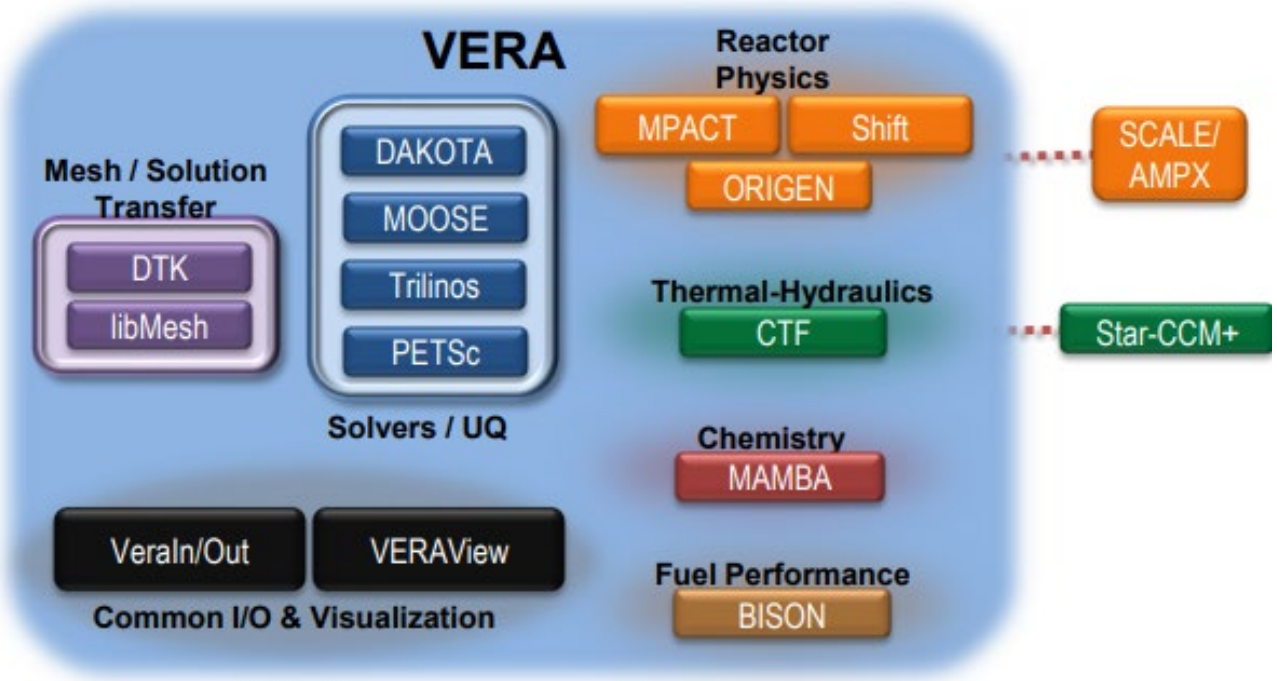


From M. Tonks et al., Annal. Nucl. Energy 105, 11–24 (2017).

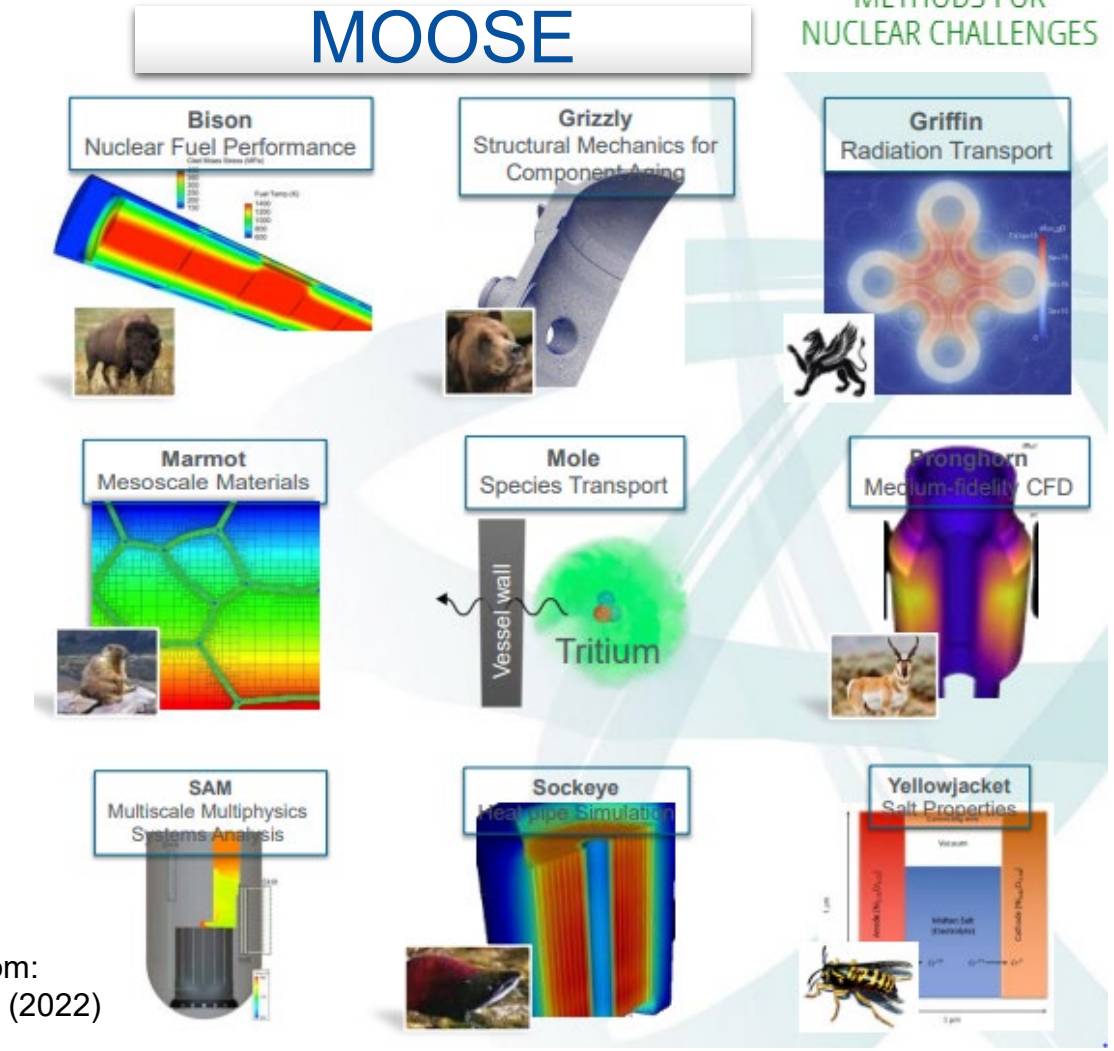
Taken from:
Andersson, D. (2022)

Part-3:

Modeling: Computational Tools



Taken from:
Kropaczek, D. (2022)



Taken from:
Gehin, J. (2022)

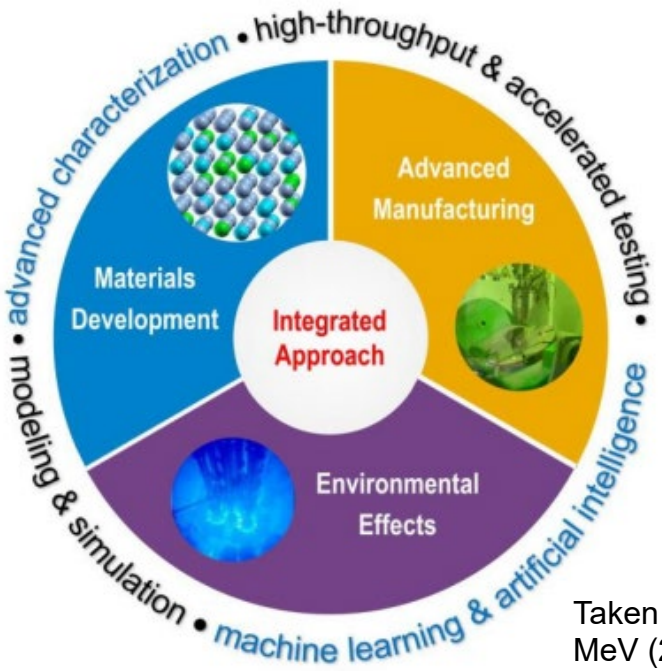
Part-3:

Experiment: Irradiation Testing and Examination

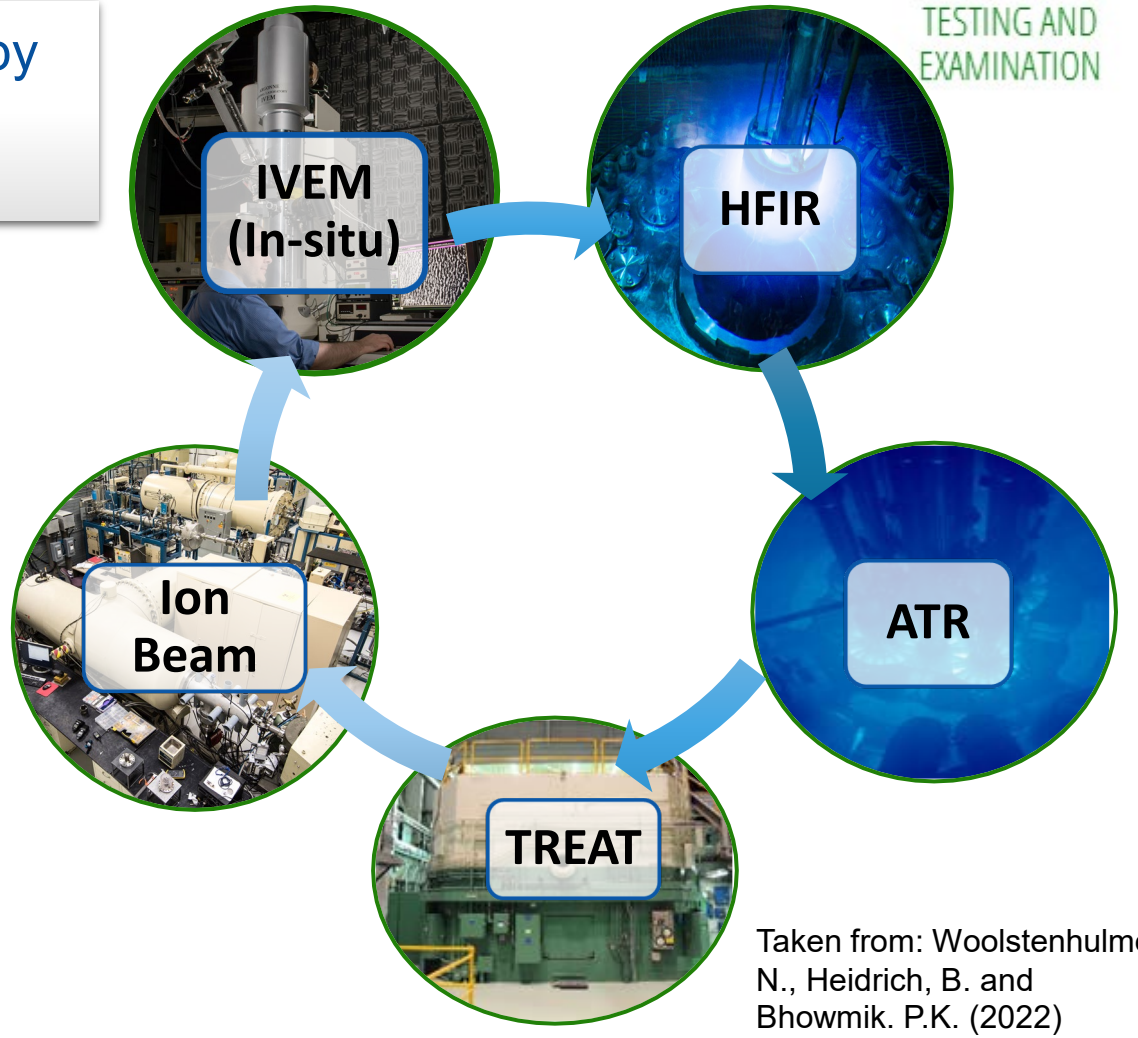
IRRADIATION TESTING AND EXAMINATION

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

Advanced Materials & Manufacturing Technologies



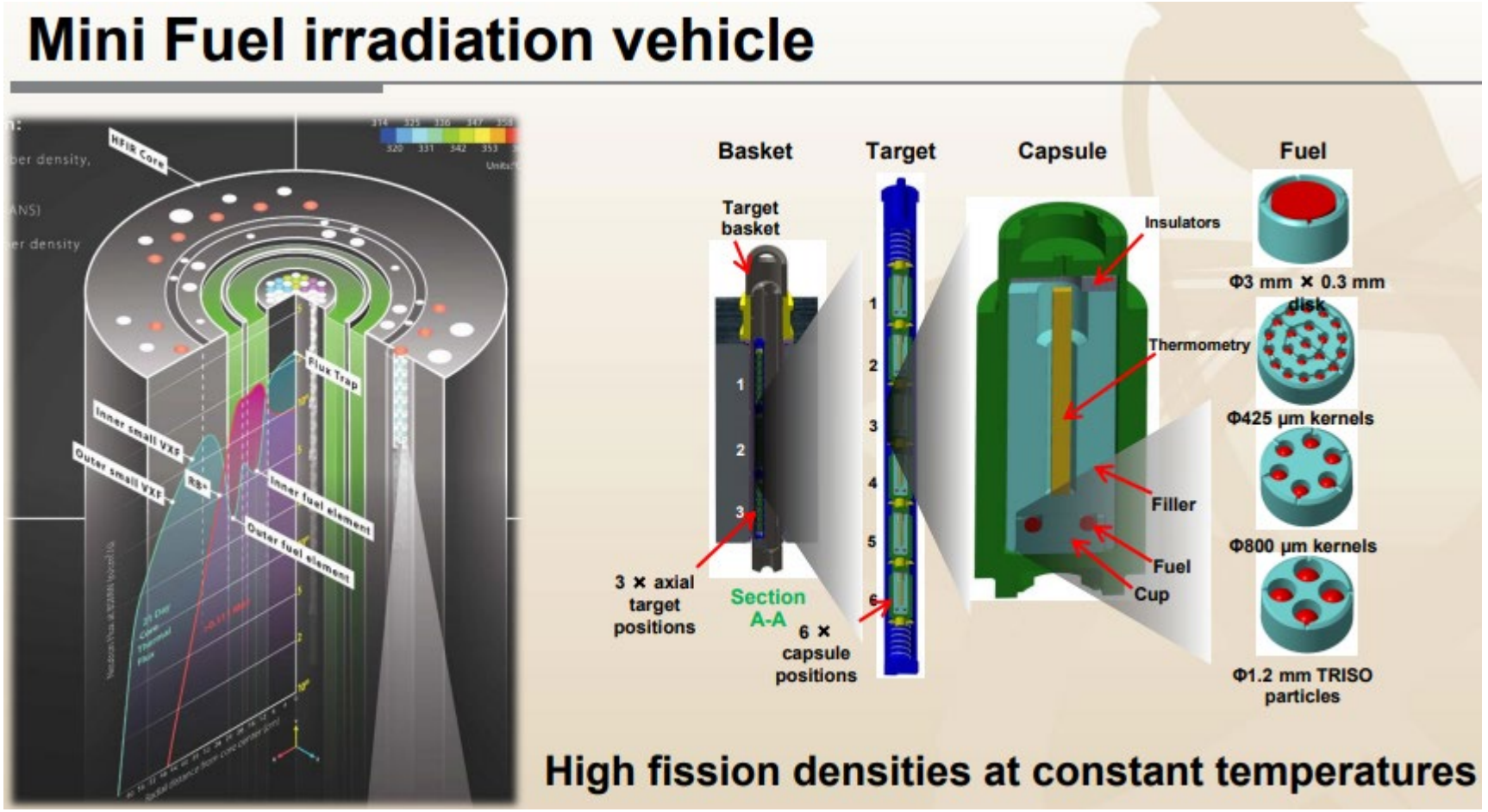
Taken from: MeV (2022)



Taken from: Woolstenhulme, N., Heidrich, B. and Bhowmik. P.K. (2022)

Experiment: Irradiation Test Apparatus at HFIR

IRRADIATION TESTING AND EXAMINATION

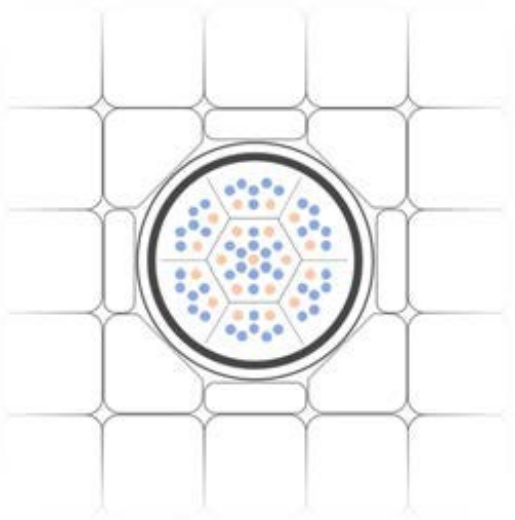


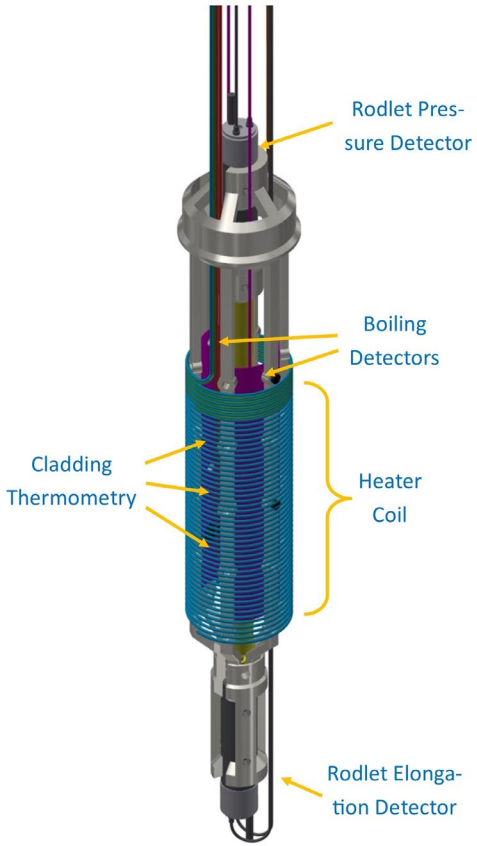
Taken from:
Bhowmik. P.K. (2022)

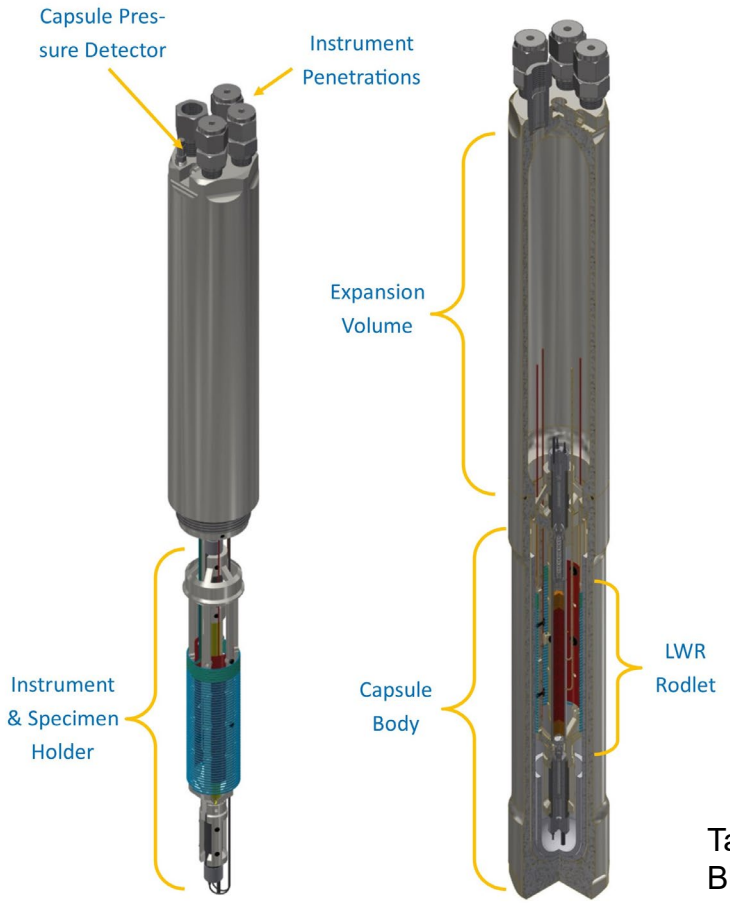
Experiment: Irradiation Test Capabilities at TREAT

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





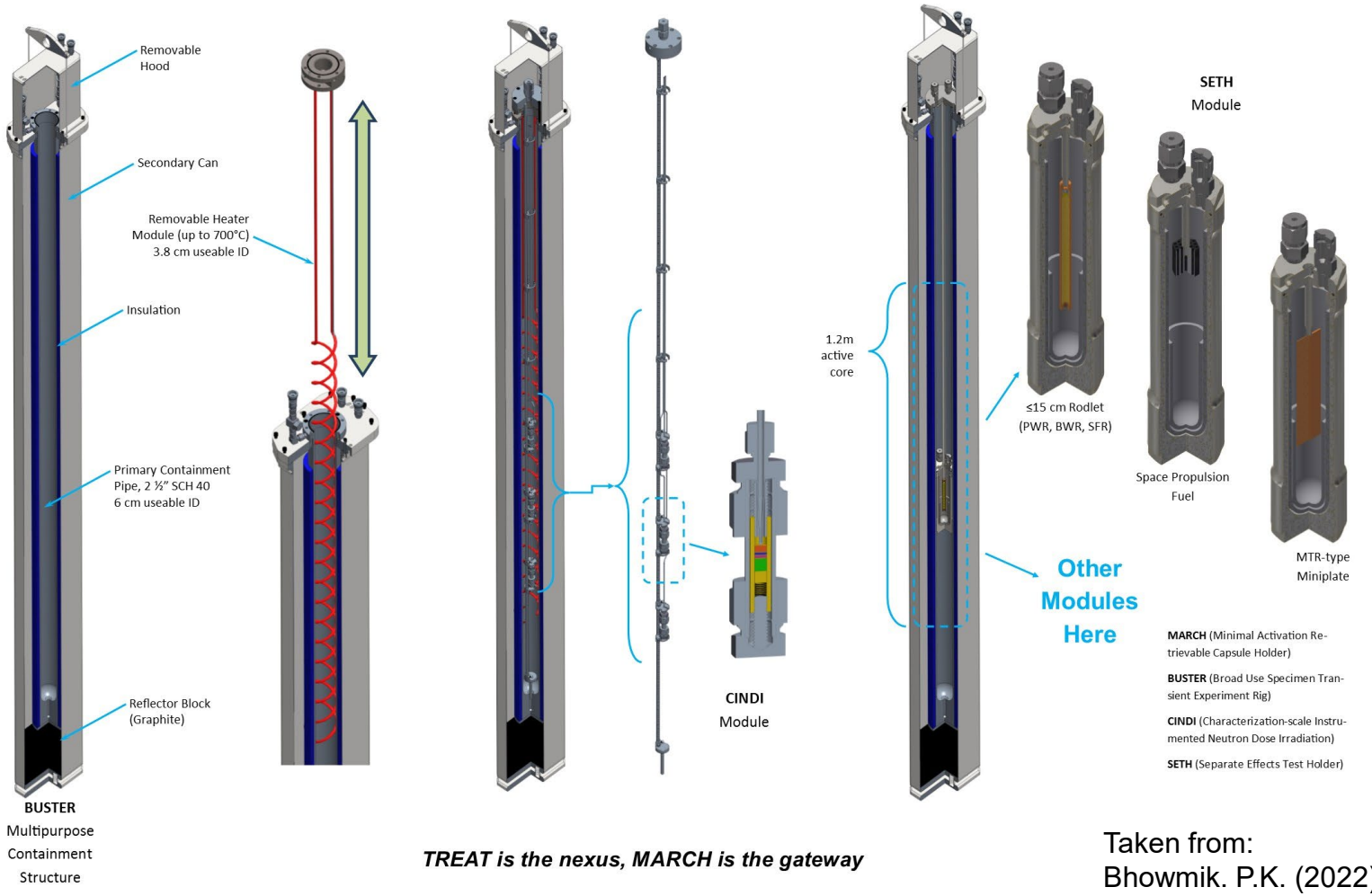


Taken from:
Bhowmik. P.K. (2022)

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

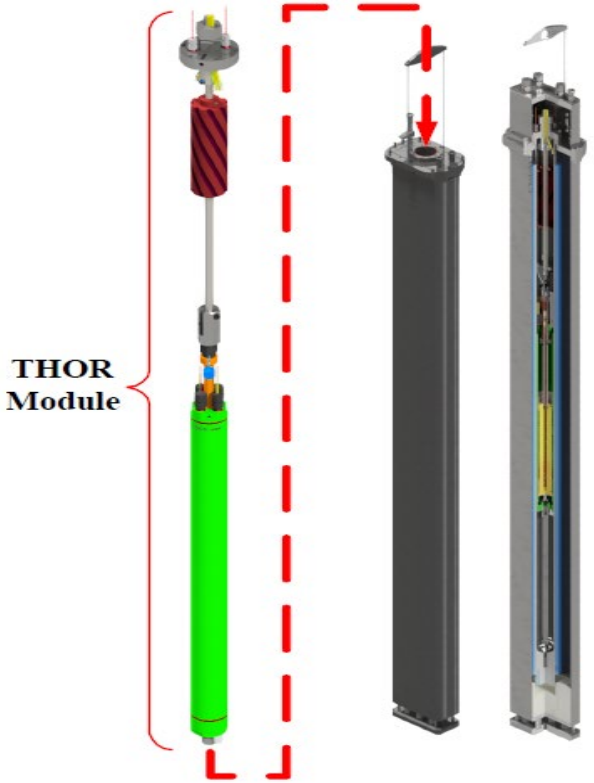
IRRADIATION TESTING AND EXAMINATION

The MARCH System



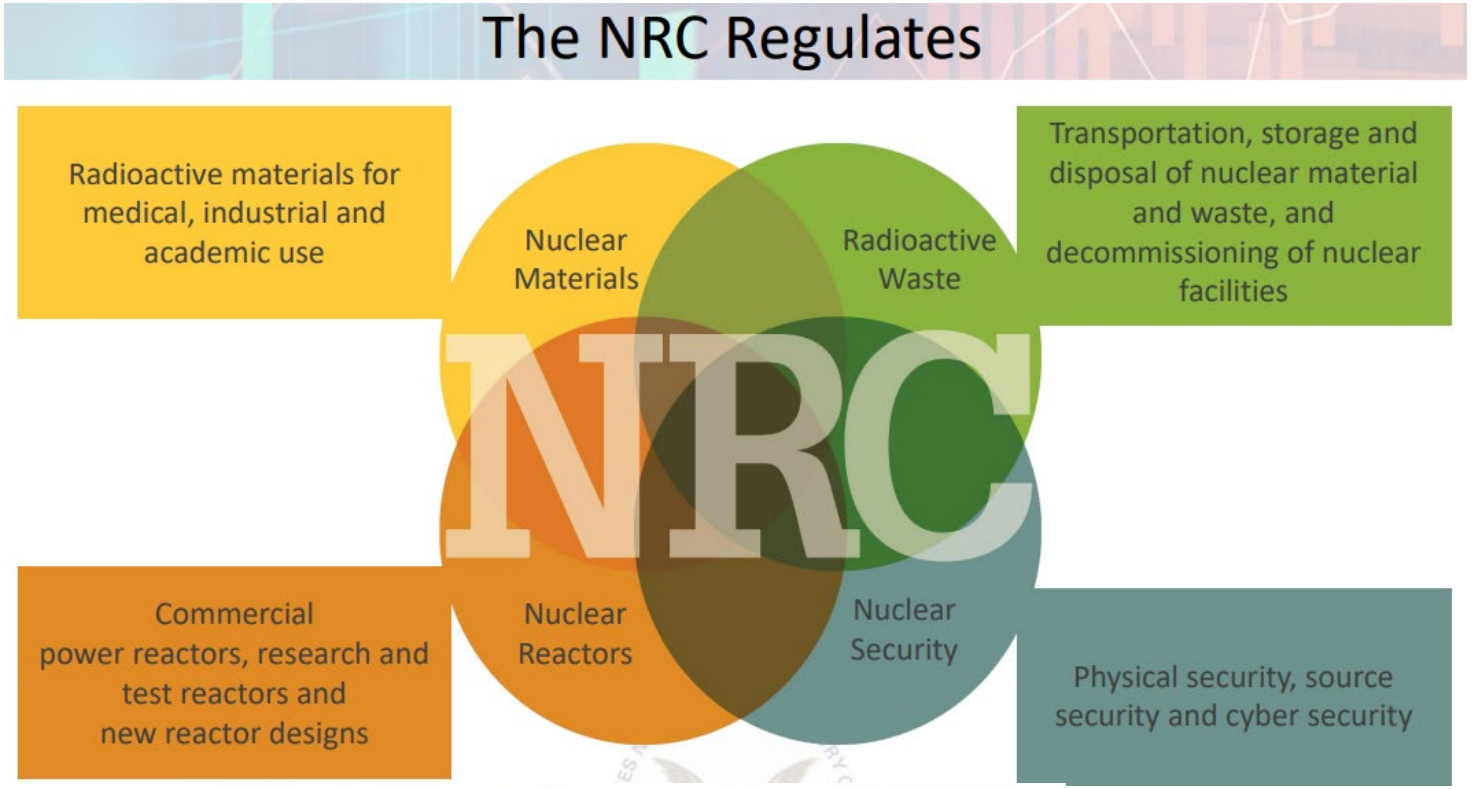
TREAT is the nexus, MARCH is the gateway

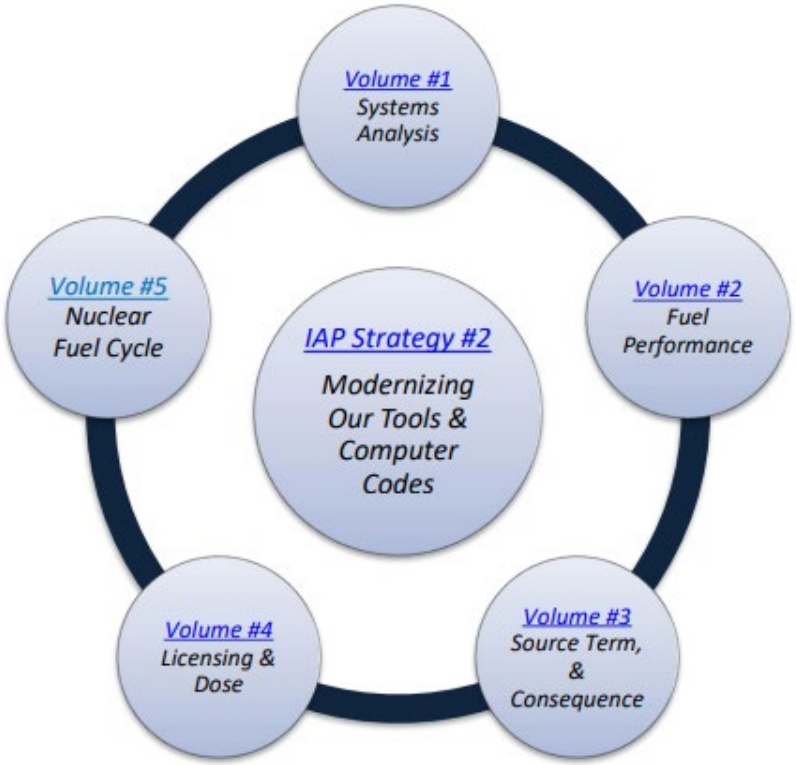
Taken from:
Bhowmik. P.K. (2022)



Temperature Heatsink Overpower Response (THOR)

Validation: Reactor Fuel and Materials Licensing Approaches





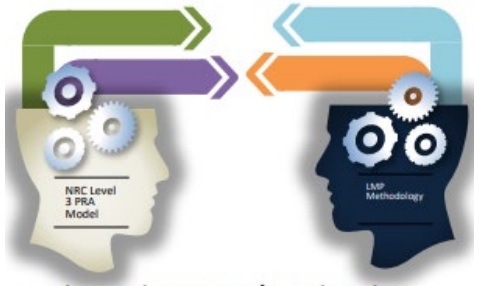
NRC advancing by

Taken from:
Furstenau, R. (2022),

Part-3:

Validation: Reactor Fuel and Materials Licensing Challenges

Advanced Manufacturing Technologies (AMT)



Licensing Modernization Project

Advanced and New Fuels

Components of an AMT Qualification Program

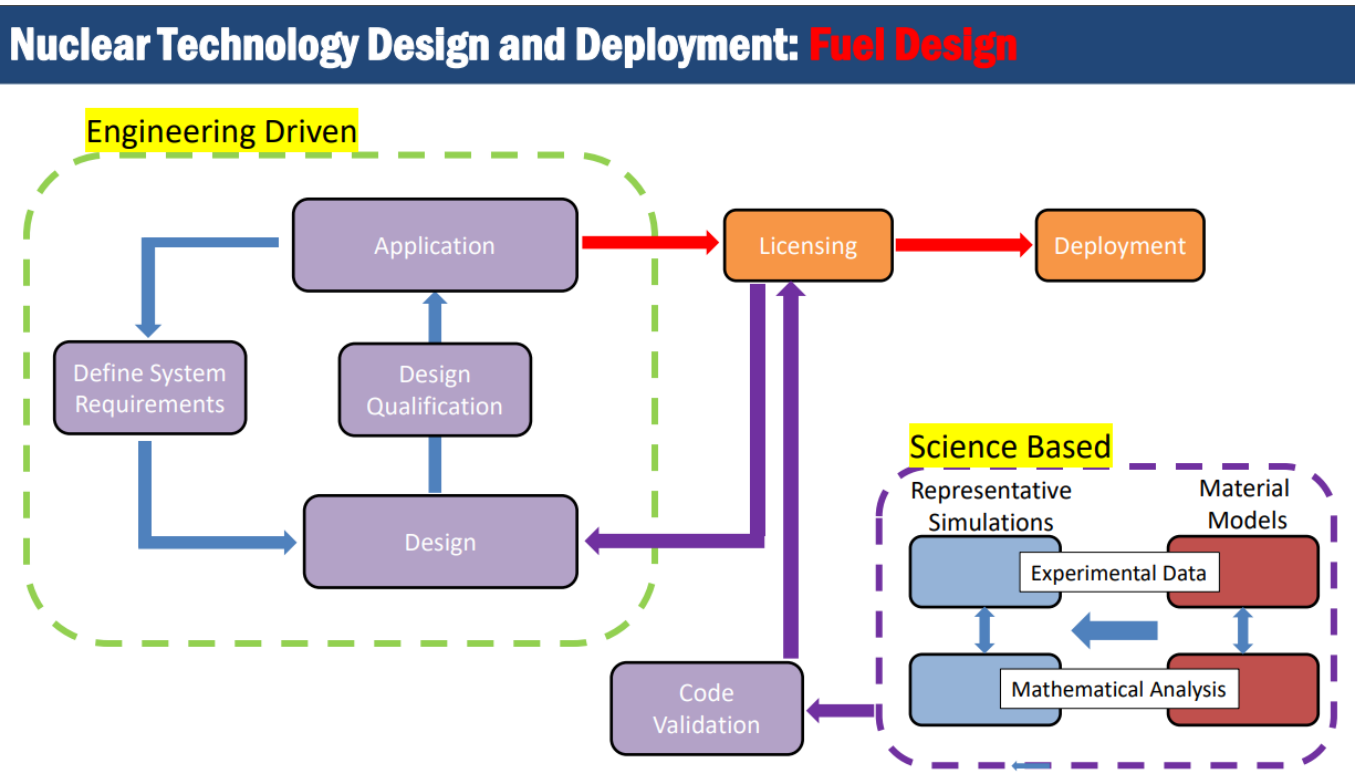
Fabrication Process Qualification	Supplemental Testing	Production Process Control and Verification	Performance Monitoring
Approved Quality Assurance Program			

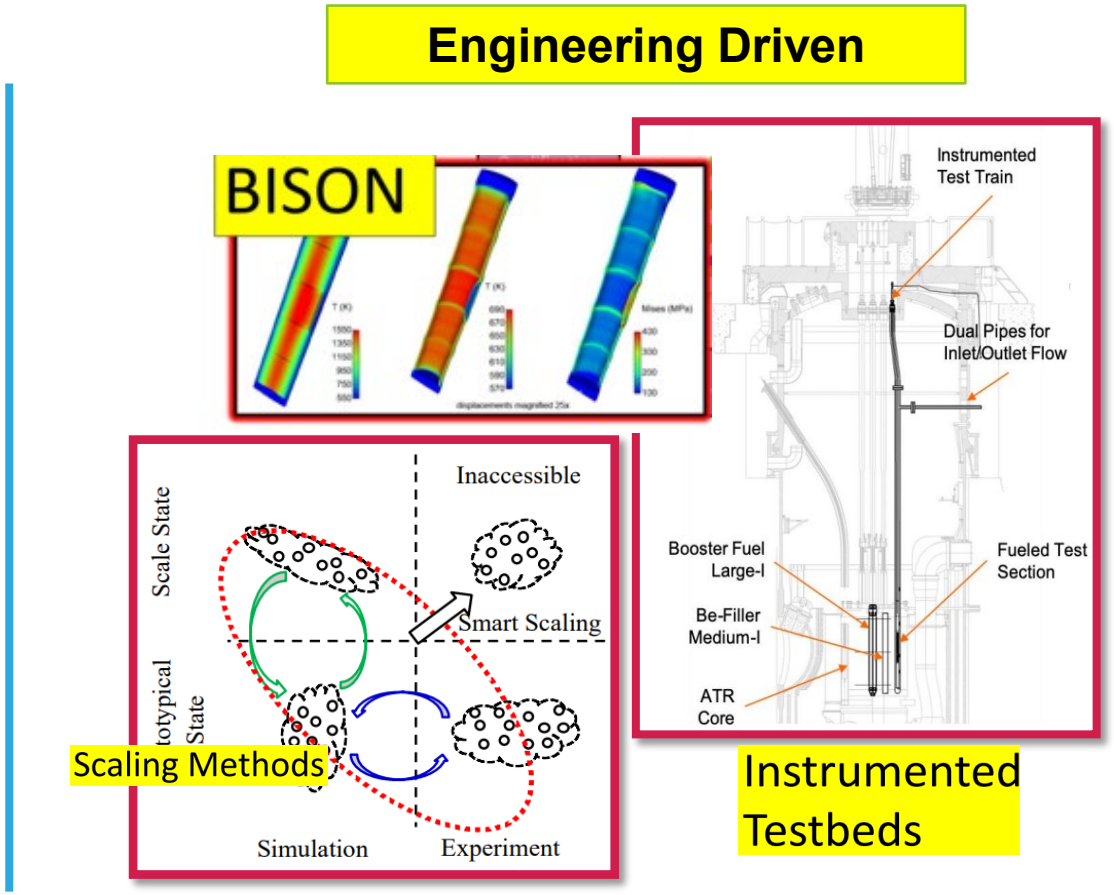
Unirradiated Materials Testing	Test Reactor Irradiations and Testing	Lead Test Assembly Irradiations and Testing	Transient Irradiations and Testing	Updates to Analyses of Record
Source Term and Other Non-Fuel Performance Testing				

Taken from:
Furstenau, R. (2022),

Part-3:

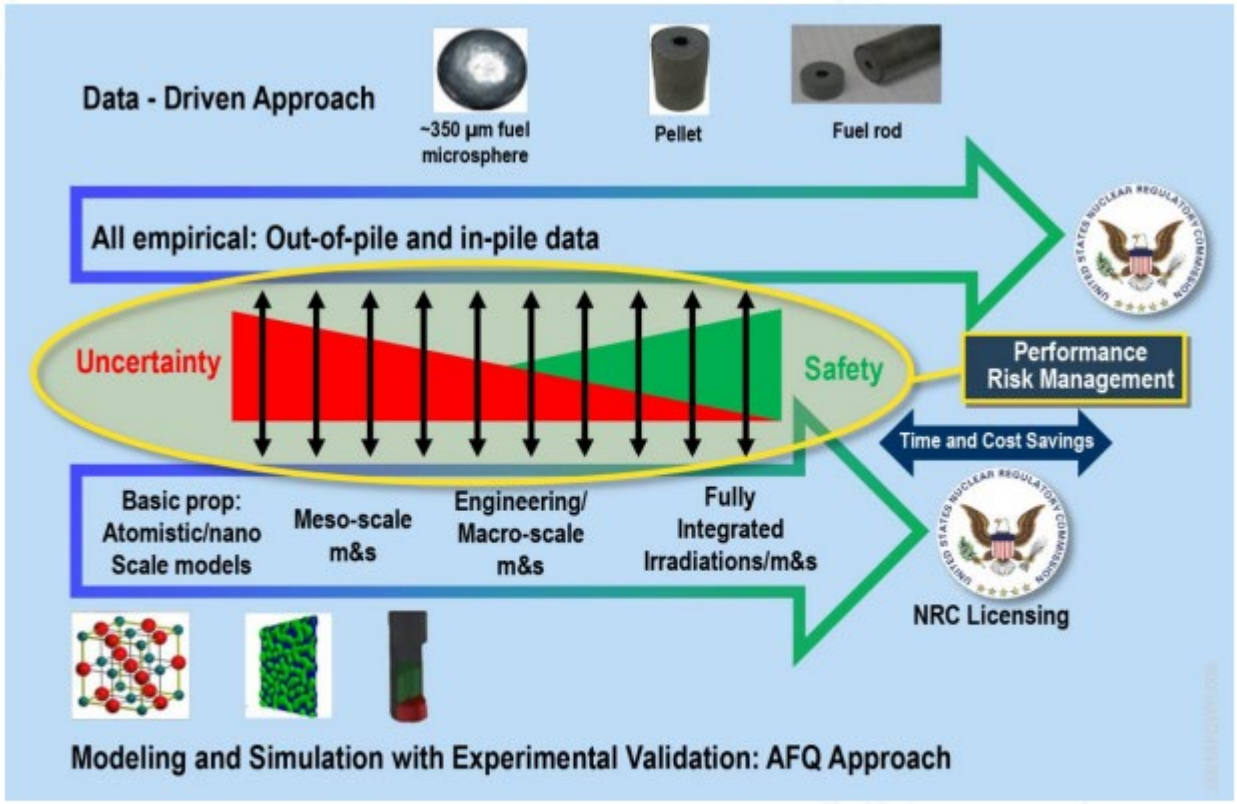
Validation: Fuels and Materials Licensing Pathways





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)

MeV Modeling, Experimentation & Validation SUMMER SCHOOL

Accelerating nuclear fuels and materials qualification by

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

References

- Allen, T. (2022), “Key Challenges to R&D,” Lecture notes, MeV Summer School, University of Michigan.
- Demkowicz P. (2022), “Tristructural Isotropic (TRISO) Fuel,” Lecture notes, MeV Summer School, Idaho National Laboratory.
- Furstenau, R. (2022), “NRC Perspectives,” Lecture notes, MeV Summer School, Nuclear Regulatory Commission.
- Gehin, J. (2022), “Introduction to Today's Nuclear R&D,” Lecture notes, MeV Summer School, Idaho National Laboratory.
- Heidrich, B. (2022), “Nuclear Science User Facilities (NSUF),” Lecture notes, MeV Summer School, Idaho National Laboratory.
- Kropaczek, D. (2022), “Challenges Facing Commercial LWR Industry,” Lecture notes, MeV Summer School, Oak Ridge National Laboratory.
- MeV, Modeling Experiment & Validation Summer School, 2022. www.MeVSchool.net
- Rebak, R. B. (2022), “ATF Cladding,” Lecture notes, MeV Summer School, General Electric Research.
- Bhowmik, P. K., “Irradiation Experiments and Thermal Analysis for Reactor System Design and Analysis at INL,” INL/RPT-22-65890-Rev000, Idaho National Laboratory.
- Paviet, P. (2022), “Overview of the Nuclear Fuel Cycle,” Lecture notes, MeV Summer School, Pacific Northwest National Laboratory.
- Sham, S. (2022), “Overview of Structural Materials and their Qualification for Advanced Reactors,” Lecture notes, MeV Summer School, Idaho National Laboratory.
- Wirth, B. (2022), “Fundamentals: Techniques for Modeling Radiation Damage,” Lecture notes, MeV Summer School, University of Tennessee.
- 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.
- Zinkle, S. (2022), “Fundamentals of Radiation Damage in Materials,” Lecture notes, MeV Summer School, University of Tennessee.

Idaho National Laboratory

Thank you for your attention!

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