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Capability Needs for Irradiated and Radioactive Material

Idaho National Laboratory

NSUF

Nuclear Science
User Facilities

Introduction

Department of Energy, Office of Nuclear Energy (DOE-NE) mission goals:

- enable the continued operation of existing U.S. nuclear reactors.
- enable the deployment of advanced nuclear reactors.
- develop advanced nuclear fuel cycles.
- maintain U.S. leadership in nuclear energy technology

It is essential that the U.S. nuclear energy community to have access to world-leading equipment suitable for conducting research on both nuclear fuels and neutron irradiated, and therefore activated, materials.

Office of Nuclear Energy: Strategic Vision

Highlights a series of research challenges based on its mission

- Accident tolerant fuel
  - irradiation and safety testing, and advance modeling and simulation.
- Continued long term operation
  - deeper understanding of how materials perform (also applicable to advanced reactor technologies).
- Advanced fuel cycles
  - sustainable fuel systems that
    - reduce used nuclear fuel (UNF) and waste
    - improve performance
    - use of resources efficiently
    - enhance safety.
- High burn-up fuel
- Commercial UNF and waste

Identified key infrastructure needs including

- advanced modeling capabilities
- advanced manufacturing
- Facilities for enhanced analysis of irradiated fuels and understanding of materials aging

Ad hoc Committee on Capability Needs for Irradiated and Radioactive Materials Research

- What scientific or engineering knowledge gaps in radioactive materials and radiation effects are most limiting in (i) the sustainability of current light water reactor technologies and (ii) the development and deployment of advanced reactor concepts?
- What currently unavailable experimental capability or modeling and simulation tool is needed to address these knowledge gaps?
- If an available facility is capable of addressing the knowledge gaps, what physical modifications, permission enhancements and/or rule changes are needed to allow progress?
- Can structural and microstructural characterization utilizing synchrotron technologies be used to address the recognized knowledge gaps and, if yes, are these the optimal capabilities to be used or are there more appropriate capabilities?

Committee Members

- Kurt Edsinger (Chair)
  Director of Research & Development, EPRI
- Brian Cummings
  Lead Operations Engineer, Kairos Power
- Michael Ickes
  Senior Materials Integrity Engineer, Westinghouse Electric Company
- Christopher Stanek
  National Technical Director for DOE’s Nuclear Energy Advanced Modeling and Simulation program, Los Alamos National Laboratory
- Steven Zinkle
  Governor’s Chair for Nuclear Materials, University of Tennessee Knoxville
- Simon M. Pimblott (Executive Secretary)
  Laboratory Fellow, Idaho National Laboratory

Needs to Enable Continued Operation of Existing U.S. Nuclear Reactors

"EPRI Materials Degradation Matrix Revision 4"

- summarizes state of industry knowledge about degradation mechanisms and related R&D activities supporting the continued operation of the U.S. light water reactor (LWR) fleet

Key materials knowledge gaps are highlighted as:

- Data supporting embrittlement trend correlations including the characterization of high fluence embrittlement trends for pressurized water reactors (PWRs) and the factors contributing to increased embrittlement rates at lower neutron flux for boiling water reactors (BWRs).
- Stress corrosion cracking (SCC) which is considered the primary challenge to light water reactor integrity and where predicting future behavior is not currently possible as knowledge gaps concerning degradation processes modeling capabilities are limited.
- Data on behavior of irradiated materials used on the periphery of the core which will experience significant end-of-life neutron fluences in life-time extension scenarios.

Specific Challenges

- Embrittlement:
  - understanding and prediction of ductile to brittle transition temperature (DBTT) as matrix copper decreases in high fluence materials such as reactor vessel low alloy steel and other high fluence damage phenomena
- Void swelling:
  - complex phenomenon is dependent on chemical composition of the medium and thermal mechanical treatment as well as irradiation conditions
  - more data for 304 and 316 SS from samples taken “from long time operated PWRs”.
- IASCC:
  - understanding of IASCC processes and characterization of the parameters influencing IASCC susceptibility
  - predicting IASCC initiation in high fluence materials in PWR environments
  - identifying of key factors influencing IASCC initiation and growth in welded SS materials exposed to coolant in BWR

Needs to Enable Deployment of Advanced Concept Nuclear Reactors

High-level impediments to the deployment of advanced reactor concepts:

- Understanding, prediction and control of the behavior and performance of new coolants,
- Better understanding of material physics
- Neutron irradiation of nuclear fuels and materials
- Mitigation, reuse, and/or disposal of radioactive waste

"The U.S. Nuclear R&D Imperative. A Report of the American Nuclear Society Task Force on Public Investment in Nuclear Research & Development"

Specific research needs

- High performance computational modeling of materials for advanced reactor designs
- Investigations of the behavior and performance of advanced fuels under operating and off-normal conditions
- Development of alternative materials
- Prediction of component aging and replacement

Requires “a set of unique national facilities”, including test reactors, hot-cells and other PIE facilities, HPC capabilities, databases, and that enhanced capability programs are required to maintain, enhance and expand infrastructure and provide “best in class” research tools.

Access to such programs is currently available through National Reactor Innovation Center (NRIC), Gateway for Advanced Innovation in Nuclear (GAIN) and the NSUF.

“ROSATOM has the crucial advantage of the world’s only fast neutron test reactor – BOR-60.”

Needs to Enable Deployment of Microreactors and Small Modular Reactors

Top-level challenges:

- structural materials performance
- legacy fuel qualification
- advanced fuel fabrication and supply
- performance of the TRi-structural ISOtropic (TRISO) particle fuel form
- structural materials irradiation data

GAIN Micro-reactor Program Workshop held in May 2021

Needs to Enable Deployment of Microreactors and Small Modular Reactors

Knowledge gaps on post irradiation performance of materials:

- thermophysical and mechanical properties, including
  - measurements of swelling
  - thermal expansion
  - elastic properties
  - thermal diffusivity
  - microstructure
  - hardness

Careful balance required between what is needed by industry and what [academic and national laboratory] researchers want to do

- timely studies to fill knowledge gaps rather than to develop understanding.

GAIN Micro-reactor Program Workshop held in May 2021

Approach to Understanding Research Needs

Used two different approaches:

1. Considering the types of data needed to address the needs of DOE-NE to meet its mandated mission, for instance mechanical and thermophysical properties and the relationship of these properties to the underpinning microstructural material properties and their dynamic evolution under irradiation.

2. Considering generic data needs rather than the needs for a specific reactor type.

The highlight R&D challenges can be divided into two specific classes, structural materials and fuels, and a third catch-all group for other important research needs.

Structural Materials

a) In situ methods to diagnose degradation and its evolution
b) Accelerated qualification of new materials—including a side-by-side comparison with currently qualified materials
c) Synergistic effects of temperature and irradiation—collecting material properties in reactor environments—creep and creep rupture
d) Materials performance at very high temperatures, including embrittlement—microreactors vs current reactors
e) Dimensional stability of ceramic vs metallic materials
f) Relationship between power history and fatigue

Fuels

a) Fragmentation of high-burnup fuel
b) Fuel performance in accident scenarios—development and deployment of accident-tolerant fuels
c) Fuel-clad chemical interactions
d) Modeling and simulation of fuel behavior

Other

a) Modeling and simulation for a mechanistic understanding of ion beam effects and their efficacy in predicting neutron studies

b) Chemistry underpinning advanced reactor concepts—molten fuel salts, the role of impurities, corrosion processes in nonaqueous environments

c) Data management and analysis—artificial intelligence and machine learning.

Relative Importance of Capability Needs

- Over vs under supply—Are current capabilities right sized? What is the bottleneck?
- Complexity vs cost—What is the necessary level of understanding?
- Science vs engineering approach—Can a mechanistic understanding replace (or at least reduce the need for) quantification and qualification?
- Doing more with less—What is the value of studies performed on small samples of irradiated materials with low dose rates in the absence of studies on more active larger samples?

"Tractable research" for the short and intermediate term as well as on which material behavior and performance endpoints are important to address the needs of the nuclear industry

Priority Gaps

- Radiological facilities for irradiated material and fuel Studies.
- Storage capability for a comprehensive well-catalogued library of fuel and irradiated material samples.
- Dedicated hot cell capabilities that facilitates “clever testing” and the accelerated measurement of creep at the microscale.
- High temperature molten salts loop capabilities able to mimic advanced reactor environments of not only temperature and salt composition but also intense neutron and gamma radiation.
- Irradiation facilities with precise control of experiment temperature.

Conclusions

The key challenges to continued operation of existing U.S. nuclear reactors and to realizing advanced nuclear concepts are **quantifying and predicting material performance**.

To fulfil its stated mission goals DOE-NE needs **access to the most advanced characterization techniques for technologically relevant materials**.

“The U.S. Nuclear R&D Imperative. A Report of the American Nuclear Society Task Force on Public Investment in Nuclear Research & Development, American Nuclear Society, 2021” clearly says

1. testing and “hard data” are essential to support the design, development, and deployment of advanced reactor concepts, incorporating advanced nuclear fuels and materials
2. it is imperative to “build and maintain [research] infrastructure” and to “strengthen and expand capabilities” that are at the foundation of U.S. nuclear science and technology.

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