



Capability Needs for Irradiated and Radioactive Materials Research

April 2022

Ad Hoc Committee Summary Report

Kurt Edsinger, Electric Power Research Institute (Chair)

Brian Cummings, Kairos Power

Michael Ickes, Westinghouse Electric Company

Chris Stanek, Los Alamos National Laboratory

Steven Zinkle, University of Tennessee at Knoxville

Simon M. Pimblott, Idaho National Laboratory (Executive Secretary)



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

DISCLAIMER

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

Capability Needs for Irradiated and Radioactive Materials Research

Ad Hoc Committee Summary Report

Kurt Edsinger, Electric Power Research Institute (Chair)
Brian Cummings, Kairos Power
Michael Ickes, Westinghouse Electric Company
Chris Stanek, Los Alamos National Laboratory
Steven Zinkle, University of Tennessee Knoxville
Simon M. Pimblott, Idaho National Laboratory (Executive Secretary)

April 2022

**Idaho National Laboratory
Nuclear Science User Facilities
Idaho Falls, Idaho 83415**

<http://www.inl.gov>

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

Page intentionally left blank

Summary

It is essential for the United States nuclear energy community to have access to world-leading equipment suitable for conducting research on both nuclear fuels and structural materials, including neutron irradiated—and therefore activated—materials. To address future research infrastructure requirements to support the Department of Energy Office of Nuclear Energy mission, the Office of Reactor Fleet and Advanced Reactor Deployment established an ad hoc committee to gather information on potential capability gaps for radioactive materials and radiation effects research. This document summarizes the discussions of that committee addressing the high-level challenges in irradiated and radioactive materials research and the capabilities needed to address these challenges. After considering various needs, the committee agreed on four top-level targets and priority capability gaps, including:

1. Radiological facilities for irradiated material and fuel studies, such as the refurbishment or replacement of the unique inert atmosphere hot-cell facilities at the Hot Fuel Examination Facility in the Materials and Fuels Complex at the Idaho National Laboratory site
2. Storage capability for a comprehensive well-catalogued library of fuel and irradiated material samples
3. Dedicated hot-cell capabilities that facilitate “clever testing” and the accelerated measurement of creep at the microscale
4. High-temperature molten-salt loop capabilities able to mimic advanced reactor environments (temperature and salt composition, intense neutron and gamma radiation, etc.)
5. Irradiation facilities with precise control of experiment temperature.

Page intentionally left blank

Contents

Summary	iii
Acronyms	vii
INTRODUCTION	1
Committee Membership	2
CHALLENGES IN IRRADIATED MATERIALS AND NUCLEAR FUELS RESEARCH	3
Operation of Existing Nuclear Reactors	3
Needs for the Deployment of Advanced Reactor Concepts	4
Deployment of Microreactors and Small Modular Reactors	5
Discussion of R&D Challenges	5
COMMITTEE APPROACH TO UNDERSTANDING R&D CHALLENGES	5
RESEARCH CAPABILITY NEEDS	6
CRITICAL CAPABILITY GAPS	7
Gap 1: Radiological Facilities for Irradiated Material and Fuel Studies	7
Gap 2: Storage Capability for a Comprehensive Well-Catalogued Library of Fuel and Irradiated Material Samples	8
Gap 3: Dedicated Hot-Cell Capability that Facilitates “Clever Testing” and the Accelerated Measurement of Creep at the Microscale	8
Gap 4: High-Temperature Molten-Salt Loop Capabilities Able to Mimic Advanced Reactor Environments (Temperature and Salt Composition, Intense Neutron and Gamma Radiation, Etc.)	8
Gap 5: Irradiation Facilities with Precise Control of Experiment Temperature	9
CONCLUSIONS	9
REFERENCES	10
OTHER LITERATURE REVIEWED	10
Appendix A Committee Terms of Reference	12
INTRODUCTION	13
CONSTITUTION	13
MISSION STATEMENT	13
DELIVERABLE	14

Page intentionally left blank

Acronyms

DOE	U.S. Department of Energy
DOE-NE	U.S. Department of Energy, Office of Nuclear Energy
DOE-SC	U.S. Department of Energy, Office of Science
EPRI	Electric Power Research Institute
GAIN	Gateway for Accelerated Innovation in Nuclear
IASCC	irradiation-assisted stress corrosion cracking
INL	Idaho National Laboratory
LWR	light-water reactor
NFML	Nuclear Fuels and Materials Library
NSUF	Nuclear Science User Facilities
PWR	pressurized-water reactors
R&D	research and development
UNF	used nuclear fuel
U.S.	United States

Page intentionally left blank

Capability Needs for Irradiated and Radioactive Materials Research

INTRODUCTION

The United States (U.S.) Department of Energy, Office of Nuclear Energy's (DOE-NE's) mission goals are to:

- 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.

To meet these goals, it is essential for the U.S. nuclear energy community to have access to world-leading equipment for conducting research on both nuclear fuels and structural materials, including neutron irradiated—and therefore activated—materials.

DOE-NE maintains unique research and development (R&D) infrastructure that supports not only the U.S. nuclear industry, but also nuclear capabilities central to the missions of the National Aeronautics and Space Administration, Department of Defense, and Department of Energy's (DOE's) National Nuclear Security Administration (e.g., support of radioisotope thermoelectric generators, mobile microreactors, nuclear weapons stockpile, naval nuclear propulsion, and research reactor high-assay low-enriched uranium conversion).

In its Strategic Vision [1], DOE-NE recognized that a series of research challenges resulted from its mission:

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

and it identified key infrastructural needs, including advanced modeling capabilities, advanced manufacturing, enhanced analysis of irradiated fuels, and an understanding of materials aging processes.

To address future research infrastructure requirements to support the DOE-NE mission, the Office of Reactor Fleet and Advanced Reactor Deployment established an ad hoc committee to gather information on potential capability gaps for radioactive materials and radiation effects research.

The committee was tasked with considering the following questions:

- What scientific or engineering knowledge gaps regarding radioactive materials and radiation effects are most limiting in terms of the sustainability of current light-water reactor (LWR) technologies and 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 can address the knowledge gaps, what physical modifications, permission enhancements, and rule changes are needed to foster 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 ones?

The deliverable of the committee is this technical document, through which a list of identified capability gaps is being submitted for review by DOE-NE's Office of Reactor Fleet and Advanced Reactor Deployment.

This summary document addressing the high-level challenges in irradiated and radioactive materials research and the capabilities needed to address these challenges was prepared from notes taken during committee discussions, selected literature sources, and notes from relevant reactor development and deployment meetings workshops. The document specifically considers research needs related to the continued operation of existing U.S. nuclear reactors and the deployment of advanced nuclear reactors, including the deployment of microreactors and small modular reactors.

Committee Membership

The ad hoc committee is a small working group of subject matter experts facilitated by the Nuclear Science User Facilities (NSUF) program. Under its Terms of Reference (Appendix A), the committee comprised five members representing:

- The U.S. Nuclear industry, including advanced reactor concept developers, reactor infrastructure vendors, and reactor operators
- Federal national technical directors associated with the Reactor Fleet and Advanced Reactor Deployment and the Nuclear Fuel Cycle and Supply Chain programs
- Electric Power Research Institute (EPRI)
- Gateway for Accelerated Innovation in Nuclear (GAIN) associated technology working groups
- World-renowned experts from U.S. academia.

The members of the ad hoc committee include:

Brian Cummings, lead operations engineer, Kairos Power

Kurt Edsinger, director of research & development, EPRI

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

Members were invited to participate as individuals rather than as representatives of a company, trade organization, etc. The chair of the committee, Kurt Edsinger, was elected by the committee at its first meeting on November 2, 2021.

The NSUF program was tasked with facilitating and supporting the work of the committee, with the NSUF chief post-irradiation scientist, Simon M. Pimblott, acting as executive secretary. The NSUF director, J. Rory Kennedy, and chief irradiation scientist, Brenden J. Heidrich, participated in committee meetings as nonvoting observers.

Other individuals, including DOE-NE program office staff, were invited to attend committee meetings to address specific subjects, but they had an advisory, nonvoting role.

The committee convened on four occasions between November 2 and December 13, 2021. The following text represents a summary of the committee's discussions.

CHALLENGES IN IRRADIATED MATERIALS AND NUCLEAR FUELS RESEARCH

Among the key challenges to the continued operation of existing U.S. nuclear reactors and the realization of advanced nuclear concepts are the quantification and prediction of material performance. To fulfill its stated mission goals, DOE-NE requires 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 and Development* [2] clearly states that testing and hard data are essential to support the design, development, and deployment of advanced reactor concepts that incorporate advanced nuclear fuels and materials. It goes on to recognize the necessity of building and maintaining [research] infrastructure and strengthening and expanding capabilities that are pivotal to U.S. nuclear science and technology.

Operation of Existing Nuclear Reactors

The state of industry knowledge regarding degradation mechanisms and related R&D activities that support the continued operation of the U.S. LWR fleet is documented in depth in the *Electric Power Research Institute Materials Degradation Matrix, Revision 4* [2], which provides a review of age-related degradation mechanisms in the primary systems of nuclear plants.

The following key material-related knowledge gaps are highlighted:

- Data supporting embrittlement trend correlations, including the characterization of high-fluence embrittlement trends for pressurized-water reactors (PWRs) and the factors that contribute to increased embrittlement rates at a lower neutron flux for boiling-water reactors
- Stress corrosion cracking, considered the primary challenge to LWR integrity, because its behavior cannot be predicted, as knowledge concerning degradation process modeling capabilities is limited
- Data on the behavior of irradiated materials used on the periphery of the core and that experience significant end-of-life neutron fluences in lifetime extension scenarios.

These knowledge gaps suggest several key issues for future research on irradiated materials, including irradiation embrittlement, void swelling, irradiation creep and stress relaxation, and irradiation-assisted stress corrosion cracking (IASCC)—all part of the larger challenge involving stress corrosion cracking.

The following specific challenges are identified:

- Embrittlement. Understanding and prediction of the ductile-to-brittle transition temperature as matrix copper decreases in high-fluence materials (e.g., reactor vessel low-alloy steel) and other high-fluence damage phenomena are currently absent in mechanistically guided predictive models. Quantifying the effects of high-fluence embrittlement phenomena on the ductile-to-brittle transition temperature shift is important for maintaining safety throughout extended component lifetimes.
- Void swelling. This complex phenomenon depends on the chemical composition of the medium and thermal mechanical treatment involved, as well as on the irradiation conditions. More data are needed, especially regarding 304 and 316 stainless steel samples taken from PWRs with a long history of operation.
- IASCC. Research needs include furthering the understanding IASCC processes, characterizing those parameters that influence IASCC susceptibility, predicting IASCC initiation in high-fluence materials in PWR environments, and identifying key factors that influence IASCC initiation and growth in welded stainless-steel materials exposed to coolant in boiling-water reactors. Of particular importance are details on the exact mechanisms of

IASCC, as well as the individual effects of material and environmental parameters on IASCC susceptibility, such as effect of neutron fluence and stress, that would enable IASCC behavior to be predicted.

The report also highlights specific concerns over the performance of high-chromium nickel-based alloys, the dilution and heat-affected zones in welds, the behavior of core periphery materials, and the fact that data on irradiated materials are very limited, especially for samples exposed to high fluences, and for industrially important materials such as Alloy X-750, Type XM-19, and Alloy A-286.

Needs for the Deployment of Advanced Reactor Concepts

High-level impediments to deploying advanced reactor concepts are discussed in the recent report The U.S. Nuclear R&D Imperative: A Report of the American Nuclear Society Task Force on Public Investment in Nuclear Research and Development [3]. The report recommends:

- An examination of new coolants
- A better understanding of material physics
- Neutron irradiation
- The mitigation, reuse, and disposal of radioactive waste.

and highlights the following specific research:

- High-performance computational modeling of materials for advanced reactor designs
- Investigations into the behavior and performance of advanced fuels under operating and off-normal conditions, keeping in mind that “ROSATOM has the crucial advantage of the world’s only fast neutron test reactor: BOR-60”
- Developing alternative materials
- Predicting component aging and replacing components accordingly.

The report states that the design, development, and deployment of advanced reactor concepts—including treatment processes or interim and permanent UNF storage—relies on “a network of world-leading capabilities for performing specialized testing, analysis, development and deployment” (i.e., national R&D testbeds, cutting-edge experimental capabilities, computational capabilities and databases, and experts who can maintain the flexibility and relevance of the testbeds and capabilities). Consequently, the report suggests that DOE-NE “needs to maintain a set of unique national facilities.” These testbed capabilities include test reactors, hot cells, and other post-irradiation examination facilities, high-performance computing capabilities, and databases. It also suggests that enhanced capability programs are required to maintain, enhance, and expand infrastructure and to provide best-in-class research tools.

Testbed capabilities are specialized large, capital-intensive demonstration facilities and neutron sources, such as the Idaho National Laboratory (INL) Advanced Test Reactor, INL Transient Reactor Test Facility, Oak Ridge National Laboratory High Flux Isotope Reactor, and Massachusetts Institute of Technology Reactor—all of which are considered national resources. Access to such capabilities is currently granted via the National Reactor Innovation Center, GAIN, and NSUF. The report emphasizes that overcommitting to a single capability would offer temporary gains but be detrimental to long-term balanced progress. Furthermore, the potential value of a testbed is best demonstrated by the involvement of private demonstration partners since this serves to evidence commercial interest. In this regard, an analysis of submissions to recent industrially targeted NSUF Access Projects afforded anecdotal evidence of important capability needs.

Finally, the report highlights the fact that the deployment of advanced nuclear energy systems relies on a sustainable fuel cycle, beginning with sufficient fissile material and ending with the “safe, environmentally responsible disposal of byproducts.”

Deployment of Microreactors and Small Modular Reactors

The GAIN initiative's Microreactor Program Workshop, held in May 2021, highlighted the following challenges of deploying microreactors and small modular reactors:

- Structural material performance
- Legacy fuel qualification for commercial use
- Advanced fuel fabrication and supply
- Performance of the tri-structural isotropic particle fuel form
- Structural materials irradiation data.

Knowledge gaps identified in the workshop presentations concerning the post-irradiation performance of materials pertained to thermophysical and mechanical properties, including measurements of swelling, thermal expansion, elastic properties, thermal diffusivity, microstructure, and hardness.

Anecdotal comments from industry-based workshop attendees emphasized the need for radiation experiments and materials testing and knowledge gaps in:

- Differences between wrought and additively manufactured material properties
- Core materials and fuel behavior.

A second concern was the paucity of research on commercial fuel development based on legacy fuel studies. Furthermore, industry participants emphasized the importance of striking a careful balance between what industry needs and what academic researchers wish to do (i.e., studies that aim to fill applicable knowledge gaps rather than simply further understanding).

Discussion of R&D Challenges

The key challenges to the continued operation of existing U.S. nuclear reactors and the realization of advanced nuclear concepts are the quantification and prediction of fuels and material performance. To fulfill its stated mission goals, DOE-NE requires 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 and Development* [3] clearly states that testing and hard data are essential to support the design, development, and deployment of advanced reactor concepts that incorporate advanced nuclear fuels and materials. It goes on to state the necessity of building and maintaining [research] infrastructure and strengthening and expanding capabilities that are pivotal to U.S. nuclear science and technology.

COMMITTEE APPROACH TO UNDERSTANDING R&D CHALLENGES

The ad hoc committee considered the most pressing research needs using two different approaches by:

- 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
- 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. The recognized challenges were recognized as:

1. 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
2. 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
3. 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.

The committee considered Topic 3.c particularly important as a potential route for addressing a large number of important challenges facing nuclear energy systems, including, but not limited to, the discovery of new materials for nuclear applications. The fundamental underpinning requirement for artificial intelligence and machine learning methods is library data for training, especially experimental data sets. Consequently, correctly addressing capability needs for research is also central to success in this field.

RESEARCH CAPABILITY NEEDS

Topics the committee considered when discussing the relative importance of the various identified capability needs were:

- 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?

The initial discussion focused on the definition of “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. This discussion led to the capabilities needed to interrogate the material endpoints in evolving nuclear environments.

Infrastructure needs highlighted in the discussion were:

- Facilities for handling radioactive materials emitting nontrivial levels of radiation as current hot-cell facilities are limited, aging, and difficult to access
- Equipment for post-irradiation creep testing of structural materials, including He gas effects incorporating environmental control

- Capabilities for the in situ characterization and study of materials behavior and performance (i.e., materials surveillance in situ and in operando). This target arises from the desire to qualify a material for operation rather than for system lifetime. It is based on the concept of characterization as a way develop a constitutive model, such as a structure-mechanics model to assess creep. (The importance of migrating the capabilities for in situ testing of materials from the Halden project to the Advance Test Reactor was emphasized.)
- Advanced characterization infrastructure and methodologies for the staged development of materials and fuels through a side-by-side comparison of new materials with qualified materials to accelerate deployment
- Facilities allowing the accelerated interrogation of synergistic radiation effects, as well as separate effects testing (the sequential approach, high-temperature testing → irradiation-only testing → in situ ion beam studies → in situ neutron studies, has served well but is already showing “diminishing returns”)
- Capabilities for combined effects studies, such as multi-effect environment testing the coolant, irradiation, and stress effects simultaneously
- Nuclearized techniques for accelerated material testing (rather than simply accelerated material production)
- Extreme environment fuel testing—facilities are “waning” for hard experiments, such as high-burnup fuel evaluation and transient fission gas production and release
- Thermophysical property testing at higher temperatures (i.e., moving from metallics to ceramics, for instance)
- Capabilities to determine the chemistry and thermophysical properties of the coolants underpinning advanced nuclear systems, such as “molten-salt cooled” and “molten-salt cooled and fueled” reactors.

CRITICAL CAPABILITY GAPS

After considering the various needs highlighted in Section 4, the committee agreed on the following key top-level targets to meeting DOE-NE’s mission goals over the next 5 years.

Gap 1: Radiological Facilities for Irradiated Material and Fuel Studies

All of the R&D challenges highlighted in Section 2 emphasize the need for increased access to capabilities for handling irradiated materials, for performing fuels studies and with the ability to interrogate ex-reactor materials. The principal and most urgent capability gap that ought to be developed, and supported, by DOE-NE is radiological handling (i.e., hot-cell) facilities in which currently available and newly developed characterization technologies can be nuclearized. Current hot-cell capabilities throughout the national laboratory complex as well as at universities are aging and in need of refurbishment or replacement due to decades of under investment.^a Consequently, the progress is slow on projects central to the sustainability of the current reactor fleet and the design and deployment of advanced reactor concepts, and the increasing backlog of projects involving irradiated materials and fuels is a significant hindrance to meeting program goals.

Advanced characterization and post-irradiation examination methods have developed significantly, and it is now possible to work with smaller samples than was historically the case; however, while this ability to do more with less has led to increased scientific understanding, the development of micro-structure-property-behavior relationships and more importantly material qualification still require studies with conventionally sized samples.

^a A list of currently available hot-cell capabilities as well as glove box capabilities for research with nuclear fuels and materials is on the Nuclear Energy Infrastructure Database accessible from the NSUF website. [4]

The committee feels that it is essential to be able to handle materials with considerable activity as well as fuel samples with reasonable alpha radiation emitting content (i.e., not just “a few rem at 30 cm”). This emphasis highlights historical, continuing, and ongoing issues with access to cutting-edge science capabilities at DOE Office of Science (SC) user facilities, particularly synchrotrons and other light sources, as well as neutron scattering capabilities, that need to be addressed. The committee also noted that the neutron beam lines at NIST are considerably more user friendly than comparable facilities at the DOE-SC supported SNS and HFIR. Performing experimental studies on irradiated structural materials and nuclear fuels at DOE-SC facilities is a formidable, in fact almost impossible, task. It is important to facilitate and increase access to DOE-SC User Facilities for research utilizing irradiated materials and nuclear fuels of significantly higher activity and with alpha radiation emitting content.

Gap 2: Storage Capability for a Comprehensive Well-Catalogued Library of Fuel and Irradiated Material Samples

Along with the need for capabilities to handle irradiated materials and fuels, interrogative studies of materials and fuel performance require access to an extensive collection of unirradiated and irradiated samples. The variety of material samples currently available in the NSUF Nuclear Fuels and Materials Library (NFML) is limited despite recent efforts to increase the collection size. Furthermore, the NFML is dispersed over a number of (containment) capabilities at various national laboratories and industrial research locations. A desirable option is a common location for the NFML sample library as well as a significant increase in its contents, including a larger number of ex-plant materials and additional samples from targeted library irradiations of various materials under different environments, with the ultimate goal being a comprehensive library of model fuels and structural and cladding materials as well samples from decommissioned commercial reactors.

Gap 3: Dedicated Hot-Cell Capability that Facilitates “Clever Testing” and the Accelerated Measurement of Creep at the Microscale

One of the most pressing industrial needs for both existing reactor operation and the development and deployment of advanced concept reactors is the ability to predict the creep performance of materials. Researchers urgently need the capabilities to perform creep testing on irradiated materials to allow at least the empirical prediction of, if not a thorough mechanistic understanding of, performance.

The microscale examination of material properties offers the possibility of a significant acceleration in creep testing as well as the provision of significant mechanistic information. The required technology is available and has been demonstrated (by for instance Peter Hosemann at the University of California Berkeley). To translate the results of microscale studies to bulk material behaviors, the approach needs to be validated by comparing multiple microscale tests against macroscale tests. In addition, data analytic methods are required to understand and compensate for stochastic effects.

“Gee whiz” one-off demonstration studies (often performed by academic researchers) are not needed or helpful. Rather infrastructure that will facilitate coordinated synchronized campaigns is required. Such campaigns will overcome the stochastic effects inherent in microscale studies of material behaviors providing a microscale understanding and prediction of bulk properties and performance.

Gap 4: High-Temperature Molten-Salt Loop Capabilities Able to Mimic Advanced Reactor Environments (Temperature and Salt Composition, Intense Neutron and Gamma Radiation, Etc.)

Learning from the Molten Salt Reactor Experiment, which operated briefly at Oak Ridge National Laboratory in the 1960s, the principal chemical concern for advanced molten-salt fueled and cooled reactor concepts as well as the Kairos Power molten-salt-cooled tri-structural-isotropic-fueled reactor design is keeping the salt clean. The R&D challenges include:

- Understanding the role and effects of impurities—vapor pressure of lanthanides and actinides – thermophysical properties
- Detecting and quantifying radiation for dilute solutions—needs an in situ approach (vs current ex situ sampling method)
- Determining H-3 sorption onto reactor materials and moderators
- Developing sensors for active, high-temperature monitoring and control under neutron environments.

Many of these needs are clearly about taking the plant to operation and are short-term and applied science or engineering in nature; however, there is a paucity of facilities capable of providing the required experimental data and underpinning chemistry needed to develop current and advanced nuclear system models and codes, especially for molten-salt reactor concepts.

The committee discussion decided that the biggest priority for investment in this area was *in situ capabilities*. One specific example is detection and characterization methods of trace impurities of actinides and other fission products. For example, in molten fluoride salt reactors, the circulating salt will have an intense gamma radiation field, and the current approach of pulling samples for *ppm* chemical analysis is not satisfactory. Targets would include the development of radiation hard sensors for O₂ and H₂O control and redox chemistry control and investigating chemical momentum.

The need for coolant chemistry test bed capabilities is not limited to molten-salt systems. There is a similar need for all nonconventional coolant concepts. In addition, it is important that in-reactor loop capabilities are available for studies in reactor environments.

Gap 5: Irradiation Facilities with Precise Control of Experiment Temperature

While the provision of material irradiation facilities does not fall within the scope of the ad hoc committee, the committee would like to emphasize a significant capability challenge associated with current test reactors. To perform meaningful experimental research campaigns and obtain appropriate information for the design and deployment of advanced reactor concepts, researchers need irradiation facilities that can more precisely control experiment temperature. Temperature control at the nuclear material irradiation workhorse utilized for many experimental campaigns, INL's Advanced Test Reactor, is currently +/- 50°C. This level of precision is wholly unacceptable for mechanistic and interpretive studies. The factors affecting and determining this (lack of) precision are well understood and could be mitigated with advanced planning and holding the reactor operation to an established plan.

CONCLUSIONS

The ad hoc committee feels that DOE-NE needs to take a strategic, rather than responsive, approach to capability development (i.e., develop a plan for an investment in capabilities). In a world with finite available resources, the development of costly facilities of limited applicability prevents investment elsewhere. The ad hoc committee suggests that the development of radiological capabilities for the deployment of advanced characterizing and testing methodologies is the most important gap that needs to be addressed to allow studies of highly irradiated materials and nuclear fuels.

REFERENCES

- [1] Office of Nuclear Energy. 2021. “Strategic Vision, Department of Energy.” <https://www.energy.gov/sites/default/files/2021/01/f82/DOE-NE%20Strategic%20Vision%20Web%20-%20001.08.2021.pdf>
- [2] Electric Power Research Institute. 2018. “EPRI Materials Degradation Matrix Revision 4.” EPRI Technical Report 3002013781. <https://www.epri.com/research/products/000000003002013781>.
- [3] American Nuclear Society. 2021. “The U.S. Nuclear R&D Imperative: A Report of the American Nuclear Society Task Force on Public Investment in Nuclear Research & Development.” <https://www.ans.org/policy/rndreport/?msclkid=3fbaacc4d09a11ecaf3a6cad39b60497>.
- [4] <https://nsuf-infrastructure.inl.gov/Browse/Map> Accessed March 2022. Requires login.

OTHER LITERATURE REVIEWED

A Strategy for Nuclear Energy Research and Development, INL/EXT-08-15158, 2008.

Advanced Fuels Campaign Execution Plan: Nuclear Technology Research and Development, INL/EXT-10-18954, Revision 9, 2018.

Advanced Nuclear Reactors: Technology Overview and Current Issues, Congressional Research Service R45706, 2019.

Assessment of Materials Issues for Light-Water Small Modular Reactors, PNNL-22290, 2013.

BWRVIP-167, Revision 4: BWR Vessel and Internals Project: Boiling Water Reactor Issue Management Tables. EPRI 3002018319, 2020.

Criteria and Planning Guidance for Ex-Plant Harvesting to Support Subsequent License Renewal, PNNL-27120 Rev. 1, 2019.

DOE-NE Light Water Reactor Sustainability Program and EPRI Long-Term Operations Program – Joint Research and Development Plan, INL/EXT-12-24562, 2013.

Expanded Materials Degradation Assessment (EMDA) Volume 1: Executive Summary of EMDA Process and Results, NUREG/CR7153. Vol. 1, US NRC, 2014.

Light Water Reactor Sustainability Program — A Summary of Collaborative Research and Development Activities, INL/EXT-19-52416, 2019.

Light Water Reactor Sustainability Program Materials Research Pathway Technical Program Plan, ORNL/TM-2020/1846, 2020.

Long Term Operation R&D to Investigate the Technical Basis for Life Extension and License Renewal Decisions, IAEA-CN-194-008.

Materials Reliability Program: PWR Internals Aging Degradation Mechanism Screening and Threshold Values (MRP-175), EPRI Topical Report 1012081, 2005.

Materials Reliability Program: Pressurized Water Reactor Issue Management Tables - Revision 4 (MRP-205), EPRI 3002018255, 2020.

Nuclear Energy Research and Development Roadmap: Future Pathways, HM Government, 2013.

Nuclear Energy Research, Development and Demonstration Roadmap: Report to Congress, DOE, 2015.

Nuclear power in the 21st century: Challenges and possibilities, Ambio 45, 38–49 (2016).

Research and Development Needs for Current and Future Nuclear Energy Systems, NEA No. 4453, OECD 2003.

Results of U.S. Nuclear Industry Council 2021 Advanced Nuclear Survey, USNIC, 2021EPRI Materials Degradation Matrix Revision 4, EPRI Technical Report 3002013781, 2018.

Page intentionally left blank

Appendix A

Committee Terms of Reference

Ad Hoc Committee on Capability Needs for Irradiated and Radioactive Materials Research: Terms of Reference

INTRODUCTION

To meet the DOE-NE mission goals to:

- 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 for 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.

The aim of the ad hoc committee is to gather information about the potential need for advanced characterization capabilities for use on neutron-irradiated materials and highly radioactive nuclear fuels to support the DOE-NE mission.

CONSTITUTION

The committee shall be a small working group of subject matter experts facilitated by NSUF. The committee shall have a maximum of five members comprised of individuals from:

- The U.S. nuclear industry, including advanced reactor concept developers, reactor infrastructure vendors, and reactor operators
- Federal national technical directors associated with the “Reactor Fleet and Advanced Reactor Deployment” (NE-5) and the “Nuclear Fuel Cycle and Supply Chain” (NE-4) programs
- EPRI
- GAIN technology working groups
- World-renowned experts from U.S. academia.

The members of committee are invited to participate as individuals rather than as representatives of a company, trade organization, etc. The chair of the committee will be elected by the committee at the first meeting.

The program office of the DOE-NE NSUF will facilitate and support the committee’s work, with the NSUF chief post-irradiation scientist acting as executive secretary. The NSUF director and chief irradiation scientist may participate in committee meetings as nonvoting observers.

Other individuals may be invited to attend committee meetings to address specific subjects, but they shall have an advisory, nonvoting role.

MISSION STATEMENT

The committee will consider the following questions:

- What scientific or engineering knowledge gaps in radioactive materials and radiation effects are most limiting in the sustainability of current LWR technologies and 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 address the knowledge gaps, what physical modifications, permission enhancements, and 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?

DELIVERABLE

The committee's deliverable will be a draft factual document and recommendation submitted to NSUF program management at DOE-NE.

At the committee's first meeting:

- DOE-NE agreed to postpone the report deadline until "mid-January"
- DOE-NE requested that the panel focus on the "near term" (i.e., a 5-year horizon) and on the big picture rather than one or two targets.